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AKADEMIJA STROJNIŠTVA 2025

INŽENIRSTVO – STABILNOST V ČASU STRATEŠKIH PREOBRAZB

17. NOVBMBRA 2025 OB 18³⁰



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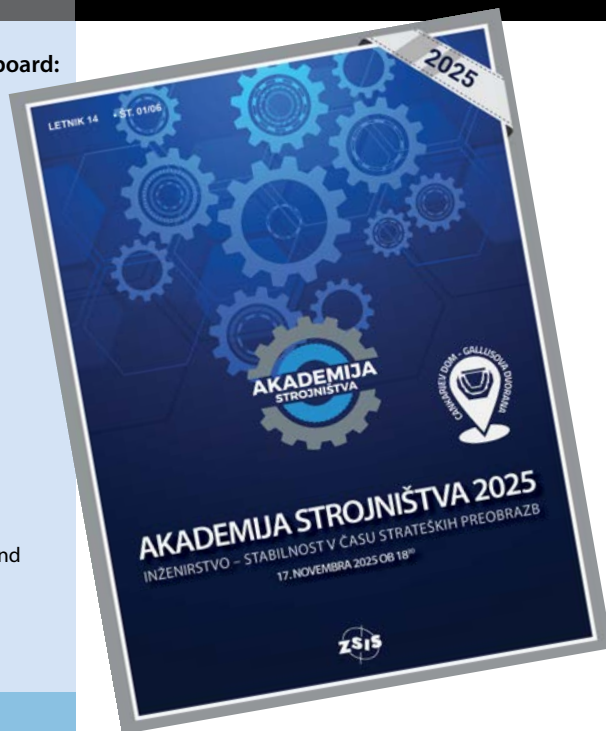
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Akademija strojništva november 2025

Spoštovani,

Leto 2025 prinaša gospodarstvu in družbam številne preizkušnje; od motenj v globalnih verigah in naraščajoče geopolitične negotovosti do podnebnih pritiskov, kibernetских grožnj in preobrazbe energetskih sistemov. Svet se spreminja hitro in pogosto nepredvidljivo.



V tej realnosti postaja inženirstvo tisto sidro stabilnosti, ki s svojim znanjem, sistemskim razmišljanjem in ustvarjalno močjo omogoča napredek, prilagodljivost in zaupanje v prihodnost. Slovensko strojništvo, zasidrano v tradiciji in hkrati usmerjeno v digitalne in zelene preboje, ima moč, da oblikuje rešitve – ne le za industrijo, ampak za celotno družbo.

Akademija strojništva z vašo pomočjo iz leto v leto raste, tako kot raste in se razvija inženirska stroka. Hvaležni smo, da se moč inženirstva tudi s tem dogodkom v družbi povečuje.



AKADEMIJA STROJNIŠTVA 2025

INŽENIRSTVO – STABILNOST V ČASU STRATEŠKIH PREOBRAZB

LJUBLJANA, CANKARJEV DOM TER PREK SPLETA

17. NOVEMBER 2025 OB 18³⁰



ZVEZA STROJNIH INŽENIRJEV SLOVENIJE
WWW.ZVEZA-ZSIS.SI

PROGRAM

UVODNI NAGOVORI

PODELITEV NAGRAD

NAGRADA ZA GLOBALNO PRODORNOST SLOVENSKEGA INŽENIRSTVA

NAGRADA ZA ŽIVLJENJSKO DELO NA PODROČJU STROJNIŠTVA

IZ RODA V ROD SI INŽENIRSTVO UTIRA POT

OKROGLA MIZA

ZSIS - ZVEZA STROJNIH INŽENIRJEV SLOVENIJE



Predhodnica Zveze strojnih inženirjev Slovenije je Zveza strojnih inženirjev in tehnikov Slovenije (ZSITS). Ustanovljena je bila leta 1961 na pobudo prof. Alberta

Strune. Že takrat je ZSITS dobila organizacijsko strukturo - obliko povezave krajevnih in strokovnih društev v krovno Zvezo. V letu 2002 se je Zveza strojnih inženirjev in tehnikov preimenovala v Zvezo strojnih inženirjev Slovenije (ZSIS), pri čemer se je status vseh članic Zveze ohranil.

Danes ZSIS združuje pod svoje okrilje 15 članic. Zveza strojnih inženirjev Slovenije samostojno ali prek svojih članic sodeluje z izobraževalnimi,

razvojnimi in raziskovalnimi organizacijami, z zbornicami in drugimi organizacijami in institucijami.

Zveza strojnih inženirjev Slovenije za namene pospeševanja in uveljavljanja strojne stroke in strokovnosti sodeluje tudi z drugimi zvezami in organizacijami izven meja Slovenije. Vizija Zveze je postati in obdržati prepoznavno vlogo stroke, prakse in znanosti na področju strojništva in vseh iz tega razvitih področij.

Poslanstvo Zveze je promocija, razvoj, izobraževanje in izmenjava izkušenj med društvi in njihovimi člani s pomočjo organizacije posvetovanj, konferenc izobraževanj, delavnic ter nenehnim informiranjem in sledenjem tehničnega in tehnološkega razvoja dejavnosti v okviru bogatega področja strojništva.

RAZVITO V SLOVENIJI



Projekt Razvito v Sloveniji / Created in Slovenia
Prikazi slovenske ustvarjalnosti!

Projekt Razvito v Sloveniji / Created in Slovenia je namenjen vzpodbujanju ustvarjalnosti slovenskega gospodarstva in predstavitvi tehničnih dosežkov na Slovenskem. Projekt je bil prvič realiziran leta 2009.

V letu 2017 je Zveza strojnih inženirjev Slovenije nadgradila projekt Razvito v Sloveniji / Created in Slovenia ob upoštevanju že znanih stališč:

- Vsak narod mora poleg lepote naravnih bogastev svoje dežele v borbi za svojo nacionalno integriteto promovirati svoje tehnične dosežke in posameznike.
- Slovenska tehnična dediščina je izjemno bogata, a žal premalo prepoznana. Izjemno pomembno je, da podkrepimo družbeni interes za inovativno ustvarjalno delo z visoko dodano vrednostjo.
- Potrebno je spodbujati mlade za naravoslovne in tehnične znanosti. Inženirji se moramo prilagoditi novim trendom in izobraževati naslednje generacije za delo v prihodnosti.

Projekt je prosto dostopen na spletnem naslovu www.razvitovsloveniji.si/ in obsega pregled slovenskega gospodarstva glede na dvanajst statističnih regij, pri čemer je omogočeno podatkovno razvrščanje glede na zeleno kategorijo. V projekt se postopoma vključujejo nova podjetja, ki s tem širijo mozaik pregleda slovenskega gospodarstva.

RAZVITO V SLOVENIJI

RAZVITO V SLOVENIJI

WWW.RAZVITOVVSLOVENIJI.SI



PRIKAZ SLOVENSKE USTVARJALNOSTI!

VZPODBUJANJE USTVARJALNOSTI
SLOVENSKEGA GOSPODARSTVA.

INOVATIVNO USTVARJALNO DELO!

SPODBUDIMO MLADE ZA NARAVOSLOVNE
IN TEHNIČNE ZNANOSTI.

LETOŠNJI
NAGRAJENEC

mag. VALTER LEBAN

predsednik uprave skupine Kolektor

NAGRADA ZA GLOBALNO PRODORNOST SLOVENSKEGA INŽENIRSTVA



Valter Leban je Idriččan, inženir in menedžer, ki je v letu 2022 postal predsednik uprave Kolektorja. Je človek premišljenih dejanj in iskanja nenehnih novih znanj za premagovanje izzivov prihodnosti. Leta 1988 je diplomiral na Fakulteti za strojništvo v Ljubljani, magistrski študij je nadaljeval na področju poslovanja (MBA) na Ekonomski fakulteti v Ljubljani.

Svojo profesionalno pot v skupini Kolektor je pričel leta 1988. Po nekaj letih vztrajnega ter predanega dela je postal direktor obrata Veliki komutatorji, nato je bil izvršni direktor informatike v Kolektorju, med letoma 2004 in 2009 je vodil podjetje Kolektor Sikom, nato je leta 2009 postal izvršni direktor skupine za področje produkcije in nabave. Leta 2014 je prevzel vlogo člana uprave in leto kasneje odločno sprejel izziv ustvarjanja novega poslovnega modela na področju digitalizacije. Z jasno usmerjeno vizijo je kot predsednik uprave uvedel reorganizacijo skupine Kolektor v tri glavne skupine: Kolektor Mobility, Kolektor Technologies in Kolektor Construction. Vodi strateške usmeritve skupine, ki vključuje več kot 30 podjetij doma in po svetu. Vodijo ga vrednote: zvestoba, pravičnost

in vztrajnost. Leta 2017 je bil imenovan za častnega konzula Mehike v Sloveniji. Je član upravnega odbora Združenja za kovinsko industrijo pri Gospodarska zbornica Slovenije.

Gospod Valter Leban črpa modrost iz življenjskih izkušenj ter okolja, v katerem deluje, velik pomen namenja tudi družini in dobremu počutju.

Kolektor je bil že od nekdaj usmerjen v tehnološki napredek. V letu 2023 ste praznovali jubilejno 60. obletnico delovanja. Kako ste vi videli začetke podjetja, njegov razvoj ter kakšna je vizija skupine v prihodnje?

Kolektor je bil že od ustanovitve sinonim za tehnično odličnost, inovativnost in predanost razvoju. Zasnovan je bil kot podjetje, ki povezuje inženirsko znanje in podjetniško vizijo. Pri tem je bila stalna intenzivna usmerjenost v razvoj, v

NAGRAJENCI 2025

investicije in v vlaganje v znanje oziroma kadre. Kolektor je v šestih desetletjih prehodil izjemno pot – od majhnega monokulturnega podjetja iz Idrije s par deset zaposlenimi v globalno prisoten konglomerat, ki danes deluje na treh različnih strateških področjih – mobilnosti (Kolektor Mobility), energetiki (Kolektor Technologies) in gradbeništvu (Kolektor Construction) ter pod svojim okriljem združuje več kot 30 podjetij doma in po svetu. Za vsa naša podjetja je značilen izrazit razvojni potencial, ki nas je na primer na področju energetike pripeljal do ponudnika najzahtevnejših transformatorjev do napetosti 400 kV, gradbenike z največjim potencialom in največjimi referencami do najzahtevnejših infrastrukturnih projektov in podjetja s področja mobilnosti iz ponudnikov komponent v ponudnike kompleksnih sistemov. Kolektor je rasel in širi svoj portfelj z organsko rastjo in ciljnim akvizicijami. Pomembno je, da smo pravočasno prepoznali

model diverzifikacije. Naša prihodnost je s tremi močnimi poslovnimi skupinami varna, ker nastopamo v različnih panogah, z različno dinamiko razvoja poslovnega mega okolja. Prihodnost je svetla, ker imajo vsi novi izdelki in storitve, ki jih razvijamo in za katere smo pridobili naročila, bistveno višjo dodano vrednost. Zaradi nje in potencialov znanja, ki je za temi izdelki, ni nobene skrbi, da ne bi bila skupina Kolektor uspešna tudi naprej. Naša vizija za prihodnost temelji na nadaljnji digitalizaciji, razvoju pametnih in trajnostnih rešitev ter tehnološki odličnosti. Želimo (p)ostati prepoznaven globalni igralec na področjih, kjer lahko z lastnim znanjem ustvarjamo dodano vrednost in prispevamo k bolj trajnostnemu svetu. Zame osebno je Kolektorjeva zgodba o uspehu zgodba o znanju, predanosti in sposobnosti, da se vedno znova prilagodimo spremembam.





Trenutno vlada precejšnja geopolitična negotovost, dogajajo se kibernetske grožnje in preobrazba energetskih sistemov. Svet potrebuje pametne preboje, strateške povezave in ljudi, ki znajo načrtovati prihodnost. Kako vam uspeva načrtovati prihodnost v trenutnih negotovih časih?

Negotovost je postala stalnica, zato se moramo nanjo odzivati z agilnostjo in odpornostjo. Ključnega pomena je, da imamo jasno strategijo in zaupamo lastnim kompetencam. Kolektorjeva misija je zagotoviti, da skupina uspeva v svetu mobilnosti, gradbeništva, energetike, infrastrukture in digitalizacije. V Kolektorju velikovlagamo v kibernetско varnost, digitalno infrastrukturo in diverzifikacijo poslovanja. V svoje poslovne modele

vkjučujemo visoke tehnologije s področja velikih podatkov, oblachnega računalništva, umetne inteligence, agilne robotike, interneta stvari, tridimenzionalnega tiskanja in podobnih tehnologij. Našo prihodnost gradimo na partnerstvih – znotraj skupine in z zunanjimi deležniki – saj verjamemo, da se največji preboji zgodijo, ko se povežejo različna znanja in izkušnje. Pomemben del naše usmeritve je tudi skrb za okolje – trajnostno delovanje je vgrajeno v naše poslovne procese. Z energijsko učinkovitimi rešitvami, razvojem okolju prijaznih materialov in zniževanjem ogljičnega odtisa želimo prispevati k zelenemu prehodu in odgovorni prihodnosti. Kljub zahtevnim razmeram ostajamo optimistični, saj imamo jasno strategijo, močno kulturo inovacij in sposobne ekipe, ki znajo izzive spremeniti v priložnosti.



Ena izmed prioriteta skupine je grajenje vizije 'One Kolektor'. Nam lahko zaupate, kaj se skriva pod tem poimenovanjem?

Vizija 'One Kolektor' je koncept, s katerim gradimo blagovno znamko, ki predstavlja naše podjetje in je podoba, ki si jo naši zaposleni ter stranke predstavljajo. V osnovi pomeni enotno skupino, povezano z enotnimi cilji, vrednotami in kulturo. To je velik podvig, ki se dotakne celotnega našega delovanja: zakaj delamo, kaj delamo in kako delamo. Temelj 'One Kolektor' so vrednote, ki jih živimo in jih skozi delo širimo ter s tem oblikujemo našo organizacijsko kulturo. Gre za koncept sodelovanja in sinergije – ne glede na to, ali delujemo na področju mobilnosti, gradbeništva ali energetike. Ta vizija spreminja naše obnašanje, način sodelovanja, kako razporejamo vire in kako opolnomočimo

naše najproduktivnejše kadre. Želimo, da vsi zaposleni čutijo pripadnost isti zgodbi, razumejo našo skupno vizijo in prispevajo k njej s svojim znanjem. Hkrati pa pomeni tudi večjo integracijo poslovnih procesov, izmenjavo dobrih praks ter skupno digitalno in trajnostno usmeritev. Ta pristop nam omogoča, da kot skupina delujemo hitreje, bolj prožno in bolj trajnostno. S tem krepimo moč skupine kot celote.

Poznani ste po tem, da gradite povezanost med zaposlenimi, krepite timski duh na športnih in kulturnih dogodkih, vzpodbujate inovativnost in jo med zaposlenimi tudi nagrajujete, izbirate najboljše sodelavce, podpirate mlade ... Kakšne spremembe in novosti še uvajate?

Ljudje so srce Kolektorja. Zato želimo, da vsak zaposleni čuti pripadnost, priložnost in ponos. V zadnjih letih veliko vlagamo v razvoj notranje kulture. Krepimo programe usposabljanja, mentorstva in sodelovanja z izobraževalnimi ustanovami. Povezujemo se z mladimi talenti, jih vključujemo v razvojne projekte in jim ponujamo možnost karijerne rasti. Zaposlene spodbujamo k inovativnosti, razvijamo digitalne platforme, ki omogočajo učenje in izmenjavo znanja znotraj skupine. Posebno pozornost namenjamo tudi zdravju, ravnotežju med delom in prostim časom ter aktivnemu vključevanju v lokalno okolje. Naš cilj je ustvariti delovno okolje, v katerem se vsak posameznik počuti cenjenega in motiviranega ter prispeva k skupnemu uspehu. Verjamem, da je uspešno podjetje tisto, katerega zaposleni verjamejo vase in v vizijo, ki jo skupaj gradimo. Vse naštet o niso časovno omejeni projekti, ki imajo svoj začetek in konec, ampak procesi, ki jih postopoma razvijamo, dopolnjujemo in nadgrajujemo.

Vaše sporočilo.

Kolektor je zgrajen na znanju, sodelovanju in zaupanju. Prodornost, še posebej globalna, nikoli ni delo posameznika. Je rezultat kulture nenehnega iskanja novega znanja, timskega duha in tiste inženirske vztrajnosti, ki jo v

Kolektorju gojimo že 60 let. Živimo v časih velikih preobrazb – od okoljskih izzivov do digitalizacije. A kot inženirji smo po naravi optimisti; v izzivih vidimo priložnosti. Naša naloga ni, da čakamo na prihodnost, ampak da jo s premišljenimi dejanji aktivno sooblikujemo. Moje sporočilo je zato jasno: »Verjemimo v slovensko znanje.« Ostanimo zvesti svojim vrednotam – poštenosti, pravičnosti in medsebojnemu spoštovanju. Gradimo povezane ekipe, kot to počnemo z vizijo 'One Kolektor', saj smo le skupaj lahko zares močni. Naša naloga je, da ohranimo te vrednote, hkrati pa z odprtostjo sprejemamo spremembe in nove tehnologije. Verjamem, da prihodnost pripada tistim, ki razmišljajo pogumno, delujejo povezano in ostajajo zvesti svojim načelom.

O Kolektorju

Skupina Kolektor je multinacionalka s sedežem v Sloveniji in široko razvejano mrežo podjetij in podružnic v Evropi, Ameriki in Aziji, ki deluje na industrijskem in finančnem področju. Je poslovni sistem s tremi močnimi skupinami: Kolektor Mobility, Kolektor Technologies in Kolektor Construction in pod svojo streho združuje več kot 5.500 zaposlenih. Njegova misija je, da uspeva v svetu mobilnosti, gradbeništva, energetike, infrastrukture in digitalizacije. Več: www.kolektor.com

Foto: arhiv podjetja



KOLEKTOR

LETOŠNJI
NAGRAJENEC

izr. prof. dr. JANEZ KRAMAR

upokojeni profesor Fakultete za strojništvo Univerze v Ljubljani

NAGRADA ZA ŽIVLJENJSKO DELO

Profesor Janez Kramar se je rodil v začetku leta 1940 v vasi Št. Peter pri Novem mestu in se čez dve leti z mamo in očetom preselil v bližnjo vasico Lutrško selo. V predšolskem obdobju ga je zanimala narava ter bližnja reka Krka. Štiri razrede osnovne šole je končal v vasi Št. Peter, v letu 1951/52 je nadaljeval šolanje na gimnaziji v Novem mestu, kamor se je vsak dan vozil s kolesom po 8 km v vsako smer. Ni bilo naključje, da sta ga najbolj zanimala matematika in fizika. V osmem razredu gimnazije se je udeležil tudi republiškega tekmovanja iz matematike ter prejel drugo nagrado (prva ni bila podeljena). Po opravljeni maturi leta 1959 se je želel vpisati na Fiziko na Univerzi v Ljubljani, a ker ni dobil štipendije, se je odločil za študij strojništva. Po drugem letniku, jeseni leta 1961, se je na povabilo študijskega kolega honorarno zaposlil v Litostroju v njihovem razvojnem oddelku pri dr. Vladimirju Jordanu, ki je prvi v Jugoslaviji obvladal reševanje vodnega udara v dovodnih cevovodih hidroelektrarn in v velikih črpalnih sistemih. Prvi rezultat zaposlitve je bila diplomska naloga z naslovom »Metode za določanje pritiskov pri hidravličnem udaru v tlačnem cevovodu vodnih črpalk z vetrnikom« (jeseni 1963). Za to delo z izvirno numerično metodo je leta 1964 dobil študentsko Prešernovo nagrado. Drug, veliko usodnejši rezultat študentske zaposlitve pa je izhajal iz potreb Litostroja pri reševanju trdnostnih, stabilnostnih in deformacijskih problemov pri zelo obsežnem proizvodnem programu. Po



končani vojaški obveznosti (spomladi 1968) se je zaposlil v Industriji motornih vozil (IMV) v Novem mestu, leta 1971 je dobil ponudbo Metalne Maribor za delo v njihovem oddelku v Ljubljani, kjer se je poleg še zahtevnejših žerjavov ukvarjal s hidromehansko opremo na jezovih hidroelektrarn, še večjimi cevovodi, rezervoarji, tlačnim posodami, nosilnim stolpom za parni kotel termoelektrarne Šoštanj in še drugimi projekti.

Profesor Kramar je pri svojem delu iskal povsem nova teoretična znanja, vpeljal nova računalniška orodja ter izdelal povsem izvirne rešitve. Leta 1973 je zaključil magistrski študij z nalogo, v kateri je razvil nov toroidni končni element za programski paket SHELLS, ki ga je razvijal dr. Borut Dobovišek, dipl. inž. gr.. Programski paket SHELLS so uporabljali za vse lupinaste konstrukcije, ki so imele v osnovi sestavljeno rotacijsko formo in poljubno obremenitev. V tem

obdobju je poleg številnih aplikativnih nalog poglobljeno študiral elastomehaniko ortotropnih rotacijskih lupin s pomočjo tenzorske matematike. Te študije in raziskave so rezultirale v doktorskem delu z naslovom »Prispevek k elastomehanski rešitvi splošne ortotropne toroidne lupine«, ki ga je uspešno zagovarjal leta 1987.

V času zaposlitve na Fakulteti za strojništvo je bil vodja Laboratorija za transportne sisteme ter nosilne strojne konstrukcije, bil je tudi prodekan za pedagoško dejavnost. Profesor Kramar je študente vpeljeval v praktične industrijske projekte ter jim tako omogočil vpogled v reševanje realnih izzivov.

Po upokojitvi leta 2009 je še nekaj časa predaval, a je to delo postopno predal nasledniku, izr.prof.dr. Borisu Jermanu. Tesnejše stike z industrijo je ohranjal vse do leta 2024.

Sedaj z zadovoljstvom spremlja uspehe svojih osmih vnukov in vnukinj ter se z njimi veseli že pravnukinj in pravnukov.

1. Profesor Kramar, svoje otroštvo ste preživali v Novem mestu, ko je prevladovalo še kolo kot prevozno sredstvo do šole, ki ste ga zelo radi vozili. Bili ste aktivni, vedoželjni in nad tehniko ste se navduševali že v zgodnjem otroštvu. Kdo vam je približal svet inženirstva?

Že v letih pred osnovno šolo in v prvih štirih letih osnovne šole v Št. Petru pri Novem mestu me je zelo pritegnilo opazovanje narave vključno z opazovanjem dogajanja v bližnji reki Krki. Oče, ki je obvladoval delo z lesom, me je že v rosnih letih pritegnil k opazovanju

in kasneje v pomoč. Kot ljubiteljski ribič je imel tudi manjši lesen čoln in me kot sedemletnega fantiča usposobil za upravljanje čolna z enim veslom. Po plitvinah in manjših brzicah sem hodil bos in spoznaval moč vodnega toka. V osmih letih gimnazije v Novem mestu so me zanimali predvsem naravoslovni predmeti in še posebej matematika in fizika. V višjih razredih gimnazije sem pričel razmišljati, kam po maturi. Najbolj sem si želel študirati fiziko, a so me privlačili tudi inženirski študiji. Nihal sem med elektrotehniko in strojništvom, ki sta bili tedaj v isti organizacijski enoti. Poleti, leta 1958, med mojo sedmo in osmo gimnazijo, so brigadirji gradili odsek avtoceste mimo Novega mesta. Prav ob vasici Lutrsko selo je taborila študentska brigada iz strojne fakultete beograjske univerze. V pogovorih z njimi sem prišel do argumenta, da vsaka večja tovarna potrebuje veliko število inženirjev strojništva in enega ali dva elektroinženirja. Po maturi leta 1959 nisem dobil štipendije za študij fizike in tako je postala moja izbira Fakulteta za strojništvo v Ljubljani.

2. Močna inženirska volja ter želja po znanju vas je pripeljala v vodilna podjetja takratnega časa. Opravljali ste zahtevna, odgovorna dela, sodelovali ste z različnimi profili ljudi. Kateri projekt se vam je najbolj vtisnil v spomin in ste nanj še posebej ponosni?

V razvojnem oddelku Litostroja, ki ga je tedaj vodil dr. Vlado Jordan, dipl.inž str., sem se honorarno zaposlil jeseni leta 1961, po končanem drugem letniku in odpovedal štipendijo. Dr. Jordan je bil strokovnjak z izjemno fizikalno predstavo o hidromehanskih pojavih. Njegova želja je bila, da bi sodeloval pri njegovih izračunih vodnega udara v tlačnih cevovodih pred vodnimi turbinami in v cevovodih črpalnih sistemov. Iz tega področja sem za konec študija izdelal diplomsko nalogo z izvirno numerično metodo, za katero sem leta 1964 dobil študentsko Prešernovo nagrado. Zaradi velikih potreb Litostroja pri reševanju trdnostnih, stabilnostnih, deformacijskih in dinamičnih



problemov pri obsežnem proizvodnem programu Litostroja, sem že kot študent in nato mlad inženir prešel v to področje. Delal sem s potrebnim fizikalnim razumevanjem vseh mehanskih pojavov, s širokim znanjem na področjih mehanike ter z dobro prostorsko predstavo. Ko se je pojavil problem, ki je presegal moje znanje, sem poiskal potrebno literaturo ter obvladal nov problem. V litostrojskem obdobju mojega delovanja sem uporabljal predvsem analitične metode. Po potrebi sem se povezal tudi z oddelkom za meritve. V metalniškem obdobju (1971 do 1990) so se na trgu pojavili prvi računalniški programi za napetostno-deformacijske probleme na osnovi metode končnih elementov. Bil sem med prvimi v Sloveniji, ki so uporabili ta orodja v praksi. Za povečanje učinkovitosti dela sem moral pogosto napisati konkretnemu delu prilagojene izvirne računalniške programe. V vmesnem obdobju sem bil tri leta zaposlen v Industriji motornih vozil (od 1968 do 1971) v Novem mestu, kjer sem bil dve leti vodja prototipne delavnice.

Tekom zaposlitve v omenjenih treh pomembnih podjetjih Slovenije sem prišel v strokovno in

splošno komunikacijo z mnogimi vodilnimi projektanti in tehnologi, tudi s konstrukterji različnih specialnosti in predvsem v novomeškem obdobju tudi neposredno z izdelovalnimi specialisti.

Med najbolj zahtevne projekte, ki sem jih v življenju obdelal in bil vesel, ko so bili realizirani, je zelo velik razdelilnik vode iz tlačnega cevovoda premera 11,2 m do treh turbin ter do neposrednega iztoka za HE Chiew Larn na Tajskem. Ta distributor sem najprej oblikoval za doseg čim manjših hidravličnih izgub v njem, izračunal potrebne debeline pločevin za njegovo izdelavo ter izdelal računalniško podporo za obrez razvitih pločevin za vse nastopajoče delne stožce (preko 50) ter določil tvornice za ukrivljanje omenjenih pločevin. Za celoten distributor sem nato izdelal natančen trdnostni izračun, ki ga je bilo potrebno dati v potrditev strokovni instituciji v Milanu (Italija), ki jo je investitor izbral za nadzor vseh aktivnosti izvajalca (Metalne). Zaradi velikosti objekta so v Metalni po moji numerični

podpori izdelali model razdelilnika v merilu 1:10, da bi se prepričali o mojih numeričnih rezultatih. Predtem so pločevine sestavnih delnih stožcev za manjše razcepne kose razvijali grafično na risalni deski. Model distributorja je bil več let na podstavku pred upravno zgradbo Metalne. Tudi na lokaciji vgradnje je potekalo zvarjanje sestavnih pločevin distributorja brez večjih težav.

Kot velik objekt, za katerega trdnostni in deformacijski račun sem izdelal še v Litostroju, bi lahko navedel mostni žerjav nosilnost 800 t v turbinski zgradbi HE Đerdap na Donavi, katere elektriko sta si tedaj delili Jugoslavija in Romunija (danes Srbija in Romunija).

3. Kasneje ste industrijsko okolje zamenjali z akademskim – s prihodom na Fakulteto za strojništvo se je pričelo novo poglavje vaše inženirske poti. Kaj je bil povod za prehod?

Povod za prehod iz industrijskega v akademsko okolje je bila nenadna potreba Fakultete za strojništvo po univerzitetnem učitelju s področja, ki se je zelo prekrivalo z mojim delom v industriji. Ker sem leta 1987 uspešno ubranil tudi doktorsko tezo, sem bil povabljen na pedagoški nivo delovanja. Začelo se je zares novo poglavje moje inženirske poti. Izkušnje in znanje na konkretnih objektih sem lahko prenašal na študente zadnjih letnikov (predvsem) konstrukterske smeri.

4. Ste eden redkih profesorjev, ki ste izkusili tako industrijsko kot akademsko pot. Obe imata svoje prednosti in slabosti. Katere prednosti ste videli na industrijski in katere na akademski poti? Ali vas je delo s študenti veselilo?

Na industrijski poti sem srečal zelo veliko zahtevnih strokovnih izzivov, ki so zahtevali čim krajši čas za razrešitev. Ob njih so bili

pogosto tudi znanstveni izzivi, za katere pa je skoraj vedno zmanjkalo časa. Na akademski poti je bilo načeloma dovolj časa za reševanje znanstvenih izzivov. Delo s študenti me je veselilo, ker sem med njimi našel (običajno so oni poiskali mentorja) dovolj sposobnih posameznikov, ki so bili v časovno pomoč pri raziskavah in tudi kakšnega posameznika, ki je prispeval povsem sveže ideje pri delu. Tudi bolj zahtevne strokovne probleme smo reševali v Laboratoriju, ki sem ga na Fakulteti vodil. Tudi na tem področju so bili študenti zelo dobri sodelavci in njihovi izdelki po skrbnem pregledu takoj uporabni za prakso.

5. Vaše sporočilo.

Moje sporočilo mladim diplomantom Fakultete za strojništvo pa tudi diplomantom drugih inženirskih fakultet je: vsake naloge se lotite z zanimanjem, odgovornostjo in z vsem pridobljenim strokovnim znanjem. V primeru, da vam manjka kakšna informacija za začetek dela, vprašajte po njej starejše kolege po starosti ali rangu. Uporabite pri delu najnovejša temeljna znanja iz literature. Če je problem obširen, pridobite sodelavce. Če čutite potrebo po sodelovanju s katero od znanstvenih institucij (raziskovalni inštituti, fakultete), to predlagajte predstojniku ali vodstvu podjetja, kjer ste zaposleni. Če ste se zaposlili na fakulteti, imejte posluš za znanstvene teme iz prakse. Po rešitvi dobljene naloge, ne glede ali gre za nov izdelek ali nov izdelovalni proces, delovanje spremljajte in sproti ugotavljajte morebitne pomanjkljivosti, ki jih boste lahko sami ali kdo od kolegov pri naslednji generaciji izdelka ali procesa izboljšali. Pomanjkljivosti so lahko tudi negativni vplivi na okolje, ki jih moramo sproti zmanjševati.

Inženirji vseh starosti se moramo zavedati, da smo eden od najpomembnejših stebrov za materialno blaginjo narodov vsega sveta. Seveda pričakujemo tudi, da drugi odločujoči stebri to našo vlogo podpirajo (kapital, vlade in širša družbena okolja).

Foto: Luka Karničnik

Kolektor Mobility



Driving
the Future



Kolektor Construction



Kolektor Technologies

Kolektor je danes poslovni sistem s tremi močnimi skupinami. Naša misija je, da uspevamo v svetu mobilnosti, gradbeništva, energetike, infrastrukture in digitalizacije.

MAG. JOŽE BELE, predsednik uprave in direktor tovarne Revoz

Nagrajenec ZSIS za globalno prodornost slovenskega inženirstva 2024



Magister Jože Bele je menedžer, ki je že več kot 30 let povezan s podjetjem Revoz. Leta 1989 je diplomiral na Fakulteti za strojništvo v Ljubljani, študij je nato nadaljeval na Ekonomsko-poslovni fakulteti v Mariboru. Leta 2007 pridobil magisterij ekonomskih znanosti na Ekonomski fakulteti v Ljubljani.

Njegova poklicna pot je močno prepletena z avtomobilsko industrijo in dolgoročnim delovanjem v Revozu. Vodil je različne oddelke, vključno s področjem kakovosti in montaže. Več let je vodil tudi klub montažnih obratov skupine Renault, kjer je sodeloval s predstavniki Nissanovih tovarn. Aktivno je sodeloval z dobavitelji sestavnih delov in obiskoval avtomobilске tovarne v Evropi, na Japonskem in v Južni Ameriki. Leta 2017 je postal direktor proizvodnje in član uprave Revoza. Januarja 2022 je prevzel mesto predsednika uprave in direktorja tovarne.

Kot predsednik uprave je gospod Bele prevzel vodenje v obdobju pomembnih sprememb, vključno z zmanjšanjem proizvodnje in prestrukturiranjem zaradi globalnih kriz, kot so pomanjkanje polprevodnikov in padanje povpraševanja po določenih modelih.

ALENKA KNEZ,

Priznanje ZSIS za "Iz roda v rod si inženirstvo utira pot".



Alenka Knez in njen mož Marjan sta se že zgodaj podala na inženirsko pot, ona je obiskovala srednjo strojno šolo v Trbovljah, on pa v Ljubljani. Oba sta

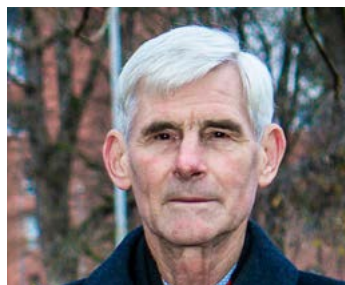
se leta 1968 vpisala na Fakulteto za strojništvo v Ljubljani ter v 2. letniku začela skupno kar 46 let dolgo pot. Radovednost ter povezovanje z industrijo je oba pripeljala do konca študija, ki sta ga zaradi štipendije z diplomsko nalogo iz gospodarstva tudi uspešno zaključila. Življenjska pot ju je peljala v Trbovlje, kjer sta si ustvarila

družino ter vse do upokojitve opravljala svoj poklic, gospa Alenka Knez kot učiteljica na Srednji strojni šoli v Trbovljah, mož Marjan pa kot inženir na Rudisu. Zavzetost za inženirstvo sta prenesla na svoja sinova Jureta in Sašo Kneza. S sinovoma so ustanovili S.O.S. šolo v pomoč staršem in učencem pri matematiki v prvih treh razredih. Njihovo požrtvovalno delo je dostopno na portalu sos-sola.si. Delujejo v okviru Katapulta Trbovlje in se povezujejo s Katapultom robotika. V družini Knez so se vedno zavedali, da je znanje edina naravna avtoriteta.

PROF. DR. VINCENC BUTALA

upokojeni profesor Fakultete za strojništvo Univerze v Ljubljani

Nagrajenec ZSIS za življenjsko delo 2024



Vincenc Butala se je rodil leta 1950 v Bistrici pri Trzinu. Osnovno šolo ter gimnazijo je obiskoval v Ljubljani. Po končani maturi se

je vpisal na Fakulteto za strojništvo v Ljubljani, in leta 1997 zagovarjal doktorsko disertacijo z naslovom »Zgorevanja premoga v kosih«, pri mentorju prof. dr. Petru Novaku. Leta 1976 se je zaposlil na tedanji Katedri za toplotno in procesno tehniko v Laboratoriju za ogrevalno, solarno

in sanitarno tehniko na Fakulteti za strojništvo v Ljubljani. Na isti katedri, preimenovani v Katedro za prenos toplote in snovi ter okoljsko tehniko, je bil zaposlen do upokojitve. Bil je vodja Laboratorija za ogrevalno, sanitarno in solarno tehniko (LOS). Pri svojem delu je največ pozornosti posvečal pedagoškemu delu.

Profesor Vincenc Butala je znanstveno-raziskovalne in druge izkušnje pridobil na Finskem, v Franciji, Švici in na Slovaškem. V letu 1987 je uspešno opravil strokovni izpit strojne stroke ter istega leta postal tudi sodni izvedenec. Vse od leta 2009 pa do novembra 2024 je bil glavni in odgovorni urednik znanstvene revije Strojniški vestnik – Journal of Mechanical Engineering.

Je velik ljubitelj košarke: do leta 2023 je bil kar dvajset let na čelu Mednarodne organizacije za veteransko košarko, je član Mednarodnega odbora FIMBA ter predsednik Komisije za veteransko košarko pri Košarkarski zvezi Slovenije.



DR. TOMAŽ KMECL, direktor podjetja Kolektor Etra

Nagrajenec ZSIS za globalno prodornost slovenskega inženirstva 2023



Dr. Tomaž Kmecl se je na inženirsko pot podal s študijem strojništva in jo kasneje nadgradil z doktorskim nazivom. S trdim delom je pridobil dragocene izkušnje

v tujini, v Švici, kjer je deloval na zahtevnih projektih velikega koncerna. Želja po ustvarjanju na domačih tleh ga je pripeljala nazaj v Slovenijo. Dr. Kmecl vodi podjetje Kolektor Etra od leta 2009. Na zahtevnem trgu elek-troenergetike je v tem času uspel umestiti družbo kot globalnega

KOLEKTOR

ponudnika kakovostnih rešitev na področju transformacije električne energije.

Visoka investicijska vlaganja v opremo, pospešeno zaposlovanje visokokvalificiranega kadra, tudi številnih magistrov in doktorjev znanosti, sodelovanje z univerzami in raziskovalno sfero, prispevajo k razvoju številnih novih proizvodov in novih tehnologij. Dr. Kmecl utrjuje uspeh podjetja na tujih trgih s hitrimi poslovnimi odločitvami, s kakovostnimi produkti in z zanesljivostjo dobave. Veliko pozornosti namenja tudi zaposlenim ter ustvarjanju učinkovitih delovnih pogojev.

DRUŽINA MEDLE,

Priznanje ZSIS za "Iz roda v rod si inženirstvo utira pot".



Podjetniško zgodbo družine Medle je pred več kot 40 leti začel pisati Alojz Medle, sprva kot monter senčil, nato pa je leta 1976 v garaži družinske

hiše odprl manjšo proizvodnjo. Podjetje se je hitro širilo in razvijalo, žena Marta je prevzela računovodske posle, kmalu pa je zaposlil prve delavce. Skupaj s podjetjem sta rasla tudi sinova Gorazd in Robert, ki sta že od malih nog pomagala pri raznih opravilih ter se navdušila za inženirstvo. V podjetju Roletarstvo Medle so s trdim delom in vztrajnostjo dosegali odlične rezultate. Da sinova nadaljujeta inženirsko

podjetniško pot, je bila njuna logična odločitev. Sin Gorazd je pri 26. letih v dogovoru s starši odprl svoje sorodno podjetje Senčila Medle, kjer je začel s proizvodnjo povsem novih artiklov s področja senčenja. Mlajši sin Robert je očetovo podjetje Roletarstvo Medle prevzel pri 30. letih. Da je podjetništvo močno zasidrano v družini Medle, kaže že tretja generacija - oba brata, Gorazd in Robert, v družinski posel že vpeljujeta svoja sinova in hčer ter jih tako navdušujeta nad inženirstvom. Družinska tradicija se nadaljuje.

MEDLE

PROF. DR. JANEZ DIACI upokojeni profesor Fakultete za strojništvo Univerze v Ljubljani

Nagrajenec ZSIS za življenjsko delo 2023



Janez Diaci se je rodil leta 1957 v Celju. Po maturi, ki jo je opravil z odliko, se je jeseni 1976 vpisal na Fakulteto za strojništvo v Ljubljani.

Dodiplomski študij je zaključil junija 1981 z odliko ter za svoje diplomsko delo prejel Prešernovo nagrado. Istega leta se je kot stažist raziskovalec zaposlil na Fakulteti za strojništvo in se vpisal na podiplomski študij na področju Avtomatizacije in proizvodne kibernetike.

Janez Diaci je uspešno zagovarjal disertacijo

decembra 1990. V disertaciji je obravnaval značilnosti mehanskih valov končne amplitude, ki nastanejo v zraku pri lasersko induciranih transformacijah snovi.

Profesor Diaci je bil vodja Laboratorija za digitalne sisteme in elektrotehniko na UL-FS. Eno mandatno obdobje je bil član upravnega odbora UL-FS, bil je predsednik akademskega zbora UL-FS in predsednik komisije za zagovor diplomskih nalog UNI. Je član EMRS - Evropske družbe za raziskave materialov s sedežem v Strasbourgu.

Decembra 1995 je prejel priznanje Fakultete za strojništvo za izjemne znanstvene dosežke. Leta 2006 je skupaj s sodelavcema prejel Puhovo priznanje za izume, razvojne dosežke in uporabo znanstvenih izsledkov pri uvajanju novosti v gospodarsko prakso na področju laserskih sistemov za tridimenzionalno merjenje oblike teles. Leta 2008 je skupaj s sodelavci prejel zlato priznanje Območne gospodarske zbornice Ljubljana in srebrno priznanje Gospodarske zbornice Slovenije za inovacije.



BOŠTJAN GORJUP, direktor družbe BSH Hišni aparati Nazarje

Nagrajenec ZSIS za globalno prodornost slovenskega inženirstva 2022



Boštjan Gorjup je študiral je na Fakulteti za strojništvo / Ekonomsko poslovni fakulteti Univerze v Mariboru in se kot univerzitetni gospodarski inženir

zaposlil v koncernu Bosch v Sloveniji. 2006 je postal direktor BSH Hišni aparati. Maja 2016 je prevzel vodenje družbe BSH Hišni aparati Nazarje in celotne regije Adriatic East, ki šteje 10

držav vzhodne Evrope.

Gospod Gorjup je menedžer, ki v ospredje postavlja cilj biti prvi po odličnosti in ne po velikosti, ter že vrsto let prispeva k razvoju v Savinjski regiji in k pozicioniranju Slovenije kot odličnega okolja za raziskave in razvoj. V podjetju je uvedel organizacijsko kulturo, ki temelji na zaupanju, odprtem komuniciranju, sodelovanju in poštenosti. Zaposleni pri njem najbolj cenijo ustvarjalnost, obvladovanje dela in usmerjanje ter izkazovanje podpore.

Boštjan Gorjup je prejel Nagrado GZS za izjemne gospodarske in podjetniške dosežke za leto 2011, priznanje Mladi manager 2012, ki ga podeljuje Združenje Manager ter prejel naziv Manager leta 2018. Bil je na čelu Gospodarske zbornice Slovenije v letih 2017-2021.

B/S/H/

BOGOMIR MIRKO STRAŠEK, ustanovitelj, direktor in lastnik družbe KLS Ljubno d.o.o.

Nagrajenec ZSIS za globalno prodornost slovenskega inženirstva 2022



Bogomir Mirko Strašek je ustanovitelj, direktor in lastnik družbe KLS Ljubno, ki izdeluje zobate obroče za avtomobilsko industrijo. Svojo poklicno pot je začel

leta 1972, ko je prevzel vodenje kovinarskega obrata SGP Gradbenik v Ljubnem ob Savinji. Po vmesnem štiriletnem skoku v politiko je prevzel mesto direktorja tedanje družbe TOZD Kovinarstvo Ljubno, ki se je pozneje

preimenovala v KLS Ljubno.

Je človek z izjemnim občutkom za sodelavce, vedno na voljo za potrebe lokalne skupnosti, za ljudi. Produktivnost v podjetju je v zadnjih 20 letih narasla za desetkrat. S svojim delovanjem je znatno prispeval k razvoju slovenskega gospodarstva in utrjevanju poslovne kulture ter k bogatitvi kakovosti življenja in dela v Savinjski dolini.

Za svoje delo ga je predsednik RS v letu 2022 odlikoval z redom za zasluge. Gospod Strašek je predsednik sveta Gazela ter prejemnik priznanja Združenja Manager za življenjsko delo na področju menedžmenta. Leta 2011 je KLS Ljubno postal zlata gazela, g. Strašek pa je prejel nagrado Gospodarske zbornice Slovenije (GZS) za gospodarske in podjetniške dosežke.

kls

IVO BOSCAROL Podjetnik in ustanovitelj podjetja Pipistrel

Nagrajenec ZSIS za življenjsko
delo 2022



Ivo Boscarol
je eden
najspešnejših
slovenskih
podjetnikov
in ustanovitelj
ter dolgoletni
direktor podjetja

Pipistrel. Sprva modelarski hobi in jadralno letenje sta prešla v resen posel, leta 1989 je ustanovil prvo zasebno tovarno letal Pipistrel. Svetovno prepoznavnost je podjetju leta 1995 prinesel razvoj prvega dvosedežnega motorno-jadralnega letala na svetu Sinus. Leta 2020 je postavil tretji mejnik v zgodovini letalstva, saj

je kot prvi na svetu uspel certificirati letalo za komercialno uporabo in prevoz potnikov tudi letalo na električni, brezemisijski pogon. Aprila 2022 je gospod Boscarol večinski delež podjetja Pipistrel prodal ameriškemu podjetju Textron.

Za svoje delo je dobil več nagrad, med drugimi najvišje priznanje mednarodne letalske zveze FAI Diploma Paul Tissandier za prispevek k razvoju letalstva 2004 ter priznanji slovenski podjetnik 2003 in GZS gospodarstvenik Slovenije 2004. Leta 2011 je zmagal na natečaju ameriške agencije NASA za najučinkovitejše letalo in osvojil najvišjo nagrado v zgodovini letalstva. 2010 je postal častni član društva slovenskih inovatorjev, istega leta je podjetje Pipistrel prejelo priznanje za najbolj inovativno podjetje v Evropi.



MARINO FURLAN, ustanovitelj in predsednik podjetja Intra lighting d.o.o.

Nagrajenec ZSIS za globalno prodornost slovenskega inženirstva 2021



Marino Furlan je svojo poslovno pot začel leta 1982, po uspešno zaključenem študiju na Fakulteti za strojništvo v Ljubljani. Leta 1989 je skupaj s svojo ženo ustanovil podjetje Intra lighting, ki je od garažne izdelave

luči prešlo do ustvarjanja svetlobe in proizvodnje arhitekturnih svetil in nudenja poslovnih rešitev. Podjetje danes zaposluje več kot 350 ljudi in je prisotno v več kot 65 državah sveta. Gospod Furlan se aktivno vključuje v razvoj novih produktov ter vodi strategijo podjetja. Je vizionar, ki razume potrebe uporabnika, in vodja, mimo katerega ne gre niti najmanjša podrobnost. Z uspešnim sodelovanjem z arhitekti in oblikovalci širom sveta soustvarja inovativna svetila, ki z zeleno usmerjeno proizvodnjo postavljajo temelje za boljši jutri.



IGOR STANONIK, predsednik uprave podjetja Polycom d.o.o.

Nagrajenec ZSIS za globalno prodornost slovenskega inženirstva 2021



Gospod Igor Stanonik je svojo poslovno pot pričel leta 1985, ko je skupaj s svojim bratom, Iztokom Stanonikom, ustanovil podjetje za brizganje plastičnih izdelkov. Leta 1990 je podjetje pridobilo današnje ime – Polycom. S preciznim delom ter pogumom so posegli v avtomobilsko industrijo in spleti

močna partnerstva. S selitvijo v nove prostore, robotizacijo in z ustanovitvijo lastnega oddelka orodjarne so pričeli izdelovati orodje za lastne potrebe, kasneje pa so vzpostavili tudi razvojno skupino. Danes proizvajajo prek 800 izdelkov za avtomobilsko industrijo, kar pomeni, da ima vsak avtomobil vgrajen najmanj en njihov izdelek. Za kupce razvijejo izdelke in zahtevna orodja za brizganje.



PROF. DR. ALOJZ POREDOŠ

Nagrajenec ZSIS za življenjsko delo 2021



Profesor Alojz Poredoš se je rodil leta 1953 v Ižakovcih. V Lendavi je uspešno zaključil Tehniško srednjo šolo ter se leta 1972 vpisal na Fakulteto za strojništvo v Ljubljani,

kjer je leta 1976 tudi diplomiral. V okviru doktorskega dela, ki ga je uspešno ubranil leta 1990, je razvil posplošeni matematični model za dimenzioniranje in preračun lamelnih prenosnikov toplote pri različnih pogojih delovanja. Na Fakulteti za strojništvo Univerze v Ljubljani je leta 1992 ustanovil Laboratorij za hladilno tehniko, od leta 2002 ter vse do upokojitve pa je bil vodja Katedre za toplotno in okoljsko tehniko. Prof. dr. Alojz Poredoš je svoje raziskovalne dosežke vztrajno širil v industrijo ter tako gradil temelje uspešnega inženirskega sodelovanja med akademsko in gospodarsko sfero. V slovenski prostor je prvi in edini vpeljal sistem daljinskega hlajenja. Rezultati njegovega znanstvenega dela so tudi objava kar 80 člankov v znanstvenih revijah, 153 prispevkov na konferencah, 4 monografije ter 4 prijavljeni in 4 podeljeni patenti.

S tem sistemom, ki je bil postavljen v mestno jedro Občine Velenje, še danes oskrbujejo objekte s hladilno energijo, ki jo proizvajajo z odvečno toploto iz termoelektrarne Šoštanj. Kot svetovalec tovrstnega hlajenja deluje v Kliničnem centru Ljubljana, ki je največji infrastrukturni energetski objekt v Sloveniji. Sodeloval je s številnimi podjetji, kot so Energetika Ljubljana, Energetika Velenje, Energetika Celje, TOM Maribor, Gorenje, LTH Škofja Loka, IMP Klimat, Hidria, SMM Maribor itd. ter spletel vezi z univerzami in inštituti po svetu.

Rezultati njegovega vztrajnega in znanstvenega dela so objava kar 80 člankov v znanstvenih revijah, 153 prispevkov na konferencah, 4 monografije ter 4 prijavljeni in 4 podeljeni patenti.

Profesor Poredoš se zaveda pomembnosti energetike v slovenskem prostoru, zato zaradi bogatih izkušenj in vpetosti v mednarodni prostor aktivno opravlja naslednje funkcije: je predsednik Sveta za energetiko SAZU, znanstveni svetnik SAZU, predsednik Nacionalnega razvojnega sveta za energetiko pri SAZU in član EASAC Energy Steering Panel pri Evropskem združenju akademij. Je ustanovitelj in predsednik Slovenskega združenja za energetiko (SZE), prek katerega si še posebej prizadeva za tesnejše povezovanje energetskih sektorjev.



MAG. MARKO GORJUP, Direktor TPV GROUP d.o.o.

Nagrajenec ZSIS za globalno prodornost slovenskega inženirstva 2020



Mag. Marka Gorjupa je inženirstvo navduševalo že od vsega začetka, zato ni naključje, da je takoj po končanem študiju na Fakulteti za strojništvo v Ljubljani začel svojo poklicno pot graditi v

podjetju TPV. Skozi različna delovna mesta je spoznaval poslovne procese podjetja ter kmalu prevzemal različne vodstvene funkcije. Znotraj Skupine TPV je vodil različna hčerinska podjetja, julija 2006 pa postal član uprave TPV d.d. Leta

2016 je prevzel funkcijo direktorja – predsednika posloводства TPV d.o.o., danes pa v vlogi direktorja TPV GROUP d.o.o. skrbi za strateški razvoj vseh družb v skupini.

Marko Gorjup je aktiven tudi v lokalnem okolju ter gospodarskih in stanovskih združenjih na nacionalni ravni. Kot član Lions kluba Novo mesto aktivno sodeluje tudi pri različnih humanitarnih dejavnostih. V sebi nosi visoko mero inovativne kulture, njegov svet je široko odprt, v katerem vidi še veliko priložnosti.



PROF. DR. JANEZ MOŽINA

Nagrajenec ZSIS za življenjsko delo 2020



Janez Možina se je rodil leta 1945 v Ljubljani. Na Oddelku za fiziko, Fakultete za naravoslovje in tehnologijo v Ljubljani je

diplomiral leta 1969, leta 1980 je doktoriral na Fakulteti za strojništvo v Ljubljani, leta 1993 pa postal redni profesor za področji Fizika in Laserska tehnika.

Pedagoško dejavnost je uspešno povezoval z raziskavami na področju laserske tehnike.

Pri svojem raziskovalnem delu se je najprej osredotočil na interakcijo med razredčenimi plini in akustično emisijo, nato pa na optoakustiko in laserske obdelovalne procese. Leta 1995 je na Fakulteti za strojništvo ustanovil Katedro za optodinamiko in lasersko tehniko, ki jo je vodil do upokojitve. Kot sintezo optoakustike in laserskih obdelovalnih procesov je dotlej ločeno obravnavane raziskovalne teme povezal v novo interdisciplinarno znanstveno področje Optodinamika. Nove vsebine je postopoma vpeljal v vse stopnje študija strojništva in s tem razširil dotedanjo študijsko smer Mehatronika v novo smer z imenom Mehatronika in laserska tehnika.

DR. MARJAN POGAČNIK, direktor podjetja Iskra Mehanizmi, d.o.o.

Nagrajenec ZSIS za globalno prodornost slovenskega inženirstva 2020



Za dr. Marjana Pogačnika je širjenje obzorij eno izmed ključnih dejavnikov uspeha. Po končanem študiju na Fakulteti za strojništvo se je zaposlil v podjetju

IskraEmeco na mestu konstruktorja v razvoju, nato je nove izzive poiskal na doktorskem študiju na strojni fakulteti. Po pridobitvi doktorskega

naziva se je kmalu vrnil v industrijo, v IskraEmeco je prevzel mesto direktorja proizvodnje, ki je takrat štela 1500 ljudi. Po nekajletnem delu je prejel povabilo k sodelovanju s strani g. Bavca, bivšega direktorja Iskre Mehanizmi. Leta 2005 je prevzel vodenje podjetja Iskra Mehanizmi.

Dr. Pogačnik največ energije posveča razvoju sistema vodenja in kontrolingu, saj v tem vidi velike koristi. Sam meni, da so za učinkovito vodenje potrebni sistem, podatki in ljudje. Njegova ambicija je narediti takšno podjetje, da lahko vse teče samo in se lahko brez bojazni umakne. Je predan delu in vedno odprt za nove priložnosti, ena takšnih je tudi nedavno odprtje tovarne na Brniku.



PROF. DR. JANEZ KOPAČ

Nagrajenec ZSIS za življenjsko delo 2020



Janez Kopač se je rodil leta 1949 v Ljubljani. Leta 1973 je diplomiral na Fakulteti za strojništvo v Ljubljani, smer Proizvodno strojništvo, leta 1986 pa doktoriral. Njegovo

področje dela je bila obdelovalnost težko obdelovalnih materialov z odrezavanjem, zato je bil močno povezan s podjetji. Leta 2000 je bil izvoljen v rednega profesorja na Fakulteti za strojništvo v Ljubljani.

Janez Kopač je leta 1991 postal vodja Laboratorija za odrezavanje LABOD, leta 2001 je ustanovil Katedro za menedžment obdelovalnih tehnologij in bil tudi njeno dolgoletno vodjo. Njegov koncept dela je teamsko delo in povezovanje s sodelavci za skupno reševanje problematike. V stilu moderne proizvodnje je vedno upošteval korake v krožnem gospodarstvu, kot so ekologija in odnos do delavca. S tega vidika je tekla smer izboljšav v slovenski proizvodni tehnologiji na MQL, HMT sisteme in kriogeno odrezavanje. V dolgoletni karieri je izvedel tehnološke rešitve v več kot 50 slovenskih podjetjih.

DR. JURE KNEZ, Soustanovitelj podjetja DEWESOFT

Nagrajenec ZSIS za globalno prodornost slovenskega inženirstva 2018



Dr. Jure Knez je doktorski študij opravljal na Fakulteti za strojništvo Univerze v Ljubljani. Življenjska pot ga je nato zanesla na področje merilne tehnike. Je soustanovitelj podjetja

Dewesoft, ki izdeluje programsko opremo, zadnje čase pa tudi kompletne merilne instrumente za fizikalne meritve za avtomobilsko, letalsko,

vesoljsko, gradbeno industrijo ter energetiko in transport. Vsi merilni instrumenti in komponente, torej strojna in programska oprema ter elektronika, so plod njihovega znanja in razvoja, inovacije pa del vsakdana.



AKAD. DR. IGOR EMRI

Nagrajenec ZSIS za življenjsko delo 2018



Akademik dr. Igor Emri se je rodil leta 1952 v Murski Soboti. Študij na Fakulteti za strojništvo Univerze v Ljubljani je zaključil leta 1974, doktoriral je leta 1981, sledila je

izvolitev v naziv docent leta 1983, v naziv izredni profesor leta 1988 in v naziv redni profesor leta 1996 za področje Mehanike. Profesorja Emrija je raziskovalna želja vodila vse višje, tako je leta 1997 ustanovil Katedro za mehaniko polimerov in kompozitov na Fakulteti za strojništvo UL ter ostal njen predstojnik vse do upokojitve. Raziskovalno delo je usmerjal na področje mehanike disipativnih sistemov s poudarkom na študiju vpliva hitrosti spreminjanja termomehanskih robnih pogojev na proces

formiranja strukture polimernih materialov in njihovih makro-, mikro- in nanokompozitov. Razvil je prvi nelinearni viskoelastični model, v literaturi znan kot model Knauss-Emri. Leta 1993 je skupaj s prof. W. G. Knaussom iz California Institute of Technology, ustvaril novo raziskovalno področje Mehanika časovno odvisnih materialov – MTDM kot oddelek ameriškega znanstvenega združenja The Society of Experimental Mechanics – SEM.

Za svoje delo je prejel vrsto nagrad in priznanj, med njimi nagrado sklada Borisa Kidriča, ambasador Republike Slovenije v znanosti za leto 2001, nagrado Kapitsa Medal (1997), ki je najvišja nagrada Ruske akademije naravoslovnih znanosti, nagrado Outstanding Engineer of the Russian Federation (2001), ki jo podeljuje Ruska inženirska akademija, ter nagradi B. J. Lazan za leto 2010 in S. Nemat-Nasser za leto 2017, ki jih podeljuje ameriško združenje The Society of Experimental Mechanics. 2005 je bil izvoljen za izrednega člana SAZU, 2013 pa za rednega člana.

IVAN KRALJ, Direktor podjetja AREX

**Nagrajenec ZSIS za globalno
prodornost slovenskega inženirstva
2018**



Gospod Ivan Kralj je človek velikih idej, ki jih hitro prenese v prakso. Že v otroštvu se je navduševal nad tehniko. Obiskoval je srednjo strojno šolo v Krškem, nato

je šolanje nadaljeval na Fakulteti za strojništvo v Ljubljani. Leta 1994 je ustanovil podjetje Arex v prostorih bivše Iskre Hipot. Po različnih

prodajno-proizvodnih programih so se leta 2000 usmerili v obrambni program – strelivo, orožje in drugo dopolnilno opremo. Družba je usmerila svojo prodajo predvsem na tuje trge, kjer ustvarijo 86 odstotkov prihodkov. Gospod Kralj je prejemnik številnih nagrad, med drugim je v letu 2017 postal nagrajenec Gospodarske zbornice Slovenije.



PROF. DR. FRANC KOSEL

Nagrajenec ZSIS za življenjsko delo 2018



Profesor Franc Kosel se je rodil leta 1943 v vasi Mišače pri Kropi. Osnovno šolo je obiskoval na Dobravi, nižjo gimnazijo pa v Radovljici. Nato se je v tovarni Kovinar v Kranju

izučil za kovinorezkalca. Na srednji tehniški šoli je leta 1964 opravil zaključni izpit in šolanje nadaljeval na Fakulteti za strojništvo v Ljubljani, kjer je diplomiral leta 1969. Vedoželjnost je profesorja Kosela gnala naprej vse do doktorata, ki ga je leta 1974 opravil na Fakulteti za strojništvo v Ljubljani. Za strokovno področje mehanika je bil leta 1975 izvoljen v naziv docent, v letu 1985 v naziv izredni profesor in v letu 1992 v naziv redni profesor. Bil je dolgoletni predstojnik Katedre za mehaniko, vodja oddelka za Letalstvo

in vodja Laboratorija za nelinearno mehaniko. Pod njegovim mentorstvom je diplomiralo okoli dvesto študentov, Na pobudo svojih kolegov je vložil kandidaturo za dekana in v letih od 1997 do 2001 prevzel glavne vaje Fakultete za strojništvo Univerze v Ljubljani. Profesor Kosel izžareva posebno življenjsko energijo, ki jo je prenesel na svoje potomce ter jih navdušil nad tehniko in naravoslovjem.

V okviru Jugoslovanskega društva za mehaniko, za predstavitev svojega doktorata na kongresu mehanikov v Sarajevu, je prejel nagrado Rastka Stojanoviča. Za doprinos k ugledu Univerze v Ljubljani iz obdobja, ko je bil dekan, je prejel zlato plaketo Univerze v Ljubljani. Kot predsednik Skupščine strojnih fakultet Jugoslavije je prejemnik več priznanj za sodelovanje na mašinijskih. V posebno veselje pa mu je nagrada, ki jo je prejel ob 70 obletnici Univerze v Ljubljani od študentov Fakultete za strojništvo.

IZR. PROF. DR. IVAN BAJSIĆ

Nagrajenec ZSIS za življenjsko delo 2017



Izr. prof. dr. Ivan Bajsić se je rodil 1950 v Lepoglavi, manjšem mestecu Hrvaškega Zagorja. Diplomiral je na univerzitetnem študiju Fakultete za strojništvo Univerze v Ljubljani leta 1975 in magistriral leta 1984 na isti fakulteti. Doktorat znanosti s področja eksperimentalnega modeliranja dvofaznega kapljičastega toka je leta 1990 pridobil na Fakulteti za strojništvo Univerze v Sarajevu. V času od 1. februarja 1974 do 21. januarja 2017 je bil neprekinjeno zaposlen na Fakulteti za strojništvo Univerze v Ljubljani. Leta 1991 je bil prvič izvoljen

v učiteljski naziv docent in leta 2002 prvič izvoljen v naziv izrednega profesorja. Rezultate raziskovalnega dela je nagrajenec predstavil v 79 izvirnih in preglednih znanstvenih člankih v tujih ter domačih strokovnih revijah. Posebej je vredno tudi omeniti prizadevnost nagrajenca kot mentorja ali somentorja, saj je bil mentor in somentor doktorantom, magistrantom znanosti, specializantom in diplomantom ter kandidatom, ki so dobili Prešernovo nagrado in priznanje s področja študija strojništva skupaj 464-krat. Osrednja področja njegovih znanstveno-raziskovalnih in strokovnih aktivnosti so s področja meroslovja s poudarkom na merilni dinamiki procesno-energetskih veličin stanja, kot so tlak, temperatura in pretok tekočin, ter načrtovanju, razvoju in meroslovni analizi različnih procesnih merilnih sistemov, ki so namenjeni za rabo v realnem industrijskem okolju.

ZASL. PROF. DR. ADOLF ŠOSTAR

Nagrajenec ZSIS za življenjsko delo 2017



Zaslužni profesor dr. Adolf Šostar se je rodil v Ljubljani, odraščal je v Mariboru, kjer je leta 1952 maturiral na I. gimnaziji. Diplomiral je leta 1960 na Fakulteti za strojništvo v Ljubljani, še pred zaključkom študija se je zaposlil v Tovarni avtomobilov Maribor v sektorju tehnološke priprave proizvodnje. Po povabilu na Višjo tehniško šolo je bil leta 1962 izvoljen v naziv honorarni asistent in leta 1966 v naziv predavatelj. Vzpostavil je izjemno sodelovanje med višjo šolo in podjetji, ki so namenila sredstva za opremljanje in gradnjo laboratorijev. Od leta 1966 naprej je vodil Laboratorij za tehnološke

meritve. Leta 1975 je doktoriral na Tehniški univerzi v Gradcu. Za vodstveno in organizacijsko delo je profesor Šostar vložil veliko svoje življenjske energije, še posebej za rast Fakultete za strojništvo in Univerze v Mariboru. Pričel je leta 1975 kot predstojnik strojništva na tedanji Visoki tehniški šoli, bil je dekan Visoke tehniške šole od 1979 do 1983, prorektor Univerze 1984/85 in od 1995 do 2001 dekan Fakultete za strojništvo v Mariboru. Mnoga leta je bil predstojnik Katedre za proizvodno strojništvo in vodja Laboratorija za tehnološke meritve. V okviru laboratorija je skupaj s sodelavci ustanovil meroslovni sistem Slovenije in ga uveljavil v svetu.

Za svoje delo je prejel več nagrad: zlati znak Univerze v Mariboru, državno odlikovanje red dela s srebrnim vencem, diplome in priznanja univerz oziroma fakultet v Gradcu, Zagrebu in Ljubljani. Na osnovi izjemnih in pomembnih dosežkov mu je Univerza v Mariboru podelila častni naziv zaslužni profesor.

MAG. TOMAŽ BERLOČNIK, PRESEDNIK UPRAVE DRUŽBE PETROL D. D.

Nagrajenec ZSIS za globalno prodornost slovenskega inženirstva 2017



Mag. Tomaž Berločnik je po duši in srcu strojnik. Obiskoval je srednjo strojno šolo in kasneje nadaljeval izobraževanje na Fakulteti za strojništvo v Ljubljani. Pot ga je nato

usmerila v ekonomske vode, postal je magister ekonomskih znanosti. Poslovno pot je začel že v času študija strojništva, ko je s prijatelji ustanovil

podjetje RVS d.o.o. (Računalništvo v strojništvu). Po končanem študiju se je kot projektni vodja za sanacijo podjetij zaposlil v takratnem Skladu RS za razvoj. Med drugim je bil tudi predsednik uprave Donit Tesnit d.d., predsednik uprave družbe Istrabenz d.d., bil je član nadzornega sveta družbe Petrol d.d., Ljubljana. Nadzorni svet ga je dvakrat imenoval na mesto predsednika uprave za petletno mandatno obdobje, s pričetkom 2011 in 2016. Mag. Tomaž Berločnik je tudi podpredsednik upravnega odbora Združenja Manager za obdobje 2014–2017, z novim mandatom do leta 2020. V sredini leta 2017 je postal predsednik slovenskega Košarkarskega kluba Petrol Olimpija.

IGOR BERCE, DIREKTOR PODJETJA BRINOX D.O.O.

Nagrajenec ZSIS za globalno prodornost slovenskega inženirstva 2017



Igor Berce je lastnik in direktor podjetja Brinox inženiring d.o.o. ter obenem diplomant Fakultete za strojništvo v Ljubljani, smer Procesno strojništvo in energetika. V podjetju

Brinox je aktivno deloval že od samega začetka, pričeli so v domači garaži z veliko entuzijazma in malo sredstvi. Gospod Igor Berce je vodenje podjetja prevzel za svojim očetom. Vodilo podjetja je, da je le vrhunski tim sposoben

zmagovati na mednarodnih trgih, zato veliko vlagajo v izobraževanje in razvoj kadrov ter v prijetno in zdravo delovno okolje. Podjetje Brinox je partnerski dobavitelj procesne opreme in sistemov štirim od petih največjih svetovnih farmacevtskih družb. Prav tako so partnerji več svetovnim koncernom na področju mlekarstva in pijač. Vsa njihova partnerstva gradijo dolgoročno, kar od podjetja zahteva kakovostno in pravočasno izvajanje projektov ter dobava procesne opreme, ki brezhibno deluje v predvideni tehnični življenjski dobi.

ZASL. PROF. DR. JOŽE VIŽINTIN

**Nagrajenec ZSIS za življenjsko delo
2016**



Zasl. prof. dr. Jože Vižintin je na Fakulteti za strojništvo diplomiral leta 1972 in doktoriral leta 1978. V rednega profesorja je bil izvoljen leta 1995. Na Fakulteti za strojništvo je ustanovil

Center za tribologijo in tehnično diagnostiko ter Katedro za tribologijo in sisteme vzdrževanja. Štiri leta je bil prorektor za raziskovalno delo Univerze v Ljubljani in ustanovitelj Inovacijsko razvojnega inštituta Univerze v Ljubljani.

Ustanovil je društvo za Tribologijo Slovenije in bil njegov predsednik 28 let. Je soustanovitelj Inženirske Akademije Slovenije, kateri je dvakrat tudi predsedoval, kasneje je opravljal funkcijo glavnega tajnika Akademije.

Za svoje delo je dobil več nagrad: Ziosovo priznanje in Zoisovo nagrado za vrhunske znanstvene dosežke na področju strojništva, zlato plaketo Univerze v Ljubljani, nagrado ameriškega združenja inženirjev ASME, Society of Tribologists and Lubrication Engineers-STLE mu je podelilo naziv Fellow. 3. decembra 2015 mu je rektor Univerze v Ljubljani dr. Ivan Svetlik podelil častni naziv - zaslužni profesor Univerze v Ljubljani.

DR. HUBERT KOSLER, direktor podjetja Yaskawa Ristro

**Nagrajenec ZSIS za globalno
prodornost slovenskega inženirstva
2016**



Dr. Hubert Kosler je že od samih začetkov zapisan vodenju. Že takoj po diplomi na Fakulteti za strojništvo je vodil projekte v ISKRI AVTOMATIKI TOZD AVN, od leta 1988 do

leta 1990 je bil pomočnik stečajnega upravitelja in vodja oddelka za inženiring TOZDA AVN v stečaju, od leta 1990 je bil soustanovitelj in direktor firme MOTOMAN ROBOTEC Ribnica,

ki jo danes poznamo pod imenom YASKAWA SLOVENIJA d. o. o. Svoje vodstvene sposobnosti je razširil in bil leta 1996 pobudnik ustanovitve proizvodnega podjetja YASKAWA RISTRO Ribnica in postal tudi njen direktor. Od leta 2009 je član upravnega odbora YASKAWA EUROPE GmbH, od leta 2010 direktor podjetja YASKAWA CZECH s.r.o. v Pragi. Za svoje delo je prejel številne nagrade: Nacionalno srebrno priznanje 2013 za inovacijo robotske varilne celice s sistemom strojnega vida MotoSENSE, nagrado GZS 2013 za izjemne gospodarske dosežke in bil je regijski finalist Gazela 2012 in 2013. Leta 2014 je bil izvoljen za izrednega člana Inženirske akademije Slovenije.

Dr. Hubert Kosler globalno prodornost vidi v tem, da smo s svojim znanjem in s tehniško inteligenco sposobni evropskemu in tudi svetovnemu trgu ponuditi rešitve na področju robotizacije, tehnoloških procesov ter v avtoindustriji. Pomembno je, da svoje izkušnje in svoje znanje tržimo v globalni areni.

ALEKSANDER ZALAZNIK generalni direktor podjetja Danfoss Trata in višji podpredsednik Commercial Controls

**Nagrajenec ZSIS za globalno
prodornost slovenskega inženirstva
2016**



Aleksander Zalaznik, generalni direktor Danfoss Trate in višji podpredsednik Danfossovega poslovnega področja Heating Commercial Controls, vodi družbo že od leta 1995. V času njegovega vodenja se

je Danfoss Trata razvila v pomemben poslovni in tehnološki center za rešitve na področju regulacije

prenosa toplote v ogrevalnih in hladilnih sistemih. Odlični poslovni rezultati, ki so rezultat zavzetih zaposlenih in zavezanosti vodstva k trajnostnemu razvoju poslovanja, kakovosti in inovativnosti, uvrščajo Danfoss Trato med vodilna podjetja v Evropi. Za svoje delo je prejel nagrado Časnika Finance za izjemne dosežke v gospodarstvu leta 2012 in nagrado Gospodarske zbornice Slovenije za izjemne gospodarske in podjetniške dosežke za leto 2007. Je tudi član Združenja Manager od leta 1998 in član upravnega odbora Združenja od 2008, aprila 2014 pa je bil izvoljen za predsednika Združenja.

Aleksander Zalaznik vidi globalno prodornost slovenskega inženirstva kot sposobnost, da znamo razviti in izdelati izdelek ali storitev, ki ga uspešno prodajamo na globalnem trgu. Inženirski poklic je eden izmed najbolj ustvarjalnih, zanimivih, pestrih poklicev, kjer smo vedno znova presenečeni nad novimi odkritji. Inženirji smo tisti, ki skrbimo za tehnični napredek in izboljšujemo kakovost življenja.

SPLETNI PRENOS DOGODKA

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V ŽIVO



PROF. DR. MATIJA FAJDIGA

Nagrajenec ZSIS za življenjsko delo 2014



Prof. dr. Matija Fajdiga je osnovno šolo in nižjo gimnazijo obiskoval v Sodražici, srednjo tehnično šolo pa v Ljubljani, kjer je maturiral leta 1959. Na Fakulteti za strojništvo v Ljubljani je leta 1964 diplomiral na področju vozil, leta 1974 magistriral in leta 1975 doktoriral. Na Fakulteti za strojništvo se je zaposlil leta 1964, leta 1996 je bil izvoljen v rednega profesorja za strojne elemente in vozila. Bil je več let predstojnik Katedre za konstruiranje, ustanovil je tudi Katedro za strojne elemente in razvojna vrednotenja ter jo vodil vse do upokojitve. Utemeljlil in vpeljal je številna področja v raziskovalni in pedagoški

program FS. Ustanovil in vodil je raziskovalni center Center za razvojna vrednotenja – CRV, ki je financiran izključno s sredstvi iz industrije. Bil je pobudnik in ustanovitelj Avtomobilskega grozda Slovenije – ACS. Programsko je zasnoval in vodil študentske raziskovalne skupine z večletno dejavnostjo, ki so bile prepoznavne doma in v tujini: Športno vozilo MM-Šinkovec (1999 in dalje), Student Roadster (2003 in dalje), Skidcar (2005 in dalje). Na Fakulteti za strojništvo Univerze v Ljubljani je eno mandatno obdobje deloval v funkciji prodekana, dve mandatni obdobji pa je bil dekan. Aktivno je sodeloval in deloval v številnih komisijah na fakulteti in na univerzi ter bil uspešen pri mednarodnih projektih.

Prof. dr. Matija Fajdiga je za svoje dosežke prejel Priznanje za uspešno delo na Fakulteti za strojništvo, Priznanje za uspešno sodelovanje s podjetji TAM Maribor, Cimos Koper ter Crvene zvezde Kragujevac, Pisno priznanje za donacije študentom FS in Zlato plaketo UNI Ljubljana.

RADOVAN BOLKO, Predsednik uprave koncerna KOLEKTOR

Nagrajenec ZSIS za globalno prodornost slovenskega inženirstva 2014



Karierna pot Radovana Bolka je tesno povezana s Kolektorjem. Začela se je leta 1976, ko je dobil kadrovsko štipendijo za študij na Fakulteti za strojništvo. Prvega marca 1981 se je zaposlil in po vmesni enoletni prekinitvi zaradi služenja vojaškega roka leta 1983 zaključil pripravništvo. Nato je opravljal dela s

področja tehnologije prešanja in brizganja ter kasneje tudi konstruiral naprave in orodja. Leta 1989 je na osnovi internega razpisa zasedel mesto vodje sektorja zagotavljanja kakovosti in s tem postal član posloводства Kolektorja. Tej funkciji je bila kasneje dodana še odgovornost za Divizijo C, dokler ni leta 2004 prevzel odgovornosti za razvoj novih (nekomutatorskih) programov in kasneje dobil tudi status namestnika predsednika. Od leta 2009 je bil na položaju glavnega izvršnega direktorja. S 1. oktobrom 2014 je prevzel mesto predsednika uprave koncerna Kolektor.

Koncern Kolektor je tehnološko podjetje, ki gradi izdelke in rešitve na tehničnem znanju. Pomnjenju Radovana Bolka je osnova tehnika, rešitve pa morajo biti drugačne, boljše od konkurence. S takimi izdelki, z dobrimi proizvodnimi procesi, z inovativnimi idejami in s pravim pristopom je treba gledati v svet in biti tudi zanj odprt, to je osnova za globalno prodornost.

PROF. DR. PETER NOVAK

Nagrajenec ZSIS za življenjsko delo 2011



Profesor Novak je leta 1955 končal gimnazijo v Novem mestu in leta 1961 zagovorjal diplomu na Fakulteti za strojništvo v Ljubljani in leta 1985 pridobil naziv rednega profesorja.



Po desetletju v pokoju ostaja profesor Novak eden glavnih ambasadrov inženirske stroke. V letu 1999 je postal zaslužni član American Society for

Heating, Refrigerating and Airconditioning Engineers (ASHRAE). Je član Evropskega

zdrženja REHVA. Skoraj deset let je bil predsednik komisije E1 Klimatizacija in član Znanstvenega sveta v Mednarodnem inštitutu za hlajenje (IIR), svetovni medvladni organizaciji z več kot stoletno tradicijo. Leta 1999 je postal član upravnega odbora in leta 2003 tudi častni član IIR. Od ustanovitve do danes je predsednik komisij za okoljske nagrade in nagrade za energetske učinkovite podjetje v Sloveniji ter član Usmerjevalnega komiteja za okoljske nagrade EU. Več kot dve desetletji pa je tudi član Sveta RS za varstvo okolja.

Profesor Novak je pomembno prispeval k razvoju Dolenjske regije, iz katere prihaja. Kot predsednik razvojnega sveta za JV Slovenijo je razvil koncept Univerze v Novem mestu in plod njegovih prizadevanj je leta 2006 ustanovljena Visoka šola za tehnologije in sisteme VITES. Dokaz njegovega vizionarstva je prizadevanje za združevanje slovenske industrije sistemov stavbnih strojnih instalacij.

VLADIMIR GREGOR BAHČ,

Predsednik uprave TPV d. d.

Nagrajenec ZSIS za življenjsko delo 2011



Svoje celotno življenjsko delovno obdobje je posvetil razvoju strojništva. Po končani srednji tehnični šoli v Krškem se je leta 1964 zaposlil v takratni Industriji motornih vozil v Novem mestu. Takoj naslednje leto je nadaljeval študij strojništva, najprej v Mariboru, nato v Ljubljani, kjer je diplomiral na Fakulteti za strojništvo.



V podjetju IMV je opravljal različna strokovna, organizacijska in vodstvena dela na področju kakovosti, tehnične priprave proizvodnje in na razvojnem inštitutu. V osemdesetih

letih je v IMV-ju opravljal številne odgovorne vodstvene dolžnosti. Uspešno je sodeloval pri sanaciji in preoblikovanju IMV, ki je leta 1989 ustanovila štiri delniške družbe.

Vladimir Gregor Bahč je del TPV-ja vse od njegove ustanovitve. Bogate izkušnje, poznavanje avtomobilske industrije, konstruktivno sodelovanje in dobri odnosi s poslovnimi partnerji so podlaga za številne uspešne posle v proizvodnji sestavnih delov za avtomobile. Vsakozi se je zavedal, da je za uspeh podjetja potrebna komercialna in kapitalska povezava s svetovno priznanimi dobavitelji.

Vladimir Gregor Bahč sodeluje v različnih odborih in komisijah gospodarskih združenj. Za svoje družbeno priznano delo je prejel številna priznanja in nagrade, med drugim nagrado Gospodarske zbornice Slovenije za izjemne gospodarske in podjetniške dosežke ter nagrado Mestne občine Novo mesto. Leta 2012 je postal častni meščan občine Metlika.

PAVEL LEDINEK, Ledinek Engineering d.o.o

Nagrajenec ZSIS za življenjsko delo 2008



Za razvoj neke osebnosti so pomembne korenine, iz katerih oseba izhaja. Tudi pri g. Pavlu je tako. Njegov ded Pavel je leta 1908 ustanovil sodarsko delavnico in je s sodi oskrboval pretežno štajerske vinogradnike. Tradicijo

podjetja je nadaljeval njegov sin in oče nagrajenca, tudi Pavel, in znanje uspešno prenesel na svojega sina. Tako je naš nagrajenec že od mladosti povezan z obdelavo lesa. Leta 1967 izdelal enega prvih večvretenskih mizarskih skobeljnih strojev

in se predstavil na mednarodnih sejmihi.

Po letu 1980 je gospod Ledinek nadaljeval z razvojem skobeljnih strojev v smeri industrijske obdelave lesa. Nastali so stroji za vsestransko vzdolžno obdelavo različnih profilov. Ti stroji so bili izjemno zmogljivi, natančni pri obdelavi in priročni za upravljanje. Z njimi je podjetje osvojilo trg in uporabnike vseh celin sveta. Leta 1986 je g. Pavel Ledinek slavnostno odprl novo tovarno in vanjo preselil proizvodnjo. Nadaljnji razvoj je šel v smeri izdelave strojev velikih zmogljivosti in točnosti obdelave. Izumil je nov horizontalno krožen princip odrezovanja lesa in izdelal stroj, imenovan »ROTOLES«. Zanj je g. Ledinek že leta 1994 na sejmu v Atlanti v ZDA prejel najvišje priznanje. »ROTOLES« je patentiran v številnih državah po svetu in še danes velja za enega najžlahtnejših dosežkov slovenske strojne industrije.

VINKO WERNIG – DIPL. INŽ.

Nagrajenec ZSIS za življenjsko delo 2008



Gospod Vinko Wernig se je rodil oktobra 1931 v Ljubljani. Takoj po diplomi, leta 1958, se je zaposlil pri Petrolu. Od leta 1965 dalje je delal v novoustanovljenem razvojnem sektorju, kjer je

svoje znanje in izkušnje koristno uporabil pri rekonstrukciji Rafinerije mineralnih olj v Mariboru in obmorske instalacije Sermin pri Kopru. Leta 1970 je bil imenovan za direktorja sektorja za investicije in vzdrževanje. V letu 1974 je postal direktor sektorja za zemeljski plin, ki se je kasneje razvil prek TOZD-a v delovno organizacijo Petrol Zemeljski plin.

Vinko Wernig je vodil celotno gradnjo slovenskega plinovodnega omrežja, ki je bila končana v roku in v predvideni ocenjeni investicijski vrednosti. Prvi zemeljski plin je po novozgrajenem plinovodu iz tedanje Sovjetske zveze v tedanjo Jugoslavijo pritekel 17. julija 1978.

Odločilen prispevek Vinka Werniga se je odrazil tudi na projektu dodatne oskrbe iz Alžirije. Prav ta projekt je še posebej neprecenljiv, saj njegova vizija o nujnosti dobav zemeljskega plina tudi iz zahodne smeri sega že v samo prvotno gradnjo plinovodnega sistema Slovenije.

Vinko Wernig je imel vedno zelo jasno vizijo o pomenu in vpetosti plinske dejavnosti v mednarodne tokove, vedno je znal reševati težave in tako omogočil bogato nadaljnjo rast in razvoj.

PROF. DR. JOŽE HLEBANJA, zaslužni profesor UL

**Nagrajenec ZSIS za življenjsko delo
2007**



Jože Hlebanja je rojen 31. 3. 1926 na Srednjem vrhu nad Kranjsko Goro. Do poletja 1946 je končal Srednjo tehniško šolo in se v jeseni vpisal na Tehniško fakulteto, Oddelek za strojništvo v Ljubljani. Diplomiral je leta

1952. Postal je asistent za transportne naprave in jeklene konstrukcije. Po treh letih se je kot projektant zaposlil v Metalni Maribor. Pod

negovim vodstvom in z njegovimi projekti je postala Metalna vodilna za gradnjo žičnic v širši regiji.

Prof. Jože Hlebanja je ob obsežnem pedagoškem delu, raziskovalnem in strokovnem delu skupaj z industrijo in za njo leta 1967 končal svojo doktorsko raziskavo "Uporabnost cikličnih krivulj za boke zob zobnikov" in dobil izredno profesuro. Ob koncu sedemdesetih let je prevzel vodenje raziskovalnega programa Transportne naprave, strojni elementi in konstruiranje. Konec 70. let in vsa 80. leta je prof. dr. Jože Hlebanja vodil obsežno pedagoško-raziskovalno skupino.

Ko je prof. dr. Jože Hlebanja leta 1991 odšel v pokoj, je na Fakulteti za strojništvo in v Sloveniji pustil urejeno strokovno področje konstruiranja. Univerza v Ljubljani mu je leta 1996 podelila naslov zaslužni profesor Univerze v Ljubljani za prispevek k razvoju visokega šolstva in znanosti.

AKAD. PROF. DR. JANEZ PEKLENIK, zaslužni profesor UL 1926 - 2016

**Nagrajenec ZSIS za življenjsko delo
2007**



Akademik profesor Janez Peklenik se je rodil 9.6.1926 v Trzinu. Po študiju strojništva na Univerzi v Ljubljani je odšel v Laboratorij za obdelovalne stroje Tehniške visoke šole v Aachnu. Po dveh letih uspešnega raziskovalnega dela je leta 1957 doktoriral na področju fizikalnih osnov

brušenja. Leta 1961 je bil habilitiran ter postal docent na Tehniški Visoki šoli v Aachnu. Temu je leta 1964 sledila izvolitev v rednega profesorja. Z ustanovitvijo prve katedre za računalniško krmiljene obdelovalne sisteme na svetu in dopolnitvijo tehnoloških raziskav je postavil

nova izhodišča za raziskovalno delo na področjih modernih proizvodnih tehnologij.

Leta 1959 je bil za svoje znanstvene dosežke odlikovan s Taylorjevo medaljo mednarodne akademije College International pour l'Etude Scientifique des Techniques de Production Mécanique. Leta 1966 je bil izvoljen za rednega člana te akademije, ki ji je tudi predsedoval, sedaj pa je njen častni član. Leta 1973 se je vrnil na Fakulteto za strojništvo Univerze v Ljubljani in ustanovil Katedro ter Laboratorij za tehnično kibernetiko, obdelovalne sisteme in računalniško tehnologijo. Na Fakulteti za strojništvo je kot dekan začel posodabljanje študij ter intenzivno širiti znanstveno-raziskovalno in razvojno delo. Leta 1987 je bil izvoljen za rektorja Univerze v Ljubljani.

Za znanstvene dosežke je akademik Peklenik prejel številna mednarodna in domača priznanja. Poleg medalje CIRP je leta 1982 prejel še ameriško medaljo F. W. Taylorja, ki se podeljuje znanstvenikom s področja proizvodnega inženirstva, in leta (1988) berlinsko nagrado Georga Schlesingerja. Doma je prejel državno Kidričevo nagrado (1975), državno nagrado RS za življenjsko delo (1996) in bil imenovan za Ambasadorja znanosti RS (1992) ter zaslužnega profesorja Univerze v Ljubljani.

UTRINKI PRETEKLIH DOGODKOV

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Analysis of the use of phase change materials in a household refrigerator

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This research paper explored the potential to enhance the energy efficiency of a household refrigerator-freezer by incorporating phase change materials (PCMs). A series of experiments were carried out to assess the performance of a modified refrigerator-freezer under real-world conditions, with different PCMs placed at various strategic points: between the evaporator fins, between the evaporator and the rear compartment wall, and inside the cooling air guide channel. The impact of PCMs with phase transition temperatures of 2°C, 0°C, -21°C, and -24°C on system performance was analysed. The findings showed that installing PCMs in the evaporator reduced cooling capacity by 19.1% and increased the ratio of average compressor on-time to the full cycle (ON/OFF ratio) by 4.35%. When PCMs were installed at all three locations simultaneously, the average cooling capacity decreased by 58.2% and the ON/OFF ratio by 84.78%.

Introduction

The population growth, economic development, and the increasing adoption of electrified technologies are driving rising energy demand [1]. In response, the Fit for 55, presented in July 2021 as part of the European Green Deal, sets ambitious targets to reduce EU greenhouse gas emissions by at least 55% by 2030 and introduces the “energy efficiency first” principle, making energy efficiency improvements a legally binding criterion in energy and construction policies [1]. The revised EU Energy Efficiency Directive (Directive (EU) 2018/2002, updated 2023) establishes a binding target to reduce final energy consumption by 11.7% relative to 2020 levels by 2030, with an annual energy savings rate of 1.5% between 2024 and 2030 [2]. These measures are designed to support the broader deployment of energy-efficient technologies, including heat pumps, improved thermal insulation, and more efficient refrigeration appliances, thereby reducing energy use and mitigating greenhouse gas emissions [3].

In Slovenian households in 2019, refrigeration appliances accounted for 10.5% of total energy demand. Of this, refrigerators and combined refrigerators made up 5.2%, while chest freezers accounted for 5.3% [4]. A promising approach to enhance energy efficiency is the implementation of PCM, a substance that absorbs in and releases large amounts of thermal energy when it changes phases, usually between solid and liquid states, at an almost constant temperature. This characteristic lets PCMs store and release heat efficiently, helping to keep a steady temperature in applications like thermal management and energy storage [5]. Utilising these materials has the potential to contribute to greater energy efficiency and system stability while reducing costs for users [6].

Materials and methods

Experimental setup. All experiments were performed on a combined domestic refrigerator-freezer, equipped with a finned evaporator and microprocessor control. The unit was placed in a climate chamber that allowed precise regulation of temperature and relative humidity. Instead of a compressor, a closed cooling loop was installed, consisting of a thermal bath, a flow pump and evaporator. The controller was modified to switch the pump on/off instead of a compressor to simulate the operation of the appliance as intended by the manufacturer, while enabling precise control of the system and the temperature and flow of refrigerant at the inlet to the evaporator. Temperature measurements were performed in the same manner as the manufacturer, using ten T-type thermocouples arranged throughout the refrigerator and freezer compartments at two chamber temperatures: 16 °C and 32 °C. To determine the cooling capacity of the replacement system, the refrigerant temperatures at the inlet and outlet of the evaporator using two type K thermocouples were measured. This setup ensured that heat losses between the thermal bath and the evaporator could be neglected.

Choice of PCMs: Considering the operating temperature ranges of the appliance, five suitable PCMs were selected to evaluate the impact of different phase change temperatures on the operation of the appliance. For the refrigerator compartment, two Rubitherm RT PCMs with phase transition temperatures of 2 °C and 0 °C were selected, while three PCMs with phase transitions at -17 °C, -21 °C, and -24 °C were chosen for the freezer compartment. Rubitherm PCM SP-17 was subsequently excluded from the measurements due to chemical reactions with the copper containers.

Testing locations: The PCMs were installed in three positions: between the evaporator fins, between the evaporator and the back wall of the freezer, and inside the cooling air guide channel. The PCM containers were designed to enable straightforward fabrication in the laboratory using copper plates and for quick PCM replacement between experiments.

Baseline measurements: By adjusting the refrigerant mass flow rate through the pump and the temperature of the thermal bath, it was possible to obtain the same ON/OFF ratio as specified by the manufacturer. These measurements, performed at 16 °C and 32 °C, with a mass flow rate of 97 kg/h and a thermal bath temperature of -25 °C, served as the baseline for comparison. The ON/OFF ratio was calculated according to equation (1)

$$\frac{ON}{OFF} = \frac{t_{on}}{t_{cycle}} \quad (1)$$

Where t_{on} is the activation duration of the compressor, and t_{cycle} is the duration of the whole cooling and warming cycle.

Cooling capacity. The cooling capacity $\dot{Q}$ of the system was determined from the temperature drop across the evaporator, the specific heat of the refrigerant (c_p) and the mass flow rate ($\dot{m}$), calculated using equation (2)

$$\dot{Q} = \dot{m} c_p \Delta T, \quad (2)$$

where ΔT is the temperature drop in the evaporator. For each measurement we averaged the cooling capacity throughout the pump activation cycle. The initial spike in cooling capacity observed at the beginning of each measurement was caused by refrigerant stagnation in the piping between measurements and was disregarded.

Measurements. Following the control measurements, the effects of empty containers and fan speed on system performance were evaluated. The measurements were then carried out for each location separately, with two different PCMs, at 16 °C and 32 °C. The efficiency of each PCM was assessed based on the change in cooling capacity, ON/OFF ratio and temperature profiles of the PCMs. Finally, a combined measurement was performed in which the selected PCMs were installed simultaneously in all three locations.

Results and discussion

Effect of PCM placement in the refrigerator section: The presence of empty containers in the cooling air duct affected airflow, leading to a reduction in cooling capacity and an increase in the ON/OFF ratio. These changes led to temperature stratification (−2 °C to +8 °C) while simultaneously reducing temperature fluctuations within both the refrigerator and freezer sections. When Rubitherm PCMRTO and Rubitherm PCM RT2 were installed in the containers, the average cooling capacity decreased, and the ON/OFF ratio increased compared to empty containers. Also, Rubitherm PCM RT0 was more effective at higher ambient temperatures and had a greater influence on the system's operating parameters.

Effect of PCM placement in the evaporator: Once again, the effect of empty containers on the PCM was first examined. Empty containers in the evaporator reduced the cooling capacity and increased the ON/OFF ratio; however, the effect was offset by the higher fan speed.

A comparison of SP-21 and SP-24 showed a similar effect on the ON/OFF ratio and cooling capacity. Compared to empty containers in the evaporator, both PCMs increased the average cooling capacity and reduced the ON/OFF ratio. At 16°C, the ON/OFF ratio increased by 4.4% compared to the measurement without PCM, representing the smallest difference among all experiments. The greatest difference was evident in the temperatures: Rubitherm PCM SP-24 varied between -25°C and -17.8°C, which means that a phase change occurred, while Rubitherm PCM SP-21 remained in a solid state, and its latent heat was not utilized.

Effect of PCM placement between the evaporator and freezer section. The large container with Rubitherm PCM SP-21 had a significant impact on the system: the ON/OFF ratio increased by 65.2%, the cooling capacity decreased by 37.6%,

while the frequency of pump activations (approximately one per hour) remained comparable to the control measurement.

Effect of combined installation. In the combined measurement, in which PCMs were installed in all three locations simultaneously, and the fan speed was increased, the most pronounced changes were evident. The ON/OFF ratio increased by 84.8%, and the average cooling power decreased to its lowest recorded value of 57 W. The frequency of pump activations did not increase; however, the cycle at lower cooling power was extended. Temperature stratification was observed in both sections, most notably in the refrigerator compartment, due to the containers disrupting airflow in the guide channel.

Overall, the reduction in average cooling capacity (Figure 1) may allow for the use of a lower power compressor, potentially reducing energy losses and improving overall system efficiency. Extending the operating cycle results in fewer compressor start-ups, each of which is associated with additional power losses and mechanical wear. Moreover, slower cooling at lower power levels will result in a more stable and uniform temperature distribution within the refrigerated compartments during operation.

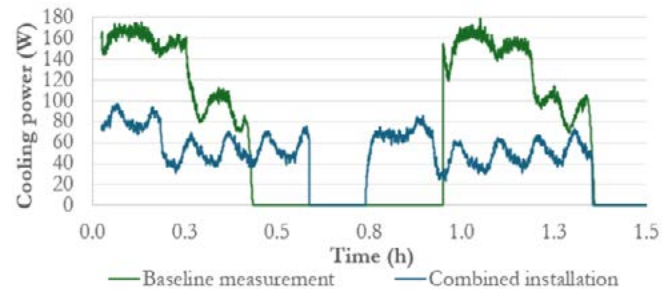


Figure 1: RA cooling power for baseline measurement and combined installation at environment temperature 16°C.

Conclusions

It has been shown that combining PCMs with the right phase change temperatures in carefully chosen spots within a household refrigerator-freezer can affect its performance:

- The use of PCMs contributes to reduced temperature fluctuations and improved system stability.
- Installing a PCM in the evaporator and cooling channels decreased the average cooling capacity by up to 19.1% while increasing the ON/OFF ratio by 4.4%.
- Installing PCMs at all three locations resulted in a 58.2% decrease in cooling capacity and an 84.8% increase in the ON/OFF ratio.

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Vpliv laserskega udarnega utrjevanja na izboljšanje funkcionalnosti superelastične Nitinol zlitine

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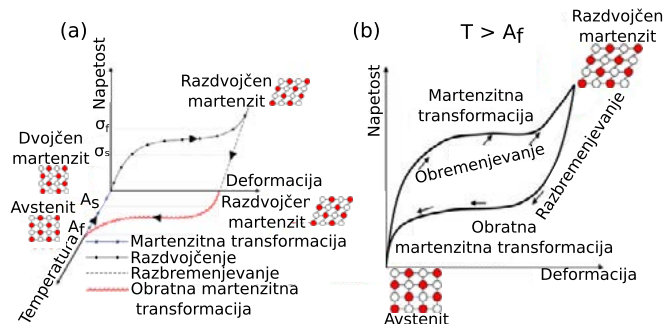
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Raziskava obravnava vpliv laserskega udarnega utrjevanja (angl. *Laser Shock Peening* - LSP) na mikrostrukturne in mehanske lastnosti superelastične ekvatomske Nitinol zlitine. S spreminjanjem gostote moči laserskih impulzov smo analizirali inducirane zaostale napetosti, mikrotrdoto ter spremembe v mikrostrukturi. Rezultati kažejo, da višje gostote moči vodijo do zmanjšanja velikosti kristalnih zrn na površinskih plasteh, povečanja mikrotrdote ter izboljšanja mehanskega odziva materiala. LSP se tako izkazuje kot učinkovita metoda za izboljšanje odpornosti proti utrujanju, ki sicer omejuje življenjsko dobo in zanesljivost komponent iz Nitinola.

Uvod

Nitinol, skoraj ekvatomska zlitina niklja in titana, je zaradi svojih funkcionalnih lastnosti – superelastičnosti, oblikovnega spomina in elastokaloričnega učinka – nepogrešljiv v številnih visokotehnoloških aplikacijah. Uporablja se v medicinskih vsadkih, ortodontskih lokih in kirurških orodjih ter komponentah v letalski, avtomobilski in energetski industriji, kjer se izkorišča njegova spodobnost dušenja vibracij in biokompatibilnost.

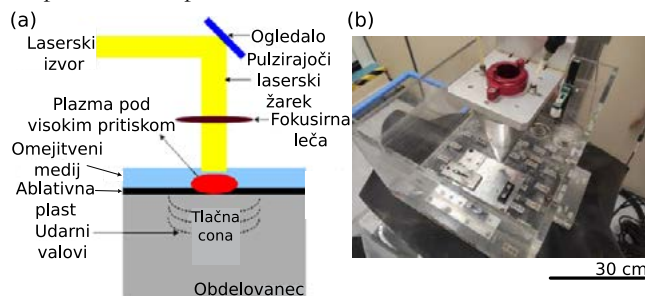
Funkcionalne lastnosti NiTi zlitine temeljijo na reverzibilni martenzitni transformaciji med avstenitno in martenzitno fazo. Ta fazna sprememba vključuje strižni premik atomov brez prekinitev vezi, kar omogoča spremembo oblike materiala brez pretrganja atomskih vezi. Deformacija v martenzitni fazi se ob segrevanju povrne v prvotno stanje – **oblikovni spomin** (slika 1 (a)). Če pa material v avstenitni fazi obremenimo z dovolj visoko napetostjo, pride do napetostno inducirane martenzitne transformacije, ki omogoča veliko reverzibilno deformacijo – **superelastičnost** (slika 1 (b)) [1].



Slika 1: prikaz (a) oblikovnega spomina in (b) superelastičnosti.

Elastokalorični učinek je termomehanski pojav, pri katerem se material med mehansko obremenitvijo segreje, ob razbremenitvi pa ohladi. Njegova učinkovitost je odvisna od hitrosti obremenjevanja in mikrostrukturnih lastnosti [1,2].

Za izboljšanje mehanskih lastnosti Nitinola, zlasti odpornosti proti utrujanju, se uporablja lasersko udarno utrjevanje (angl. *Laser Shock Peening* – LSP). Gre za površinsko obdelavo, pri kateri visokoenergijski laserski impulzi ustvarijo udarne valove, ki inducirajo tlačne zaostale napetosti in mikrostrukturne spremembe. V primerjavi z obstreljevanjem s kroglicami, LSP omogoča globlji vpliv ter boljšo kakovost površine [3]. Postopek je prikazan na sliki 2 (a) shematično in (b) eksperimentalna postavitve.



Slika 2: Prikaz postopka LSP (a) shematičen prikaz, (b) eksperimentalna postavitve.

Procesni parametri LSP – energija pulza, trajanje, gostota moči, oblika žarka ter uporaba ablativne/omejitvene plasti – bistveno vplivajo na rezultat obdelave. LSP lahko spremeni mikrostrukturo, zmanjša velikost zrn, poveča gostoto dislokacij ter vpliva na korozijsko odpornost, utrujenost in funkcionalne lastnosti Nitinola [4].

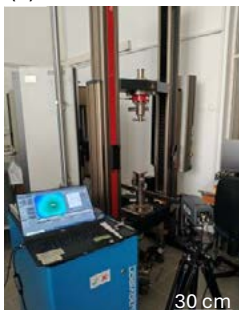
Materiali in metode

V eksperimentalnem delu je bil preučen vpliv LSP na mehanske in mikrostrukturne lastnosti superelastične Nitinol zlitine. Osnovni material je bila žarjena in jedkana 1 mm debela NiTi plošča po ASTM F2063 standardu, s temperaturo fazne transformacije (A_f) 5 ± 7 °C. LSP obdelava je bila izvedena na obeh straneh plošče v laboratoriju PIMM v Parizu z Nd:Yag laserjem (532 nm, 3 J, 7,1 ns), prikazanem na sliki 2 (b). Vzorec je bil med obdelavo potopljen v vodo kot omejitveni medij, površina pa zaščitena z aluminijasto ablativno plastjo. Obdelava je potekala na štirih območjih z različnimi gostotami moči (3-6 GW/cm²) in 50 % prekrivnostjo. Po obdelavi je bila ablativna plast odstranjena, kar je omogočilo analizo vpliva LSP na površino materiala.

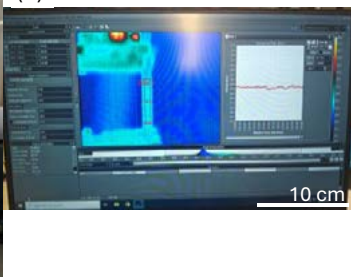
Za karakterizacijo materiala so bile izvedene številne analize. Topografija površine je bila ocenjena z digitalnim mikroskopom Keyence VHX 6000. Za merjenje zaostalih napetosti sta bili uporabljeni 2 metodi in sicer rentgenska difrakcija in merjenje zaostalih napetosti z metodo vrtnja luknje. Mikrostruktura je bila raziskana s pomočjo digitalnega mikroskopa in vrstičnega elektronskega mikroskopa (FIB-SEM).

ZEISS CrossBeam 550), kjer je bila izvedena tudi EBSD analiza za določitev kristalografske orientacije zrn. Poleg tega smo na vzorcih merili še mikrotrdoto po Vickersu s 100 g obtežbo in sicer na površini ter do globine 0,8 mm. Mehanske lastnosti smo preučili z nateznimi testi, izotermnimi, adiabatsnimi in trening preskusi na napravi Zwick/Roell Z100 (slika 4 (a)). Med adiabatsnimi testi smo beležili elastokalorični odziv z uporabo termalne kamere FLIR A6753sc, pri čemer so bili vzorci premazani z barvo visoke emisivnosti. Slika 4 (b) prikazuje posnetek preizkuševališča, zajet s termalno kamero.

(a)



(b)



Slika 4: (a) prikaz postavitve za mehanske preskuse in (b) posnetek termalne kamere.

Rezultati in diskusija

Topografija in hrapavost

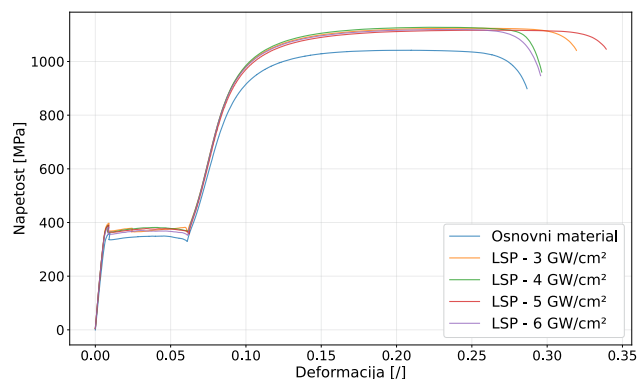
Meritve so pokazale, da se je hrapavost ablativne plasti povečala z večanjem gostote laserske moči, medtem ko je površina po odstranitvi zaščitne plasti ostala nespremenjena.

Mikrostruktura in mikrotrdota

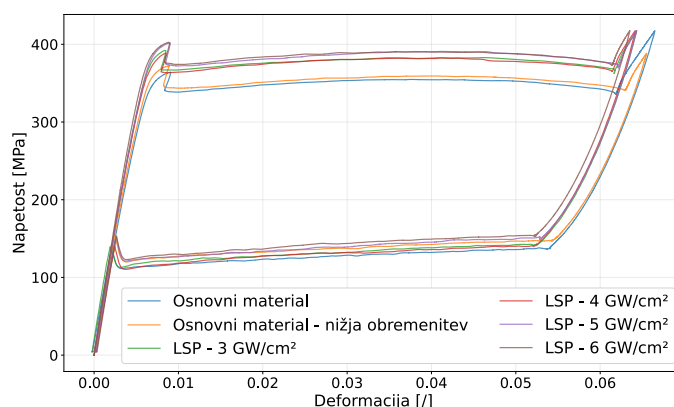
Rezultati so potrdili ugoden efekt zmanjšanja velikost kristalnih zrn po postopku LSP (29,3 μm proti 12,55 μm). Spremenila se je kristalna struktura, pojavili so se vključki, in dvojčenje, kar kaže na plastično deformacijo. Površinska trdota se ni bistveno spremenila, vendar so bile v globini 50-100 μm izmerjene višje vrednosti, kar nakazuje na lokalno utrditev zaradi mikrostrukturnih sprememb.

Mehanski preskusi

Izotermni natezni testi do porušitve so pokazali povečano maksimalno napetost pri LSP obdelanih vzorcih – s 1041 MPa pri osnovnem materialu na 1120 MPa pri vzorcu obdelanem s 6 GW/cm² (slika 5). Manjša deformacija in ožja histerezna zanka nakazujeta na večjo togost in stabilnejši odziv materiala, kar ugodno vpliva na odpornost proti utrujanju (Slika 6).



Slika 5: Rezultati nateznega testa do porušitve.



Slika 6: Rezultati izotermnega mehanskega preskusa.

Elastokalorični učinek

Adiabatsni testi so pokazali, da se temperaturna sprememba ob obremenitvi in razbremenitvi bistveno zmanjša po LSP obdelavi. Medtem ko je osnovni material dosegel temperaturno spremembo do +13,3 °C pri obremenitvi in -9,1 °C ob razbremenitvi, so se LSP obdelani vzorci segreli le med +4,0 °C in +6,7 °C ter ohladili med -4,0 °C in -6,2 °C. To kaže na zmanjšan obseg fazne transformacije, kar je lahko posledica utrditve in sprememb v mikrostrukturi.

Zaključki

Namen raziskave je bilo oceniti vpliv laserskega udarnega utrjevanja na izboljšanje lastnosti Nitinol zlitine, s poudarkom na izboljšanju odpornosti proti utrujanju. Ugotovili smo:

- LSP je povzročil zmanjšanje velikosti zrn na površini Nitinola (z 29,3 μm na 12,55 μm in bolj intenziven pojav dvojčenja ter vključkov, ki izboljšajo trdnost in mehanski odziv materiala,
- Trdota se na površini ni bistveno spremenila, medtem ko je v podpovršinskih bilo mogoče zaznati porast,
- Funkcionalne lastnosti, kot sta superelastičnost in elastokalorični učinek, so se po LSP obdelavi poslabšale, mehanske pa izboljšale – histerezna zanka se je zožila, deformacija zmanjšala, temperaturne spremembe so bile manj izrazite.

Zahvala. Avtorji se zahvaljujejo Javni agenciji ARIS za podporo v okviru raziskovalnega programa P2-0270 ter projektov J2-60033 (SuperShocked) in N2-0328. Zahvaljujemo se tudi partnerstvu za trajnostno modro gospodarstvo v programu Horizon Europe (SBEP) za financiranje projekta CORRASBlue.

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Vpliv procesnih parametrov FSW na lastnosti raznorodnih Al spojev

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Članek obravnava izdelavo in karakterizacijo raznorodnih spojev Al zlitin 7075-T651/2017A-T451, izdelanih s postopkom trenja in mešanja (angl. *Friction Stir Welding* – FSW) pri različnih hitrostih varjenja in razmerjih vrtenja orodja. Z namenom določitve optimalnih parametrov FSW so bili spoji ovrednoteni z analizo zaostalih napetosti, mikrostrukture in mikrotrdote. Rezultati so potrdili stabilne pogoji po celotni dolžini zvara s homogeno, drobnoznato mikrostrukturo v coni mešanja. Nižja hitrost vrtenja omogoča manjša zrna in višjo mikrotrdoto. Vsi vzorci so pokazali značilen »M-oblikovan« profil zaostalih napetosti (ZN) v vzdolžni smeri, medtem, ko so bile pri optimalnem pogoju ZN v prečni smeri enakomerneje porazdeljene, z do 38 % nižjimi nateznimi in 83 % nižjimi tlačnimi ZN. Rezultati potrjujejo pomemben vpliv parametrov FSW na mikrostrukturo in mehanske lastnosti raznorodnih Al spojev.

Uvod

V letalski in transportni industriji narašča povpraševanje po komponentah iz raznorodnih ter lahkih materialov, saj to omogoča zmanjšanje mase, nižje stroške ter izkoriščanje specifičnih mehanskih lastnosti. Vendar pa je spajanje različnih kovin zahtevnejše od spajanja podobnih zaradi razlik v njihovih fizikalnih, mehanskih in metalurških lastnostih [1,2].

Postopek varjenja s trenjem in mešanjem (FSW) se je uveljavil kot uspešna tehnologija za spajanje različnih materialov. Hkrati je FSW okolju prijazen in energijsko učinkovit postopek ter ena najugodnejših alternativ talilnemu varjenju za doseganje želene mikrostrukture in mehanskih lastnosti spojev [3,4]. FSW spada med termo-mehanske postopke spajanja, pri katerem se rotirajoči mešalni čep premika po stiku med dvema varjencema (Slika 1). Trenje med orodjem in materialom povzroči segrevanje, zaradi česar material preide v mehkejšo in bolj viskoznejše stanje. Mešalni čep dodatno premika in meša mat-

erial, kar poveča lokalno temperaturo in s tem nastanek zvarnega spoja. Hkrati se v segretem materialu ustvarja dodaten pritisk, ki ga omejujejo orodje (čep in rama), hladnejši okoliški material ter podpora [5]. Za kakovostne zware z zadostno trdnostjo in funkcionalnostjo pa je ključna izbira optimalnih parametrov FSW pri spajanju težje varivih različnih materialov. V ta namen so bili eksperimentalno preučeni čelni spoji iz dveh različnih Al zlitin serije 2xxx in 7xxx. Primerjani so bili mikrostruktura, mikrotrdota ter zaostale napetosti (ZN) z namenom določitve optimalnih parametrov FSW.

Materiali in metode

V tej raziskavi so bili **materiali** čelno spojeni z enostranskim postopkom FSW iz dveh plošč Al zlitin (osnovna materiala - OM) 7075-T651 in 2017A-T451, dimenzij 500 x 70 x 10 mm³. Mehanske lastnosti Al zlitin so prikazane v Tabeli 1.

Tabela 1: Mehanske lastnosti obravnavanih Al zlitin.

	7075-T651	2017A-T451
Modul elastičnosti (GPa)	70	71
Poissonovo število	0.32	0.33
Natezna trdnost (MPa)	550	390
Meja tečenja (MPa)	460	260
Razteznost (%)	8.2	8.4
Din. trdnost (>10 ⁷ cikl.) (MPa)	160	120
Trdota HB	150	110

Pred FSW so bile plošče očiščene z acetonom in etanolom ter hidravlično pritrjene na podporno ploščo (slika 2a). Uporabljen je bil čep s premerom zatiča 9 mm, dolžino 9,8 mm in premerom rame 25 mm (slika 2b). Prvotno so bili izvedeni preliminarni testi, kot so upogibni preizkusi, vizualni pregledi in mikrostrukturne analize (slika 2c). Končni FSW spoji so bili izvedeni pri sili orodja 38 kN (stalni nadzor sile), hitrosti varjenja 12 (FSW-1), 15 (FSW-2) in 18 cm/min (FSW-3), kar ustreza razmerju 25, 20 in 16,6 vrt./cm pomika orodja. Pri FSW-1 in FSW-2 je bila Al zlitina 2017-T451 na prednji strani in Al 7075-T651 na zadnji strani. FSW-3 je imel smer vrtenja in strani zamenjani. Med varjenjem je bila izmerjena temperatura pred orodjem 190°C, za orodjem pa 300°C.

Meritve **zaostalih napetosti** (ZN) so bile izvedene po metodi



Slika 1: Shematski prikaz FSW varjenja [5].



Slika 2: Prikaz procesa FSW (a); orodja (b) ter preliminarni testi za izbor parametrov varjenja (c).

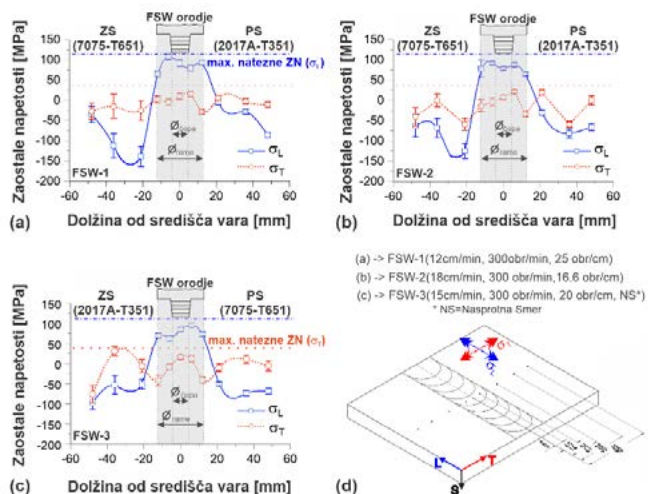
rentgenske difrakcije (XRD), vzdolžno in prečno na zvar ter smer vavljanja janya. ZN so bile določene iz difrakcijskega vrha Al {311} pri $2\theta=139^\circ$ s sistemom Proto iXRD in kolimatorjem 2 mm, po metoda $\sin^2\psi$ s stransko nagnitvijo in 9 β -koti.

Vzorci za **mikrostrukturno analizo** so bili jedkani v Barkerjevem reagentu ter analizirani s polarizirano svetlobo na digitalnem mikroskopu Keyence VHX-600.

Meritve **mikrotrdote po Vickersovu** vzdolž FSW zvara so bile izvedene z obremenitvijo 300 g v horizontalni smeri, 1 mm pod temenom vara.

Rezultati in diskusija

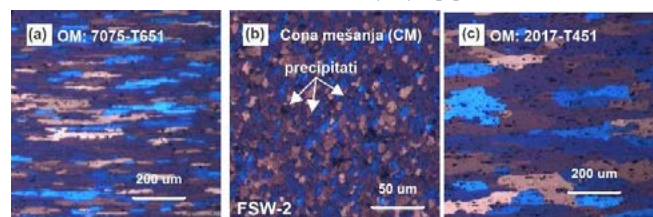
Čprav pri FSW ne dosežemo tališča kovine nastanejo **zaostale napetosti**, zaradi plastične deformacije in omejene toplotne krčitve [2,5]. Slika 3 prikazuje porazdelitev ZN na raznorodnih FSW Al spojih, izdelanih s tremi različnimi sklopi parametrov tako v longitudinalni/vzdolžni (σ_L) kot tudi v transverzalni/prečni (σ_T) smeri. V vseh primerih je porazdelitev ZN asimetrična, kar je pričakovano pri raznorodnih spojih s tipično »M-oblikovano« porazdelitvijo.



Slika 3: Potek ZN v vzdolžni (L) in prečni (T) smeri; (a) FSW-1, (b) FSW-2, (c) FSW-3, (d) prikaz merilnih mest.

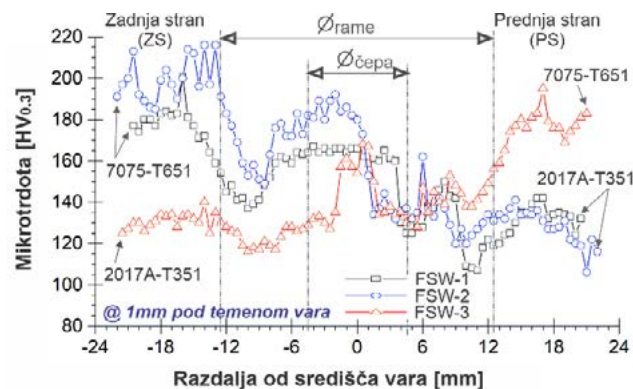
Rezultati ZN potrjujejo, da višje razmerje vrtiljajev na pomik orodja (zaradi večjega trenja in toplote) generira večji linijski vnos energije in s tem manj stabilen tok materiala ter slabšo kakovost zvara. Največje natezne ZN (107 ± 11 MPa) so bile tako opažene pri vzorcu FSW-1 z najvišjim razmerjem vrtiljajev na pomik orodja (25 vrt/cm).

Nasprotno pa je FSW-2 z najnižjim razmerjem 16,6 vrt/cm pokazal enotnejšo cono mešanja in manjše natezne ter tlačne ZN v okoliških območjih, kar ugodno zavira nastanek in širjenje razpok. Hkrati rezultati kažejo, da je pri obremenitvah pravokotno na smer FSW pričakovati boljšo odpornost proti dinamičnim obremenitvam oz. utrujanju [2].



Slika 4: Mikrostrukturne slike; (a) in (c) OM, (b) FSW-2.

Osnovna materiala (sliki 4a in c) jasno kažeta razliko v obliki in velikosti zrn. Po podatkih iz [4] je povprečna velikost zrn zlitine 7075-T651 $35 \pm 17 \mu m$, kar je približno 77 % manj kot pri AA2017-T4 ($62 \pm 26 \mu m$). V območju CM FSW spoja (slika 4b) so se zaradi intenzivnega pretoka, povišane temperature in popolne dinamične rekristalizacije (DRX) oblikovala enakoosna zrna, manjša od 10 μm .



Slika 5: Profili mikrotrdote v vodoravni smeri, 1 mm pod zgornjo površino (temenom) zvara.

Slika 5 potrjuje, da imajo FSW-parametri izreden vpliv na potek trdote, t.j. nižji vnos energije omogoča najvišjo mikrotrdoto. Tako je največje vrednosti dosegel vzorec FSW-2, varjen pri 16,6 vrt/cm. Hkrati osnovni material 7075-T651 izkazuje višjo mikrotrdoto kot 2017A-T451, kar je pričakovano glede na njihove osnovne vrednosti HB (Tabela 1). Hkrati je pri vseh pogojih vzdolž zvara razvidna fluktuacija mikrotrdote v področju CM. Ta pojav je posledica pasaste oziroma premešane strukture v območju CM (slika 2c).

Zaključki

Na podlagi opravljenega dela podajamo naslednje zaključke:

- FSW omogoča izdelavo kakovostnih raznorodnih spojev težko varivih Al zlitin serije 2xxx/7xxx z drobnozrnato mikrostrukturno, zaradi efekta DRX.
- Nižja hitrost vrtenja orodja zmanjšuje vnos toplote, kar vodi do manjše velikosti zrn, nižjih ZN in višje mikrotrdote v coni mešanja.
- Analiza zaostalih napetosti je pokazala značilno »M-oblikovano« porazdelitev, pri čemer je optimalno stanje doseženo pri 16,6 vrt/min, z do 38 % nižjimi nateznimi in 83 % nižjimi tlačnimi napetostmi.
- Parametri procesa ključno vplivajo na stabilnost toka materiala, homogenost zvara ter končne lastnosti raznorodnih Al spojev.

Zahvala. Avtorji se zahvaljujejo Javni agenciji ARIS za podporo v okviru raziskovalnega programa P2-0270 ter projektov J2-60033 in N2-0328 ter EU partnerstvu za trajnostno modro gospodarstvo (SBEP), Horizon Europe za financiranje projekta CORRASBlue.

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Surface Wettability Effects on Water Harvesting Efficiency of Harp Collectors

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This study investigates the influence of surface wettability and wire diameter on the water collection performance of harp-type fog harvesting devices. Two harps were tested: a reference stainless-steel harp and a hydrophobic functionalized harp coated with Glaco. Experiments were conducted under controlled humidity and airflow conditions using ultrasonic fog generators. Results show that the hydrophilic reference harp collected significantly more water than the hydrophobic one, primarily due to enhanced droplet coalescence and larger detachment volumes. In contrast, the hydrophobic coating promoted early droplet shedding and smaller droplet sizes, reducing overall yield.

Introduction

Freshwater scarcity remains one of the most pressing global challenges, driving the need for sustainable technologies capable of capturing atmospheric moisture [1,2]. Among various approaches, fog and dew harvesting using wire-based harp structures offers a simple, energy-efficient, and scalable solution for water collection in arid regions [2]. The efficiency of such systems is strongly influenced by surface wettability, wire geometry, and airflow dynamics, which govern droplet nucleation, growth, and detachment. While hydrophobic coatings enhance droplet mobility and self-cleaning, they may reduce total water yield by limiting droplet coalescence, whereas hydrophilic surfaces favour accumulation and higher retention [1,2]. This study investigates the influence of surface wettability and wire diameter on the performance of reference and functionalized harp devices under controlled fog-generation conditions.

Materials and methods

Experimental setup. The experimental setup for water harvesting consisted of a plexiglass chamber, within which mist makers, a fan, and a water harp were placed in the center of the misted airflow. The harp base, fabricated from stainless steel 304, measured 250 mm in height and 180 mm in width between the mounting holes. A harp structure made from the same material (150 mm × 120 mm) was fixed onto the base and positioned inside the condensation chamber. The chamber comprised a trapezoidal inlet section (25 cm in height, 35 cm in length, with upper and lower widths of 20 and 65 cm, respectively) connected to a cuboidal section (65 × 65 × 35 cm), yielding a total internal volume of approximately 0.186 m³. A schematic representation of the experimental setup is shown in Figure 1. To establish a controlled and repeatable airflow environment, a low-speed axial fan with an inlet tube was mounted at the outlet of the chamber. The fan

induced gentle ventilation, ensuring homogeneous fog dispersion and stable aerodynamic conditions. Air velocity was measured using a vane anemometer (Testo 452, 10 mm probe diameter, 0.3–20 m s⁻¹ range, resolution 0.01 m s⁻¹, accuracy ±(0.2 m s⁻¹ + 1.5% of reading)). Measurements were taken at nine evenly distributed points across the harp surface (3 × 3 matrix) and along three axial planes within the chamber. The spatial velocity field was then averaged to verify flow uniformity across the measurement region. The relative humidity inside the chamber was monitored and maintained close to saturation (≈100%) during all experiments.

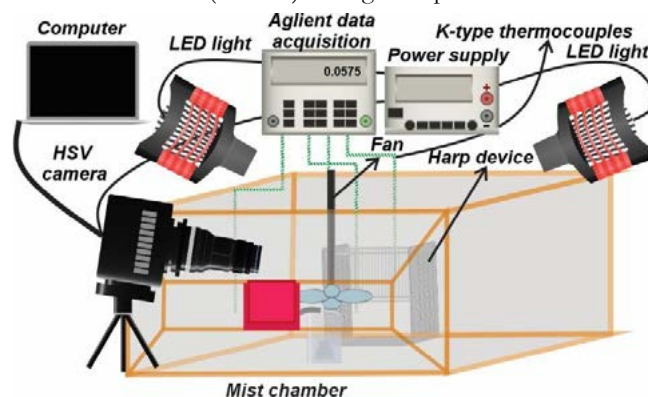


Figure 1: Experimental setup.

Four K-type thermocouples were installed to record dry- and wet-bulb temperatures, two positioned near the chamber inlet and two at the harp plane. The wet-bulb sensors were wrapped in a moistened permeate-saturated cloth before each measurement. Data were acquired via an Agilent data system. A commercial ultrasonic fog generator produced a dense aerosol consisting of 1–10 μm deionized-water droplets. The generated fog represented a non-thermal aerosol, or “cold steam,” as the atomization process involved only mechanical disruption of the liquid surface without significant heating. Two sets of tests were performed using reference and functionalized wires with a diameter of 0.2 mm, employing either one (Regime 1) or two fog generators (Regime 2) to assess the influence of aerosol density on condensation behavior. The procedure was repeated using thicker wires (0.4 mm) for both the reference and functionalized harp configurations. Initial runs were used to establish stable experimental conditions and verify measurement repeatability prior to systematic testing. To further characterize droplet formation, growth, and detachment dynamics, high-speed imaging was employed using Photron FASTCAM Mini AX100 camera. The process was illuminated by two high-intensity LED lamps to ensure uniform lighting. These measurements allowed the determination of the critical droplet size at which gravitational forces exceeded adhesive retention, leading to

droplet roll-off. Each experimental series was repeated four times to verify reproducibility. The mass of collected water was measured gravimetrically at the bottom of the chamber using a precision balance. The cumulative water yield, droplet behavior, and detachment frequency were correlated with the wire surface condition (reference vs. functionalized), wire diameter, fog intensity, and airflow velocity field.

Harp device preparation. Two harp devices were evaluated in this study: a reference and a functionalized version. The reference harp was used in its untreated state after cleaning with isopropanol to remove surface contaminants. The functionalized harp was prepared by applying a commercial hydrophobic coating (Glaco) onto the cleaned stainless-steel surface. After coating, the sample was thermally cured in an oven at 250 °C for 30 min to promote adhesion of the hydrophobic layer. To obtain a thicker and more durable coating, the application and curing procedure was repeated three times, resulting in a stable, multilayered hydrophobic surface suitable for extended condensation experiments.

Results and discussion

Four experimental configurations were tested using reference and hydrophobized harps under two fog conditions, light fog (Regime 1) and heavy fog (Regime 2), with deionized water as the working medium. The daily collected water for all cases is presented in Figure 2. A clear difference is observed between the reference and hydrophobic harps, irrespective of wire diameter or operating regime. In all cases, the hydrophobic surface reduced the collected water by approximately 38–50% compared to the reference harp. This reduction originates from distinct droplet behaviors governed by surface wettability. On the reference surface, stronger adhesion promotes droplet coalescence and growth before detachment, leading to larger droplets that contribute more significantly to the overall yield. In contrast, the hydrophobic coating lowers adhesion and contact angle hysteresis, triggering premature detachment and limited coalescence.

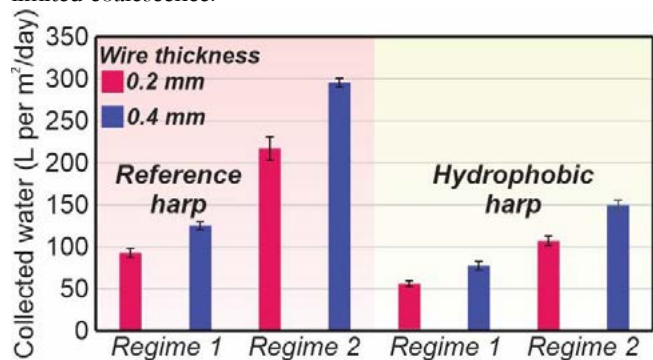


Figure 2: Collected water obtained on two harps with different wettability and wire diameters under light and heavy fog regime.

As shown in Figure 3, the average droplet diameter on the hydrophobic harp was considerably smaller than on the reference surface, indicating that droplets were removed before reaching their critical coalescence size. While rapid shedding can prevent flooding and promote self-cleaning, it simultaneously shortens droplet residence time and lowers cumulative water collection. Additionally, both the reference

and hydrophobic harps exhibited higher collection efficiency when thicker wires (0.4 mm) were used, with collected water increasing by approximately 35–40% compared to thinner wires (0.2 mm). This improvement can be attributed to the larger collection area and greater mechanical stability of the thicker wires, which reduced oscillations and facilitated stable droplet detachment. However, excessively large wire diameters could hinder airflow penetration and decrease aerodynamic collection efficiency.

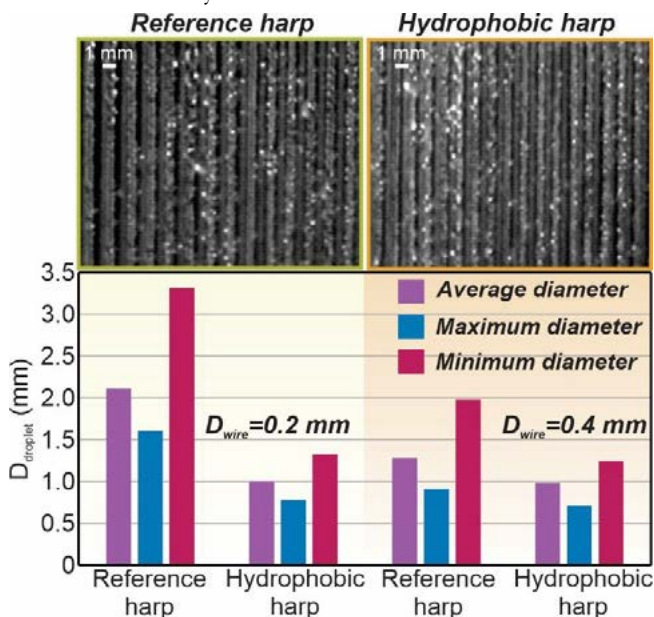


Figure 3: Droplet diameter obtained on two harps with different wettability and wire diameters under light fog regime.

The influence of fog density was also evident. Under the heavy fog regime, the amount of collected water was nearly twice that observed in the light fog regime for all tested configurations. This enhancement results from the higher concentration of suspended microdroplets available for condensation and impaction on the wire surfaces.

Conclusions

This study demonstrated that surface wettability and wire geometry strongly influence the performance of harp-type fog harvesting devices. The hydrophilic reference harp achieved up to 50% higher water collection than the hydrophobic one due to enhanced droplet coalescence and larger detachment volumes. The hydrophobic coating promoted faster shedding and smaller droplets, reducing overall yield despite improved self-cleaning. Increasing wire diameter from 0.2 mm to 0.4 mm enhanced collection by 35–40%, owing to greater surface area and droplet stability. Under heavy fog conditions, water yield approximately doubled. Efficient atmospheric water harvesting requires balanced wettability and optimized structural design for maximum capture efficiency.

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Geometric Evaluation of 3D-Printed Spools for Hydraulic Applications

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In this work, the dimensional accuracy of additively manufactured hydraulic valve spools was compared to conventionally machined steel spools. The additively manufactured spools were printed from polymer and ceramic-based resins, keeping the same geometry as the steel reference. The goal was to determine how closely the printed parts meet the tolerances required for hydraulic applications. Dimensional measurements were carried out manually and using a contact measuring system, focusing on circularity, cylindricity, and overall dimensional deviation. The results show that 3D-printed spools do not achieve the same level of precision as ground steel parts and that post-processing is necessary for practical use. Nevertheless, the accuracy achieved is sufficient for prototype validation and preliminary functional testing.

Introduction

Hydraulic valve spools are typically cylindrical, as they must fit precisely into machined holes produced by drilling, grinding, or honing. Steel is the conventional material of choice because it provides excellent dimensional accuracy, wear resistance, and long-term reliability, while being well understood in terms of manufacturing and performance. However, steel spools also have drawbacks. Their production is energy intensive, they require corrosion-resistant grades for use with water-based fluids, and they are relatively heavy compared to modern engineering polymers. This led to the idea of developing lighter, more sustainable spools that could still withstand hydraulic pressures while being manufactured with less energy. To explore this, four engineering resins with promising mechanical and thermal properties were selected and used to produce spool prototypes via Additive Manufacturing (AM) [1,2]. The spools were made with identical geometry to conventional steel parts, without any optimization [3,4], to allow direct comparison.

The focus of this study is on the feasibility of producing hydraulic spools from alternative materials using Stereolithography (SLA), evaluating the dimensional accuracy, material behaviour, and manufacturing limitations. The goal is to assess whether polymer and ceramic-based resins can serve as viable alternatives to steel in spool-type hydraulic valves.

Materials and methods

In this study, four additively manufactured materials, SLA resins, were used to produce hydraulic valve spools: **E-Rigid Form**, **HTM 140**, **SuperHDT**, and **Aceaddity ceramic resin**. Each material offers a specific advantage—E-Rigid Form provides high stiffness, HTM 140 has good temperature stability, SuperHDT combines heat resistance with chemical

durability, and Aceaddity ceramic resin offers excellent hardness and corrosion resistance.

Ceramics and SuperHDT spools were produced using the SLA process on a desktop Anycubic Photon Mono M5 printer. HTM 140 and E-Rigid Form spools were manufactured using the digital light processing (DLP) technique on an Envisiontec (ETEC) D4K printer. In all cases, manufacturer-recommended presets were applied for printing and post-processing. Post-processing steps included cleaning of residual resin, support removal, and final UV curing according to each material's specification.

All spools were based on the same geometry as the conventionally manufactured stainless-steel AISI 440-C reference spool, corresponding to a standard CETOP 3 4/3 proportional directional spool with a nominal outer diameter of 12 mm. Each chamber contains three control notches, 2.5 mm wide and 2.6 mm deep, used for proportional flow control.



Figure 1: 3D printed polymeric and ceramic spools compared to conventional spool made from 440-C.

Because the geometry was not optimized for additive manufacturing, support structures were required and later removed after printing. The reference steel spool was rough-turned, heat-treated, and fine-ground to achieve the specified tolerance. For use in water hydraulics, spools must typically meet clearances between 0 and $-2\ \mu\text{m}$ to ensure sealing between valve chambers. As no post-processing was applied to the printed parts, such tolerances were not expected to be achieved in this initial evaluation.

Dimensional evaluation of the manufactured spools was carried out in two stages. First, manual measurements were performed using a precision micrometer to determine the main diameters and overall dimensional deviations of each spool. These results provided a basic comparison of the accuracy achieved with additive manufacturing relative to the reference steel spool. In the second stage, contact 3D measurements were performed on a Mahr MMQ 500 form measuring instrument. This system was used to precisely determine circularity and cylindricity of the spool surfaces, which are the most critical parameters for achieving proper sealing and smooth movement inside the valve body. Each measurement

was repeated to verify consistency and repeatability. In addition to geometric measurements, the mass of each spool was also recorded to evaluate the effect of using alternative materials.

Results and discussion

Figure 2 shows manually measured results for spools made from different materials. SuperHDT, as well as E-Rigid Form and HTM 140, were printed below the nominal diameter, while ceramic spools were slightly above it. Compared to the grinded steel spool, which showed minimal deviation and tight distribution, all printed parts exhibited larger dimensional variation. The highest deviation was observed for E-Rigid Form, although its mean value was closest to nominal. Higher exposure times generally resulted in slightly larger printed dimensions.

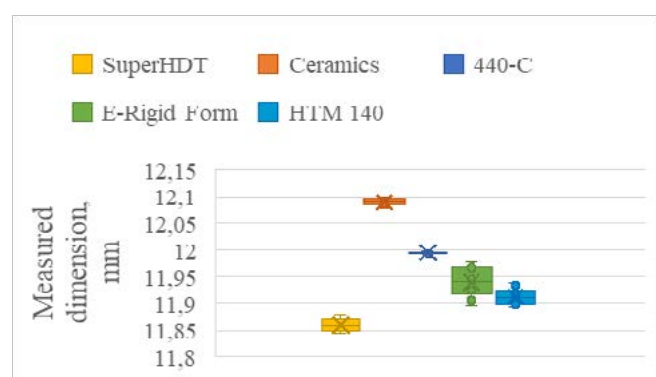


Figure 2: Manual measurements taken using micrometer.

Circularity was measured next on the Mahr MMQ 500 machine and results are presented in Figure 3). As expected, the stainless-steel AISI 440-C spool achieved the best accuracy due to grinding, with circularity of $0.9 \mu\text{m} \pm 0.4 \mu\text{m}$, well within the $2 \mu\text{m}$ tolerance. Among the printed materials, HTM 140 showed the most consistent results ($16.2 \mu\text{m}$, deviation $0.4 \mu\text{m}$), followed by SuperHDT printed ($14.9 \pm 1.5 \mu\text{m}$) and E-Rigid Form ($19.2 \pm 2.2 \mu\text{m}$).

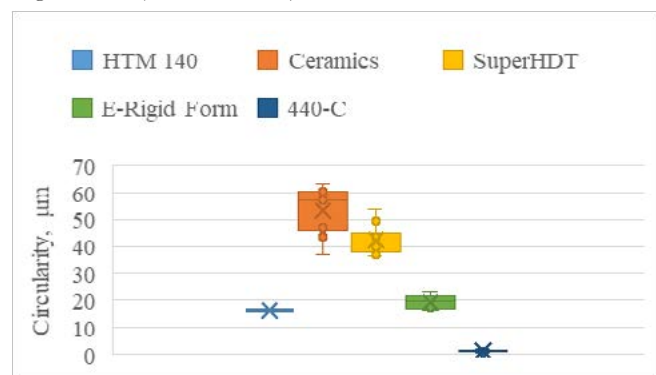


Figure 3: Results of 3d contact measurements of circularity.

Cylindricity measurements were performed to determine the deviation of each spool from the ideal cylindrical shape. As expected from the circularity results, the poorest performance was observed for ceramics with cylindricity of $83.8 \mu\text{m}$. HTM 140 ($44.7 \mu\text{m}$) and E-Rigid Form ($50.5 \mu\text{m}$) achieved moderate results. SuperHDT printed at exposure times recommended by manufacturer performed poorly ($70.7 \mu\text{m}$). The best cylindricity was again obtained for the ground stainless-steel

AISI 440-C spool, measured at $2.4 \mu\text{m}$, within the expected tolerance range.

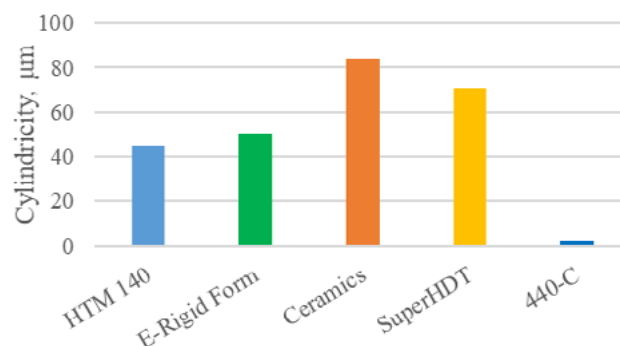


Figure 4: Results of 3d contact measurements of cylindricity.

Mass properties

The polymer-based spools weighed 6.21 g (E-Rigid Form) and 6.32 g (HTM 140), while the ceramic-filled materials showed slightly higher values—7.01 g for the 30% ceramic resin and 6.45 g for SuperHDT. In comparison, the stainless-steel reference spool weighed 44.82 g. This demonstrates that all additively manufactured spools made from alternative materials are approximately seven times lighter than the conventionally produced steel spool.

Conclusions

Additively manufactured hydraulic spools made from alternative polymer and ceramic materials showed clear potential in terms of weight reduction and material versatility. All printed spools were approximately seven times lighter than the conventionally produced stainless-steel reference, which could be beneficial for lightweight hydraulic applications. However, dimensional measurements revealed that current additive manufacturing processes do not achieve the tight tolerances required for efficient hydraulic sealing. Increased deviations in circularity and cylindricity are expected to result in higher internal leakage and reduced efficiency when assembled in the valve. Among the tested materials, HTM 140 and SuperHDT showed the most promising dimensional consistency, while ceramic-filled resins demonstrated higher deviation and lower repeatability. Further improvements through post-processing or geometry compensation would be necessary before functional hydraulic use.

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Performance Evaluation of Communication Protocols for Fanuc Robots

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Reliable and fast communication between Fanuc industrial robots and external PCs is crucial for real-time control in modern manufacturing systems. This study compares two communication approaches: HTTP requests and socket communication. Performance was evaluated by measuring the average message throughput (msg/s) under different configurations. Results show that HTTP enables approximately 28 msg/s, while socket communication can exceed 117 msg/s when robot motion is not active. However, once robot movement is initiated, performance drops sharply from 117 msg/s to below 2.5 msg/s due to single-task processing limitations on the robot controller. This issue was successfully addressed by implementing a multitasking command, which enabled the stable transmission of over 83 msg/s, even during active motion. The results provide practical insights for integrating PC-based control systems with Fanuc robots in high-speed, real-time applications.

Introduction

In modern manufacturing environments, industrial robots are increasingly integrated with external computing systems to enable flexible, automated, and data-driven operations. This integration, driven by the principles of Industry 4.0, requires efficient real-time communication between the robot and external PCs [1,2].

Fanuc robots offer several options for external communication, including HTTP requests and socket-based connections. While HTTP is simple to implement and widely supported, it introduces additional overhead that limits its suitability for high-frequency or real-time data exchange. In contrast, socket communication provides a more direct and faster channel, though its performance is highly dependent on how motion execution and data processing are managed within the robot controller [3].

This paper presents a comparative performance evaluation of these two communication protocols in the context of Fanuc robot–PC integration. The study measures the number of data lines transmitted per minute under different conditions—including passive communication, active motion control, and multitasking—to identify key performance bottlenecks. A practical solution is proposed using the RUN command in the Teach Pendant (TP) program to enable multitasking and maintain stable, high-speed data transmission. The findings provide practical insights for engineers and researchers developing real-time robot control and industrial automation systems.

Materials and methods

The experimental setup was developed and tested on a Fanuc Arc Mate 120 iD industrial robot installed at the University of Ljubljana, Faculty of Mechanical Engineering. The robot controller was connected to an external PC via a local Ethernet network, allowing for both HTTP and socket-based communication tests. The PC used for the experiments was equipped with a 12th Gen Intel® Core™ i7-12800H processor (2.40 GHz), 32 GB RAM, and a 64-bit Windows 11 operating system.

Two communication methods were implemented and compared. Both were developed using open-source Python on the PC side and the KAREL language on the Fanuc robot controller. The first approach utilized HTTP requests, and the second approach used socket communication, enabling direct and continuous data exchange between the PC and the robot. Both methods were evaluated to compare data transmission rates and overall communication stability. Figure 1 illustrates the data exchange between the PC and the Fanuc robot for both communication approaches.

The transmitted data consisted of comma-separated numerical strings representing the robot's motion and process parameters. Each line contained ten values: six Cartesian coordinates (X, Y, Z, W, P, R), motion type (linear or joint), speed register value (in millimeters per second), coordinate reference type (global or local coordinate), and welding state (on or off). The average message size was approximately 80–100 bytes, sent sequentially at high frequency during each test. The robot parsed each received line, updated its internal position registers, and executed the corresponding motion or welding command via a Teach Pendant (TP) program.

Three operating modes were tested:

1. Passive communication – data exchange without robot motion.
2. Active motion control – simultaneous data transfer and robot movement.
3. Multitasking operation – separate data transfer and robot movement.

Communication performance was evaluated by measuring the number of successfully transmitted and processed messages over a one-minute interval, from which the average message throughput (msg/s) was calculated. This metric provided a direct and quantitative comparison of communication efficiency.

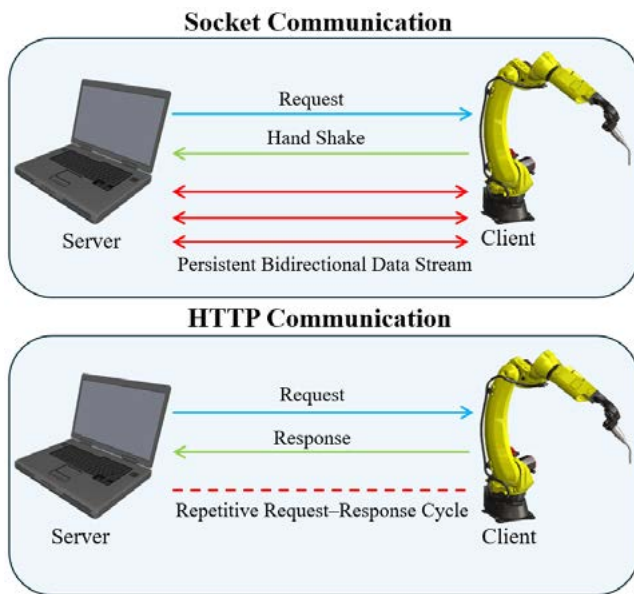


Figure 1: Comparison of HTTP and Socket-based communication between the external PC and the Fanuc robot controller.

Results and discussion

The performance of HTTP and socket communication was evaluated in terms of average message throughput (messages per second, msg/s) under various operating conditions, as shown in Table 1. The results showed clear differences between the two methods. Using HTTP requests, the average message throughput reached approximately 28 msg/s, limited primarily by the overhead of repeated request–response cycles. Due to its repetitive opening–closing mechanism, HTTP communication was not tested during active robot motion, as the latency would make real-time control impractical. For potential use in motion applications, buffered transmission of multiple position registers is recommended to minimize request frequency and latency.

In contrast, socket communication achieved up to 117 msg/s during passive operation, demonstrating the advantage of a persistent, bidirectional connection for continuous data flow. However, when the robot executed motion commands simultaneously with data exchange, the throughput dropped sharply to below 2.5 msg/s, caused by the controller’s single-task execution mode, where data handling and motion control competed for processing resources. This limitation was resolved by running the communication program as a background task using the RUN command within the TP program, enabling multitasking between motion execution and socket communication. With this improvement, the throughput increased to over 83 msg/s, ensuring both stable data exchange and smooth robot motion.

These results confirm that socket-based multitasking provides a substantial performance gain compared to conventional HTTP communication. By maintaining an open TCP connection and executing data handling in parallel with robot motion, latency is minimized and throughput remains sufficient for real-time control applications. The findings highlight the importance of program structure and task management when integrating Fanuc robots with external PC systems. This approach is particularly relevant for applications

such as adaptive control, path correction, and process monitoring, where continuous high-frequency data transfer is required.

Table 1: Communication performance under different operating modes

Communication method	Operating mode	Average message throughput (msg/s)
HTTP	Passive (no motion)	~28
Socket	Passive (no motion)	~117
Socket	Active motion	<2.5
Socket (multitasking)	Active motion (RUN used)	>83

Conclusions

This study compared two communication protocols—HTTP and socket—for real-time data exchange between a Fanuc Arc Mate 120 iD robot and an external PC. The results demonstrated that socket communication provides significantly higher throughput and better suitability for real-time control applications compared to HTTP. The persistent connection established through sockets enabled continuous data transfer and efficient multitasking, achieving over 80 msg/s during active robot motion.

In contrast, the HTTP method was limited by its repetitive open–close mechanism and was therefore tested only in passive mode. For potential implementation in motion control, buffered transmission of multiple position registers is recommended to minimize latency.

Overall, the findings confirm that effective task management and the use of the RUN command for background execution are essential to achieving stable, high-speed socket communication.

SUPPLEMENTARY INFORMATION.

Data will be made available on reasonable request.

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Vpliv parametrov laserskega varjenja na kakovost spojev bakrenih hairpin vodnikov

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Raziskava obravnava vpliv geometrije varilne poti, hitrosti laserskega varjenja in razmerja porazdelitve moči med osrednjim in obročnim delom žarka na kakovost spojev bakrenih vodnikov tipa Cu-OF. Eksperimenti so bili izvedeni pri varilnih hitrostih 200, 400 in 600 mm/s ter treh geometrijah varilne poti (elipsa, Lissajouseva krivulja 3:1 in 3:2). Kakovost spojev je bila ovrednotena z merjenjem električne upornosti (Kelvinova 4T metoda), računalniško tomografijo (CT) in trgalnimi testi. Rezultati kažejo, da se z večanjem varilne hitrosti, upornost in poroznost zmanjšujeta, trgalna sila pa povečuje. Geometrija varilne poti močno vpliva na poroznost, ki ima izrazito korelacijo z električno upornostjo in trdnostjo spoja. Merjenje električne upornosti je lahko merilo kakovosti zvarnega spoja. Optimalna kombinacija parametrov, je bila dosežena pri Lissajousevi krivulji 3:1 s hitrostjo 600 mm/s, saj smo pri tem dosegli najmanjšo električno upornost, zmerno poroznost in najvišjo mehansko trdnost spoja. Razmerje porazdelitve moči 50/50 zmanjša število in volumen por ter izboljša stabilnost procesa.

Uvod

Lasersko varjenje bakra predstavlja tehnološki izziv zaradi visoke toplotne prevodnosti, nizke absorptivnosti laserske svetlobe in velike občutljivosti procesa na že majhne spremembe parametrov [1]. V proizvodnji satorjev se je uveljavila "hairpin" tehnologija, kjer navitje sestavljajo posamezne, v obliki črke U upognjene bakrene žice pravokotnega preseka. Kakovost zvara neposredno vpliva na električne izgube in mehansko zanesljivost. V satorjih je potrebno povezati več kot 200 parov vodnikov, pri čemer je kakovost spojev ključna, saj lahko odpoved enega pomeni odpoved celotnega pogona. Namen raziskave je bil analizirati vpliv geometrije varilne poti, varilne hitrosti in razmerja moči (BrightLine Weld) na kakovost spojev z vidika električne upornosti, poroznosti in trgalne sile ter določiti optimalno kombinacijo parametrov.

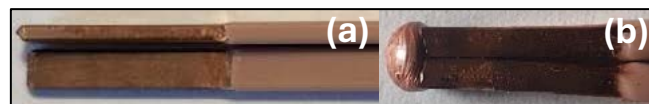
Materiali in metode

Pri raziskavi smo uporabili pravokotne bakrene vodnike s presekom dimenzij 3,32 x 1,42 mm (slika 1a). Gre za elektrolitsko rafiniran baker z izjemno visoko čistostjo, več kot 99,99 %, in zelo nizko vsebnostjo kisika – okoli 2,4 ppm. Takšna sestava je posebej primerna za lasersko spajanje, saj odsotnost kisika zmanjšuje tveganje za nastanek oksidov, poroznosti in drugih varilnih nepravilnosti. Preizkusni vzorci simulirajo dejanske povezave v satorju električnega motorja.

Varjenje je potekalo z diskovnim laserskim virom Trumpf TruDisk 6000. Deluje pri valovni dolžini 1030 nm (infrardeči

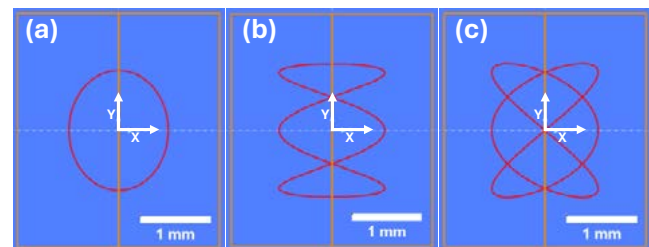
spekter) in omogoča največjo izhodno moč 6 kW. Žarek se prenaša preko dvojedrnega optičnega vlakna z notranjim premerom 50 μm in zunanjim premerom 200 μm. Usmerjanje žarka je potekalo z programabilno fokusirno optiko Trumpf PFO 33-2. Ta omogoča natančno vodenje laserskega žarka po poljubno definiranih poteh. Na sliki 1b je prikazan spoj.

Preizkušance smo izdelali s pomočjo namenske naprave, ki je žico strojno odrezala na dolžino 114 mm in odstranila izolacijo na zgornjem delu. Nato smo vzorce namestili v držalo, kjer smo del brez izolacije odrezali na ustrezno dolžino, s čimer smo zagotovili čisto in ravno površino ter pravilno oddaljenost od optike (goriščna razdalja 450 mm).



Slika 1: Prikaz oblike bakrenega vodnika (a) in zvarjenega spoja (b).

Izbrali smo tri različne geometrije poti laserskega žarka, prikazane na sliki 2, njihov matematičen popis pa v spodnjih enačbah (1), (2), (3), kjer θ označuje kot, izražen v radianih, x in y pa pozicije točk v mm. Med seboj se razlikujejo po kompleksnosti. Geometrija 1 (a) je najpreprostejša in predstavlja elipso, geometriji 2 (b) in 3 (c) pa sta parametrično popisani Lissajousevi krivulji, ki omogočajo simetričnost, cikličnost in enakomerno porazdelitev toplote. Za analizo vpliva hitrosti smo izbrali tri različne hitrosti. Varili smo pri 200, 400 in 600 mm/s, s čimer smo simulirali ± 50 % odstopanje od izhodiščne vrednosti 400 mm/s. S tehnologijo porazdelitve moči BrightLine smo preizkusili dve nastavitvi porazdelitve moči: 50 % moči v center in 50 % v kolobar ter 75 % v center in 25 % v kolobar.



Slika 2: Prikaz geometrije varilne poti (a – c).

$$(a) \quad x = 0,7 \cdot \cos(\theta); y = 0,85 \cdot \sin(\theta) \quad (1)$$

$$(b) \quad x = 0,75 \cdot \sin(3 \cdot \theta + \pi/2); y = 0,95 \cdot \sin(\theta) \quad (2)$$

$$(c) \quad x = 0,75 \cdot \sin(3 \cdot \theta + \pi/2); y = 0,95 \cdot \sin(2 \cdot \theta) \quad (3)$$

Za določitev električne upornosti je bila uporabljena Kelvinova štiri točkovna metoda z mikroohmmetrom z GW Instek GOM-804 in avtomatskim zajemom podatkov. Poroznost je bila analizirana z uporabo CT-skeniranja Zeiss Metrotom 1500, 225 kV. Preizkus natezne trdnosti smo izvedli z uporabo naprave MAV ATM 500.

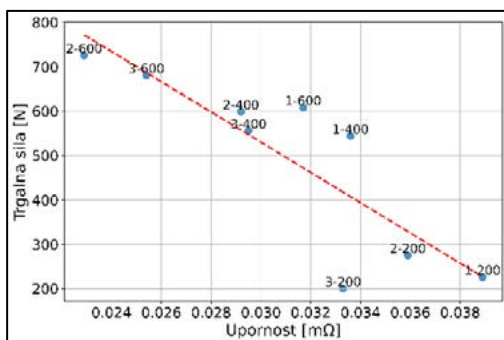
Rezultati in diskusija

Električna upornost. Rezultati kažejo, da se z višanjem hitrosti varjenja od 200 do 600 mm/s povprečna upornost zmanjšuje. Razlog za to je krajši čas segrevanja materiala in manjši vnos energije. Pri geometrijah 2 in 3 smo opazili nižjo povprečno upornost v primerjavi z geometrijo 1. Razlog je v večji pokritosti varilne površine in bolj enakomerni porazdelitvi energije.

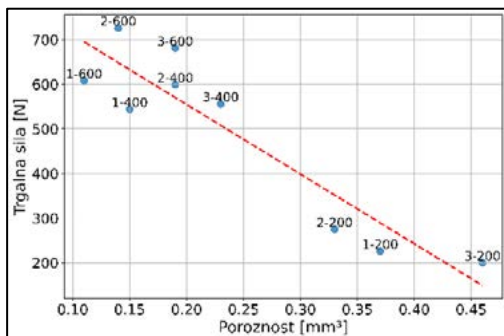
Poroznost. Rezultati kažejo, da se največ poroznosti pojavi pri nižjih hitrostih varjenja – tam je toplotni vnos večji in začne prihajati do uparjanja materiala, zaradi česar lahko v talini ostane več ujetih plinov. Kompleksnejše geometrije, zlasti geometrija 3, povzročajo manj stabilen proces in višje vrednosti poroznosti. Za zmanjšanje poroznosti in doseg ponovljivih rezultatov smiselno je izbrati manj kompleksne geometrije v kombinaciji z višjimi hitrostmi varjenja ter varjenca z dobro očiščeno izolacijo.

Trgalni test. Trgalni test je pokazal jasen trend pri vseh geometrijah: z večjo hitrostjo varjenja narašča trgalna sila. To pomeni, da višje hitrosti omogočajo krajšo, a intenzivnejšo toplotno obremenitev, kar vodi do močnejših zvarov. Rezultati so pokazali tudi, da kombinacija 2-600 edina izpolnjuje kakovostne zahteve po 5-Sigma metodi.

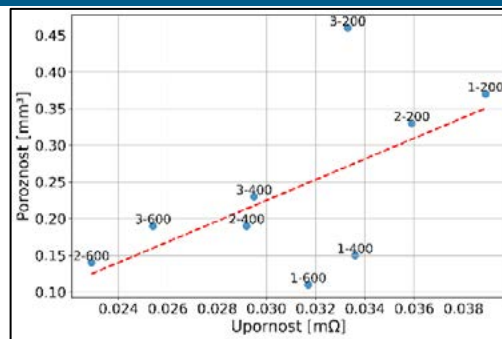
Primerjava vpliva med kazalniki kakovosti. Analizirali smo povezave med tremi izbranimi kazalniki kakovosti. Rezultati so pokazali, da obstaja jasna korelacija. Med električno upornostjo in trgalno silo (slika 3) obstaja obratna sorazmernost. Nižja električna upornost pomeni višjo mehansko trdnost. Večja poroznost vodi do nižje trgalne sile (slika 4), saj porozna struktura oslabi presečno površino zvara in deluje kot stresni koncentrador. Medtem ko pa upornost in poroznost (slika 5) kažeta pozitivno korelacijo. Višja poroznost poveča električno upornost. Kakovost spojev lahko tako ocenimo z neporušnimi testi električne upornosti in poroznosti, ki so bistveno hitrejši od trgalnih testov.



Slika 3: Korelacija med električno upornostjo in trgalno silo.



Slika 4: Korelacija med poroznostjo in trgalno silo.



Slika 5: Korelacija med električno upornostjo in poroznostjo.

Optimalna kombinacija. Na podlagi analiz in metode ocenjevanja, kjer smo kombinacije parametrov ovrednotili glede na poroznost, upornost in trdnost. Tako smo kot najbolj optimalno kombinacijo parametrov določili geometrijo 2 pri hitrosti 600 mm/s. Ta kombinacija dosega: najnižjo upornost, najvišjo trgalno silo, in zmerno poroznost, ki je le nekoliko višja od minimalne vrednosti, dosežene pri geometriji 1 pri 600 mm/s.

Porazdelitev moči center – kolobar. Pri porazdelitvi moči med centrom in kolobarjem je bila pri razmerju 50/50 dosežena najboljše stabilnost procesa in znatno zmanjšanje poroznosti: 30 % zmanjšanje volumna poroznosti in 5 spojev od 24 vzorcev več brez por. To je predvsem posledica tega, da kolobarni žarek stabilizira parnico. Vendar pa se je pokazalo, da ta nastavitev vodi tudi do nižje mehanske trdnosti in slabše električne prevodnosti, saj se gostota moči v centru zmanjša kar za 58 %, kar pomeni plitvejše zware. Nastavitev 75/25 je povzročila splošno zmanjšanje kakovosti zvarov, saj so se vse ključne lastnosti – poroznost, električna upornost in trdnost poslabšale. Sklep je torej, da lahko BrightLine z ustreznim razmerjem moči zmanjša pojav napak.

Zaključek

- Povečana kompleksnost gibanja laserskega žarka poveča trdnost spojev in zmanjša električno upornost, vendar hkrati povzroči več poroznosti. Preveč kompleksne geometrije zato niso primerne, saj vodijo v nestabilen proces.
- Pri višjih hitrostih se poroznost zmanjša, električna upornost pade in trgalna sila poveča.
- Pri porazdelitvi moči smo ugotovili, da razmerje 50 : 50 dodatno zmanjša število in volumen por, kar izboljša stabilnost procesa.
- Meritve so pokazale, da nižja električna upornost pomeni manjšo poroznost in večjo mehansko trdnost. Zato lahko električno upornost uporabimo kot hiter posreden kazalnik kakovosti spoja.
- Kot najboljša kombinacija se je izkazala geometrija 2 pri hitrosti 600 mm/s.

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Hierarchical Laser-Engineered Surfaces for Enhanced Phase Change Cooling in Confined Spaces

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A gold-coated, laser-textured copper surface was developed to investigate confined pool boiling in distilled water. Gap sizes between the boiling surface and confinement plate were systematically varied from 0.1λ to 2.5λ . Results reveal consistent enhancements of both critical heat flux (CHF) and heat transfer coefficient (HTC) compared to reference copper, with maximum improvements of 65% and 207%, respectively. The superior performance is attributed to hierarchical microchannels enabling efficient wicking, enhanced nucleation, and delayed dryout.

Introduction

Among the various cooling strategies, nucleate pool boiling remains essential for high heat flux applications, yet its performance in confined geometries is often limited by premature vapor accumulation and early CHF onset. Numerous studies have explored the influence of gap size, plate geometry, and surface wettability on confined boiling using bare or conventionally modified surfaces, revealing both enhancements and degradations depending on operating conditions [1,2]. However, despite significant advances in surface engineering, there is a lack of systematic studies investigating confined pool boiling on laser-engineered surfaces designed to enhance wicking and nucleation. In the aim of addressing this gap we investigated the boiling performance of laser-textured copper under varying confinement, demonstrating its capability to mitigate confinement-induced limitations.

Materials and methods

Surface fabrication. Copper substrates were employed for the preparation of boiling interfaces. A reference interface was fabricated by sequential polishing with PE2000 sandpaper, followed by ultrasonic cleaning in isopropanol for 10 min and subsequent UV–ozone treatment for 10 min to remove organic contaminants and activate the surface. Immediately after activation, the samples underwent ion beam sputtering for 15 min, during which a thin gold nanolayer was deposited to mitigate oxidation during boiling in deionized water and to reduce performance degradation. For the laser-textured interfaces, a comparable procedure was applied. After polishing, the copper samples were ultrasonically cleaned in isopropanol (10 min) prior to nanosecond-laser texturing. Following laser processing, an identical ultrasonic cleaning step was performed. Subsequently, the textured samples were subjected to the same UV–ozone activation and gold sputtering protocol as described for the reference interface, previously described in detail in our earlier work [3,4]. In this study, the setup was upgraded with a dedicated positioning system for the confinement plate. The confinement element, a

circular aluminum plate with a diameter of 39 mm, was machined from a solid rod. To examine the effect of confinement, the plate was initially positioned at a height of 2.5λ above the boiling surface and subsequently lowered in discrete steps to a minimum gap of 0.1λ , where λ denotes the capillary length of distilled water ($\lambda \approx 2.5$ mm). Accordingly, the tested gap sizes were 0.1λ , 0.25λ , 0.5λ , 0.75λ , 1λ , 1.25λ , 1.5λ , 2λ , and 2.5λ . The copper test sample was mounted onto a nickel-plated copper heating block, secured to the bottom flange of the chamber. It was embedded within a PEEK bushing and affixed using high-temperature adhesive to ensure thermal and mechanical stability. Temperature measurements were obtained via three K-type thermocouples inserted laterally into the sample to capture the internal temperature distribution, while an additional thermocouple monitored the fluid bulk temperature within the chamber. A schematic of the configuration is provided in Figure 1. Data reduction and measurement uncertainty evaluation followed the procedures reported in our previous studies [3,4].

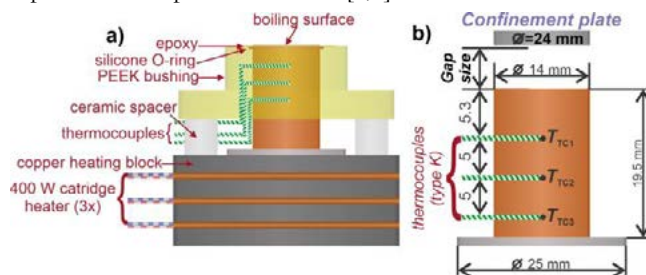


Figure 1: Schematic view of sample assembly.

Prior to boiling experiments, the working fluid was degassed for 30 min by inducing vigorous boiling with an immersion heater, after which cartridge heaters supplied a constant heat flux of 250 kW m^{-2} for an additional 15 min to fully degas the boiling surface. Subsequently, all heaters were switched off and the system was allowed to cool to saturation conditions. Boiling tests were then initiated and continued until the critical heat flux (CHF) was reached. Upon CHF onset, the experiment was terminated and the system cooled before commencing the next run. Data acquisition was carried out using DewesoftX software.

Results and discussion

Pool boiling tests were performed on gold-coated reference and laser-engineered copper surfaces in distilled water at atmospheric pressure to investigate the effect of vertical confinement. The gap between the boiling surface and the confinement plate was systematically varied from 0.1λ to 2.5λ , where λ denotes the capillary length of water ($\lambda = 2.5$ mm). For each configuration and gap size, three independent

experiments were conducted until the onset of the CHF. The obtained CHF values are shown in Figure 2. The results reveal a clear trend of decreasing CHF with decreasing confinement height for both surfaces. On the reference surface, the CHF reduced from 978 kW m^{-2} at the largest gap to 283 kW m^{-2} at the smallest, corresponding to a 71% reduction. In contrast, the laser-engineered surface exhibited a reduction from 1091 kW m^{-2} to 466 kW m^{-2} , a 57% decrease. Notably, the relative reduction of CHF on the laser-engineered surface was 14% lower compared to the reference surface across the tested confinement range. Furthermore, the laser-engineered surface consistently demonstrated significant CHF enhancement compared to the reference. At the largest gap size, the enhancement reached 12%, whereas under the most severe confinement (0.1λ) the improvement increased markedly to 65%. This superior performance can be primarily attributed to the presence of stochastically hierarchical porous microchannels on the laser-textured surface, which greatly improve liquid wicking capacity compared to the polished reference. Enhanced capillary-driven replenishment facilitates more effective liquid supply to the surface, a factor of particular importance under confined conditions where premature vapor blanket formation and impeded liquid transport promote early dryout. The efficient liquid replenishment enabled by the laser-engineered interface thus delays vapor blanket stabilization and postpones the boiling crisis, leading to a higher CHF across all tested confinements relative to the reference surface.

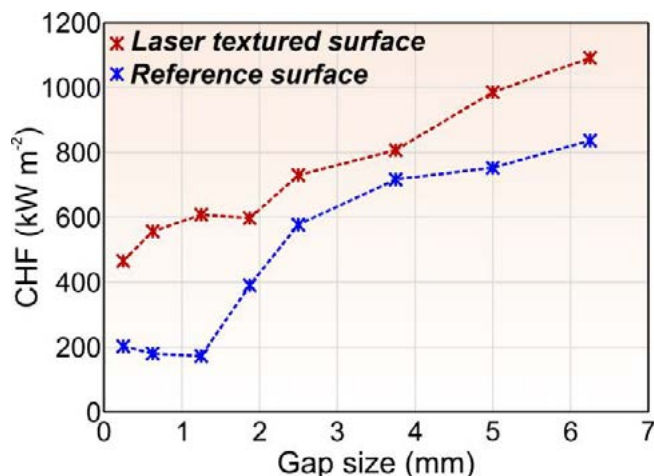


Figure 2: The effect of the gap size on CHF.

The HTC measured at CHF for reference and laser-engineered surfaces under varying vertical confinement heights are presented in Figure 3. A pronounced reduction of HTC with decreasing gap size was observed for both surfaces. Specifically, the HTC on the reference surface decreased by 65% when the gap was reduced from the largest to the smallest tested value, whereas on the laser-engineered surface the decrease was limited to 50%. Thus, the relative reduction in HTC was 15% lower for the laser-engineered surface compared to the reference. Importantly, the laser-engineered surface exhibited an enhancement of the HTC across all investigated confinement conditions. At the largest tested gap, the improvement was 115%, while under the most severe confinement of 0.1λ the enhancement increased dramatically to 207%. This behavior can be primarily attributed to the

multiscale microcavities introduced by laser texturing, which promote a significantly higher density of active nucleation sites and thereby intensify bubble generation. Under smallest confinement, where elevated nucleation activity on a conventional surface would typically accelerate vapor accumulation and premature dryout, the laser-engineered surface instead promoted the formation of smaller vapor bubbles that merged into compact clusters beneath the confinement plate. These vapor clusters were more readily detached from the surface in comparison to the larger, more stable vapor clusters observed on the reference surface. In parallel, the presence of hierarchically porous microchannels facilitated efficient capillary-driven liquid replenishment, counteracting confinement-induced vapor blanketing and sustaining active nucleation. This combined effect resulted in the pronounced HTC improvements observed, particularly at small confinement gaps.

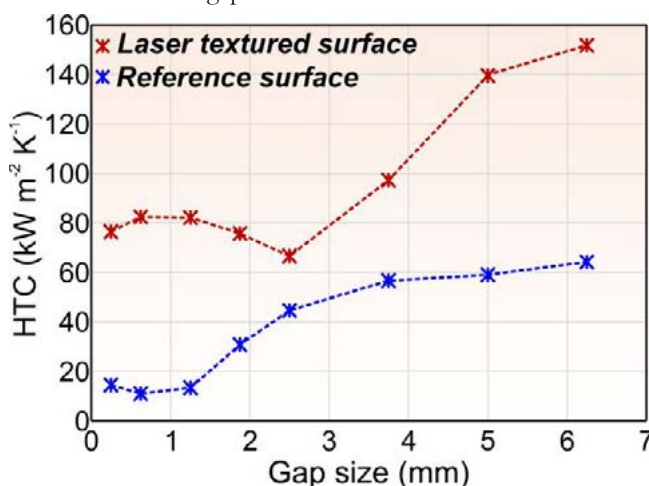


Figure 3: The effect of the gap size on HTC at the CHF.

Conclusions

We investigated confined pool boiling of gold-coated reference and laser-engineered copper surfaces in distilled water. The laser-engineered interface consistently outperformed the reference, with CHF and HTC enhancements up to 65% and 207%, respectively. These improvements arise from hierarchical microchannels and multiscale cavities that enhance wicking, increase nucleation site density and delayed dryout.

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Acknowledgements

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Konstruiranje zadnjega krila dirkalnika Formule Student

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V okviru tekmovanja Formula Student smo razvili zadnje krilo za dirkalnik ekipe Superior Engineering. Cilj naloge je bil zasnovati aerodinamično učinkovito krilo, ki izboljša zmogljivost dirkalnika in je izdelano skladno s pravilnikom. Uporabljene so bile metode računalniške dinamike tekočin ter mehanske analize in optimizacije s pomočjo metode končnih elementov. Rezultati kažejo na povečanje tlačne sile, usmerjene proti tlom, ter izboljšano togost krila.

Uvod

Formula Student je serija inženirskih tekmovanj, na katerih vsako leto sodeluje več kot 500 univerzitetnih ekip z vsega sveta. Glavni cilj tekmovanja je izdelava dirkalnika, ki ne dosega le visoke hitrosti na stezi, temveč se izkaže tudi kot ekonomsko in inženirsko učinkovit. Tekmovanje se začne s statičnimi disciplinami, kjer ekipe sodnikom predstavijo svoje inženirske in ekonomske odločitve. Sledijo dinamične discipline, v katerih se preverja zmogljivost dirkalnikov in voznikov na stezi. Ekipa vsako leto razvijejo nov dirkalnik, kar predstavlja velik časovni in finančni zalogaj, pri tem pa morajo upoštevati obsežen pravilnik, ki zagotavlja varnost in konkurenčnost ekip.

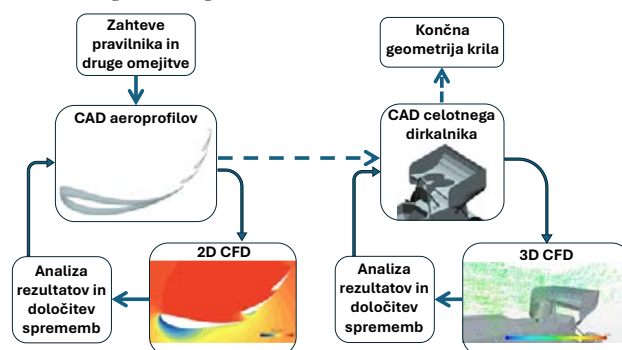
Ljubljansko univerzo na tekmovanjih zastopa ekipa Superior Engineering, ustanovljena leta 2016. V sezoni 2025/26 tako gradi že deseti dirkalnik zapored. Prva dva dirkalnika je poganjal motor z notranjim zgorevanjem, vsi naslednji pa so bili zaradi poudarka na trajnostnem razvoju izdelani z električnim pogonom. Sezono 2024/25 je zaznamoval predvsem prehod na štirikolesni pogon, zaradi česar je celoten dirkalnik doživel velike spremembe.

Cilj te naloge je zasnovati zadnje krilo, ki bo s pomočjo sile dinamičnega vzgona, usmerjene proti tlom, in s tem povečanjem sile trenja omogočalo vožnjo skozi zavoj z višjo hitrostjo ter tako pozitivno vplivalo na zmogljivost dirkalnika. Posebno pozornost je treba nameniti dodatni masi in sili zračnega upora, ki negativno vplivata na zmogljivost dirkalnika, ter vplivu zadnjega krila na druge aerodinamične komponente in vozno dinamiko.

Metode dela

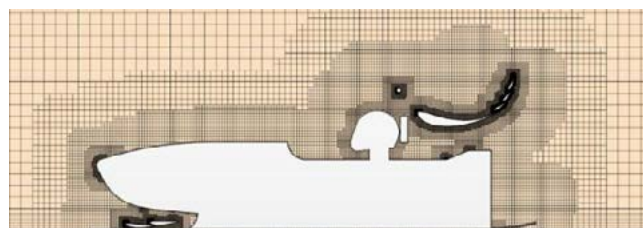
Razvoj zadnjega krila je potekal v kombinaciji 3D modeliranja geometrije in preverjanja le-te s pomočjo računalniške dinamike tekočin (Computer Fluid Dynamics – CFD). Vsako različico geometrije smo prenesli v program Siemens Star CCM+, izvedli simulacijo toka zraka, analizirali rezultate, določili nove spremembe geometrije in ponovno izvedli CFD analizo (slika 1). Predpostavili smo, da lahko obnašanje toka zraka okrog krila simuliramo z ustaljenim, nestisljivim, sklopljenim tokom zraka. Uporabili smo različico turbulentnega modela k-omega, ki temelji na prenosu strižnih

napetosti (angl. Shear Stress Transport), saj najbolje opiše separacije na površini krila. Z namenom optimizacije računskega časa smo začetne faze razvoja geometrije izvajali z ravninskimi (2D) CFD simulacijami aeroprofilov zadnjega krila, pri čemer smo uporabili nestrukturirano mnogokotno (angl. polygonal) mrežo. Po doseženi zadovoljivi obliki osnovne geometrije smo nadaljevali s 3D simulacijami toka zraka okrog celotnega dirkalnika.



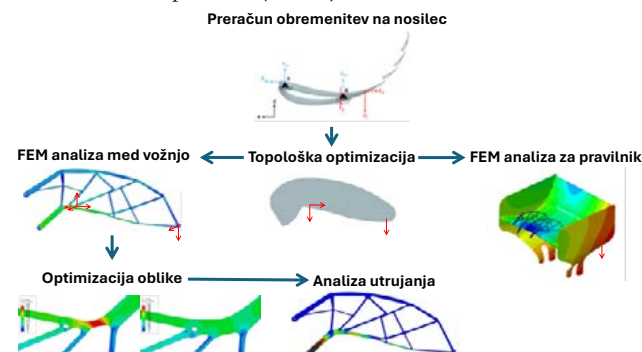
Slika 1: Potek CFD simulacij.

Za 3D simulacijsko okolje [1] smo uporabili tako imenovane obrezane celice (angl. trimmed cell). Celotna domena je obsegala približno 20 milijonov celic (slika 2).



Slika 2: Prerez mreže v 3D simulacijskem okolju.

Po izbiri končne geometrije krila je bilo potrebno oblikovati nosilce, ki izpolnjujejo minimalni dovoljeni povprečni statični obremenitveni stanju, kot je predpisano v pravilniku [2]. Prav tako morajo prenesti vse dinamične obremenitve med vožnjo. Z namenom optimizacije mase nosilcev smo izvedli trdnostni preračun, ki zagotavlja ustreznost nosilcev za oba obremenitvena primera (slika 3).

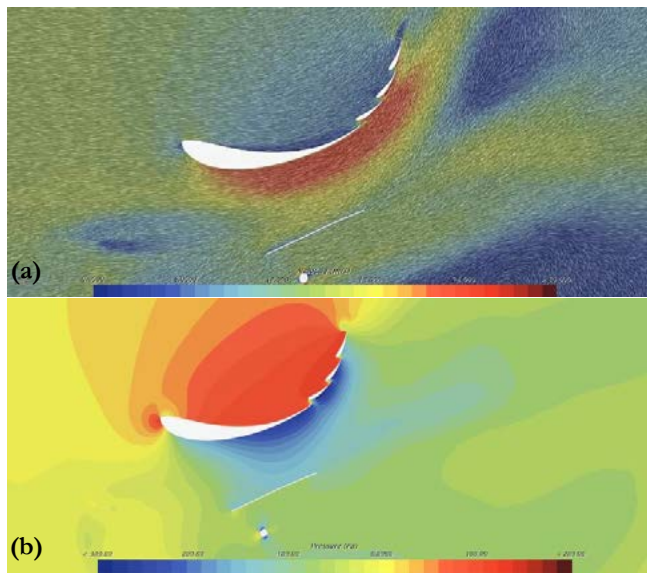


Slika 3: Potek trdnostnega preračuna nosilcev.

Izračunali smo reakcije v podporah in določili osnovno obliko za topološko optimizacijo nosilcev. Sile in osnovno obliko nosilcev smo prenesli v program Abaqus ter izvedli topološko optimizacijo. Končno obliko smo nato preverili s pomočjo metode končnih elementov (Finite Element Method – FEM) za oba obremenitvena primera. Rezultat smo prenesli tudi v program za analizo utrujanja Fe-Safe [3] in preverili število obremenitvenih ciklov do iniciacije razpoke na nosilcu.

Rezultati in diskusija

Izvedli smo približno 150 2D simulacij in nato še 30 3D simulacij toka zraka. Za končno geometrijo smo za glavno krilo izbrali MSHD aeroprofil z dolžino tetive 550 mm, ki mu sledijo tri enaka pomožna krila aeroprofila s1223 z dolžino tetive 100 mm. Vpadni kot prvega krila se po prerezu spreminja med 6° in 2° , vpadni kot zadnjega krila pa doseže 68° . Velik vpadni kot sicer povzroči večjo vrednost koeficienta zračnega upora, ki pa na dirkalnike Formule Student zaradi nizkih povprečnih tekmovalnih hitrosti nima velikega negativnega vpliva. Pri povprečni hitrosti 15 m/s zadnje krilo proizvede 174 N dinamičnega vzgona in 90 N zračnega upora (slika 4). Celoten dirkalnik pri 15 m/s proizvede 490 N dinamičnega vzgona in 179 N zračnega upora.



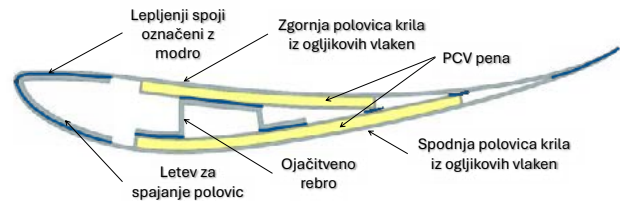
Slika 4: Rezultat hitrosti (a) in tlaka (b) 3D simulacije končne oblike krila.

Za preračun obremenitvenega modela nosilcev smo podatke o magnitudah in prijemališčih aerodinamičnih sil pridobili iz simulacije toka zraka pri končni hitrosti vozila 33 m/s. Silo teže zadnjega krila smo določili iz CAD modela, podatke o vztrajnostnih silah smo izračunali na osnovi meritev pospeškov vozila, izvedenih v preteklih sezonah.

Sledila je topološka optimizacija, ki je zagotovila ustrezen poves nosilcev, napetosti pa so bile še vedno previsoke. Zato smo uporabili optimizacijo oblike, da je bila maksimalna napetost manjša od 225 MPa, s čimer smo zagotovili varnostni faktor 2. Ustrezno varnost je potrdila tudi analiza utrujanja, ki predvideva, da se bodo prve razpoke pojavile po več kot 100.000 ciklih.

V sklopu projekta Formula Student smo zadnje krilo izdelali in ga uspešno uporabili na dirkalniku. Izdelava je potekala v treh

korakih: najprej smo na frezalnem stroju izdelali pozitivne, sledila je izdelava kalupov po postopku infuzije, nazadnje pa izdelava komponent iz ogljikovih vlaken s pre-preg metodo. Polovici krila smo združili s posebnimi deli, izdelanimi s postopkom mokre laminacije (slika 5).



Slika 5: Notranja sestava kril.

Zaključki

S pomočjo sistematičnega pristopa h konstruiranju smo razvili koncept zadnjega krila, ki je izdelano v skladu s predpisanimi pravili in pozitivno prispeva k zmogljivosti dirkalnika. Poveča silo dinamičnega vzgona, usmerjeno proti tlom, in pripomore k enakomernejši razporeditvi celotne aerodinamične sile na sprednja in zadnja kolesa. Zasnovani nosilci prenesajo zadostno število obremenitvenih ciklov, ne presegajo dovoljenega povesa in so masno optimizirani. Tako zasnovano zadnje krilo je v primerjavi s predhodniki bolj toga, lažje in ustvari več dinamičnega vzgona usmerjenega proti tlom.

Zadnje krilo je bilo uporabljeno na dirkalniku, ki je poleti 2025 dosegal zelo odmevne rezultate. Med njimi najbolj izstopa 3. mesto na dirki v Italiji v disciplini avtokros (slika 6). Poleg tega je ljubljanska ekipa na tem tekmovanju v disciplinah pospeševanja in vožnje osmice dosegla svoja najboljša časa od ustanovitve. Vse to dokazuje, da ekipa iz leta v leto napreduje in se lahko kosa tudi z ekipami najboljših univerz na svetu.



Slika 6: Dirkalnik na tekmovanju v Italiji.

ZAHVALA

V imenu ekipe Superior Engineering se zahvaljujemo sponzorjem in vsem, ki podpirajo naš projekt, sodelujejo z nami in nam svetujejo. Hvala vsem članom ekipe, ki so pomagali pri konstruiranju in izdelavi zadnjega krila ter tako prispevali k nastanku tega prispevka.

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Rapid Structural Simulation through Homogenization and Data-Driven Metamodels

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Structured PEHD soil protection mats are used to mitigate deep deformations of soft soils under heavy construction machinery. The mat's complex internal geometry was homogenized in ANSYS Material Designer, yielding an equivalent orthotropic material model validated by three-point bending tests. A layered soil model using the Mohr–Coulomb criterion was then analyzed in 2D and 3D with ANSYS Mechanical, showing that 3D modeling better captures localized tire loads. Finally, a metamodel built in ANSYS OptiSLang enabled rapid evaluation and company-wide access to simulation results, effectively transferring simulation knowledge to non-expert users.

Introduction

Heavy construction machinery operating on soft soils often induces significant ground deformation. To counteract this effect, heavy-duty portable mats are used to distribute loads and limit deep soil displacement. However, the internal structure of these mats—typically made of high-density polyethylene (PEHD) — is geometrically complex, making direct finite element modeling computationally expensive. In this work, we present a multi-stage approach combining material homogenization, soil–mat interaction analysis, and metamodel development. The first stage simplifies the internal mat structure using ANSYS Material Designer, providing orthotropic elastic properties suitable for full-scale simulations. The second stage focuses on accurate soil modeling using a layered Mohr–Coulomb representation. Finally, the third stage creates a metamodel with ANSYS OptiSLang, enabling fast analysis and knowledge transfer across the engineering team through a user-friendly Windows interface.

Materials and methods

Mat Material Homogenization

The material properties of mat were determined from tensile tests performed on PEHD specimens prepared from sheets, following the ISO 527-2:2012 standard, to obtain the input parameters for numerical simulation [1, 2]. The ground protection mat consists of a repeating internal reinforcement geometry designed to distribute heavy loads and minimize soil settlement. To simplify its complex geometry, the internal structure was homogenized using ANSYS Material Designer, resulting in an orthotropic equivalent material model of the mat's microstructure, as shown in Figure 1. ANSYS Material Designer performs numerical homogenization on a Representative Volume Element (RVE) or Unit Cell that statistically represents the internal structure [3]. It applies a series of controlled deformation states to compute equivalent

elastic constants and shear moduli, which are then used to define an orthotropic material model.

The obtained material properties were implemented into a solid continuum model representing the mat. To verify the homogenization approach, a standard three-point bending test was performed experimentally. The span between supports was 2420 mm, and a 1000 kg load was applied through a steel loading plate with a contact area of 200 × 200 mm. The mid-span deflection was continuously measured using a laser displacement sensor, and the deflection value recorded after one minute under the sustained load was taken as the reference for bending stiffness evaluation. The same test configuration was reproduced in the numerical model to compare the load–deflection behavior of the homogenized and detailed structural representations under identical boundary conditions.

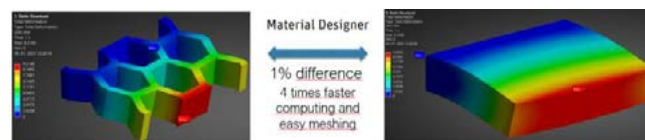


Figure 1: Homogenization of internal structure using ANSYS Material Designer.

Soil Modeling

The soil domain beneath the mat was represented by four distinct layers, based on data interpreted from CPTu field testing. Each layer was assigned Mohr–Coulomb parameters - cohesion, friction angle, Young's modulus, and density - corresponding to the measured site stratigraphy [4]. The interface between the mat and the top soil layer was modeled as frictional contact to allow realistic slip and load transfer. The bottom of the soil domain was fixed, while lateral boundaries were restrained horizontally to avoid boundary effects.

Simulation Setup

Finite element simulations were performed in ANSYS Mechanical to evaluate soil displacement under heavy vehicle loads. The applied load corresponded to the measured front and rear axle forces of a construction truck, acting through the tire–mat contact area. Owing to the high computational demand and nonlinear soil behavior, only a single axle was modeled. The mat assembly included homogenized and solid PEHD components, connected through welds and bolt locations were represented by 1D beams with pretension before external loading. The analysis was static and nonlinear, accounting for large deformations and plasticity in the Mohr–Coulomb soil model. Both 2D and 3D models were analyzed.

Metamodel Development

To make simulation results readily usable beyond the simulation team, the metamodel was integrated into a standalone application that enables fast evaluation of mat and soil performance under various loading scenarios. Metamodeling, also known as surrogate modeling, provides a computationally efficient approximation of complex finite element simulations [5]. Developed in ANSYS OptiSLang, the metamodel considers three input parameters - soil type (five soil types defined by Mohr–Coulomb parameters), vehicle weight, and number of wheels - and predicts maximum mat stress, soil displacement, and vertical stress at several depths.

Results and discussion

Homogenization and Bending Test Validation

The orthotropic properties obtained from ANSYS Material Designer accurately captured the mat's overall stiffness. In the three-point bending validation (Figure 2), the simulation using the homogenized model showed a maximum mid-span displacement of 52 mm, compared to 53 mm measured experimentally - a deviation of less than 2% in terms of maximum displacement. This validation justified the use of the homogenized material in large-scale soil–mat interaction simulations, reducing model complexity and computation time while maintaining predictive accuracy.

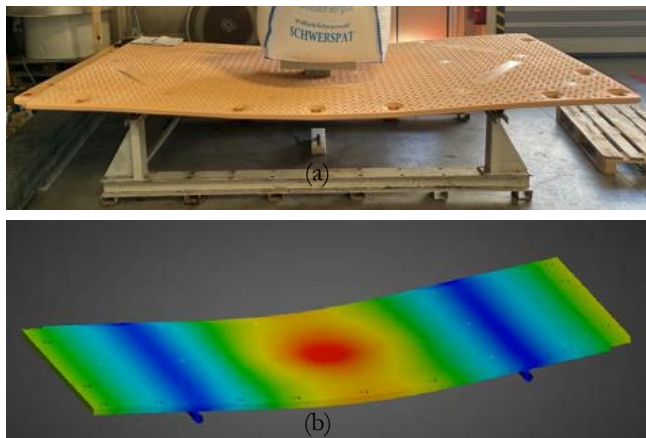


Figure 2: Validation of the mat model using a three-point bending test. (a) Experimental setup and measured deflection; (b) Corresponding numerical simulation of the homogenized mat.

Soil–Mat Interaction Simulation

In the full-scale analyses, the 3D model provided significantly improved accuracy compared to the 2D simplification. The 2D simulation overestimated peak soil deformation by approximately 30%, mainly because it could not capture the overall mat stiffness and lateral stress distribution. The maximum soil displacement under the tire load reached approximately 46 mm in the upper soil layer, while the filed data showed 45 mm. Stress distribution results showed effective load spreading across the mat and a clear reduction of deep subgrade deformation, as shown in Figure 3.

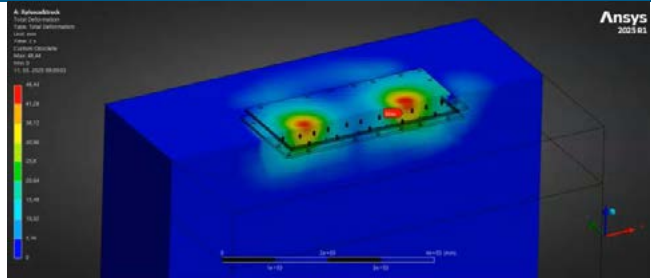


Figure 3: Simulation of a mat subjected to front-axle truck loading on soft soil.

Metamodel Performance and Knowledge Transfer

A Latin Hypercube Sampling scheme with adaptive refinement was employed, and Kriging provided the most accurate response surface with over 90% confidence, while computation time decreased from several hours to less than one second per evaluation. This workflow was implemented in a Python based Windows application (Figure 4). This workflow effectively transfers advanced simulation knowledge to non-specialist users, ensuring consistent design decisions and faster project evaluations.

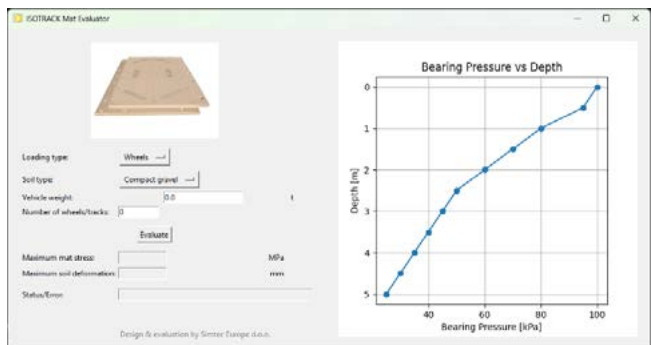


Figure 4: Windows application for democratization of advanced simulations.

Conclusions

The combined workflow of homogenization, nonlinear soil simulation, and metamodeling provides accurate, efficient, and accessible predictions of mat and soil behavior. The reinforcement geometry of PEHD mat was successfully homogenized using ANSYS Material Designer. The OptiSLang metamodel reduced computation time from hours to seconds and enabled company-wide access to reliable results. This workflow supports informed design decisions and knowledge transfer to non-specialist teams. Future work will expand metamodel validation with more soil data to improve predictions across larger soil spans.

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Fazna stabilizacija vlakenskega Mach-Zehnderjevega interferometra za zaznavanje nanodelcev

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Delo predstavlja fazno stabilizirani Mach-Zehnderjev interferometer v popolnoma vlakenski izvedbi. Razvita je bila metoda za fazno stabilizacijo na osnovi modula sposobnega lokalno prilagajati temperaturo optičnega vlakna v referenčni veji interferometra. Na ta način je bila dosežena dolgotrajna stabilnost in inicializacija interferometra v kvadrturno točko. Tako stabiliziran sistem v nadaljevanju omogoča natančne meritve spremembe faze, ki jo povzročijo različni nanodelci v merilni veji.

Uvod

Vlakenski optični interferometri so se uveljavili kot eden ključnih merilnih instrumentov v številnih senzorskih aplikacijah [1], [2]. Med različnimi konfiguracijami izstopa Mach-Zehnderjev interferometer (MZI), ki lahko v vlakenski ter posledično kompaktni izvedbi zagotavlja zelo dobro občutljivost pri merjenju spremembe lomnega količnika. Za doseganje optimalne občutljivosti je potrebno delovanje okoli kvadrturne točke, kjer dosežemo največjo občutljivost meritev, vendar nam termične in mehanske motnje povzročajo, da sistem v tej točki ni stabilen oziroma se premakne k eni od skrajnih leg. Motnje je možno močno zmanjšati s pasivno stabilizacijo, tako da sistem toplotno in mehansko izoliramo od okolice in z aktivnimi metodami. Primer slednjih predstavlja izvedba, ki temelji na uporabi piezoelektričnih elementov, s katerimi po potrebi spreminjamo dolžino optičnega vlakna [3] ali pa redkeje uporabljena modulacija toka skozi lasersko diodo in posledično valovne dolžine, pri kateri merimo [4]. Piezoelektrična stabilizacija omogoča hiter odziv, vendar je zaradi omejenega delovnega območja potrebna pogosta ponastavitev, ki prekinja meritve, medtem ko je modulacija toka skozi lasersko diodo omejena z majhnim območjem delovanja in občutljivostjo na motnje napajalnega toka. V tem delu je predstavljena metoda termične fazne stabilizacije interferometra, ki izkorišča termooptični učinek in termično raztezanje optičnega vlakna za neprekinjeno stabilizacijo faze. Metoda je bila razvita za vlakenski MZI z integriranim prostim poljem, namenjenem zaznavanju nanodelcev v vodi, kjer je dolgotrajna stabilnost interferometra ključnega pomena za zanesljivo delovanje sistema.

Materiali in metode

Eksperimentalna postavitve. Za eksperimentalno postavitve smo uporabili MZI s prostim poljem, na sliki 1. Vir je bila laserska dioda, ki je oddajala svetlobo valovne dolžine 633 nm. Sledil je optični sklopnik, ki je svetlobo razdelil tako, da je šla polovica svetlobe na merilno in polovica na referenčno vejo, ki sta bili narejeni iz enorodovnega polarizacijskega optičnega vlakna. Na referenčni veji je bil modul za stabilizacijo faze,

merilna veja pa je vsebovala merilno prosto polje. Oba žarka sta se združila in interferirala v drugem optičnem 50/50 sklopniku, izhodni signal pa smo zaznavali s pomočjo dveh fotodiod, ki sta nam omogočili merjenje fazne razlike med vejama interferometra.

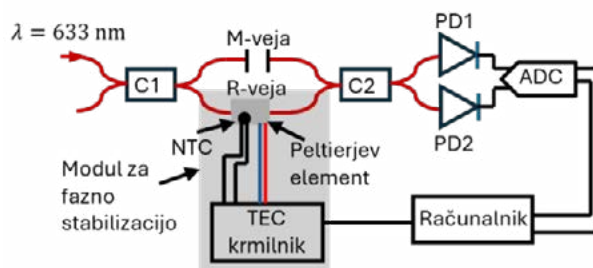
Modul za stabilizacijo faze. Ključni element modula za stabilizacijo faze je predstavljal Peltierjev element, s katerim smo lahko natančno spreminjali temperaturo dela optičnega vlakna. Modul smo krmilili na podlagi vhodnega podatka ciljne temperature glede na pomerjeno fazno razliko. Potrebno spremembo temperature smo izračunali s Python programom, ki je bral podatke z 12-bitni analogno-digitalnega pretvornika (ADC). Ta je sprejemal analogni signal iz fotodiode 1 (PD1) in fotodiode 2 (PD2) ter ga pretvoril v digitalnega. Fazni odmik od kvadrturne točke je nato program izračunal s pomočjo enačbe:

$$\Delta\phi = \frac{I_1 - I_2}{I_1 + I_2}, \quad (1)$$

Kjer sta I_1 in I_2 signala na fotodiodah 1 in 2. Glede na trenutno temperaturo je nato s pomočjo enačbe:

$$\Delta T = \frac{\Delta\phi}{k_T L} \quad (2)$$

izračunal novo temperaturo, da bo $\Delta\phi$ enak nič. L predstavlja dolžino optičnega vlakna v sklopu, k_T pa je koeficient spremembe faze s temperaturo na dolžinsko enoto optičnega vlakna, ki smo ga določili glede na uporabljeno vlakno.



Slika 1: Mach-Zehnderjev interferometer v vlakenski izvedbi, kjer sta C1 in C2 optična sklopnika, M-veja in R-veja pa merilna in referenčna veja interferometra. Modul sestavljajo še fotodiode 1 in 2 (PD1 in PD2), analogno-digitalni pretvornik (ADC), program za določanje potrebne spremembe temperature, krmilnik termoelektričnega hladilnika (TEC krmilnik), termistor z negativnim temperaturnim koeficientom (NTC) in Peltierjev element.

Rezultati in diskusija

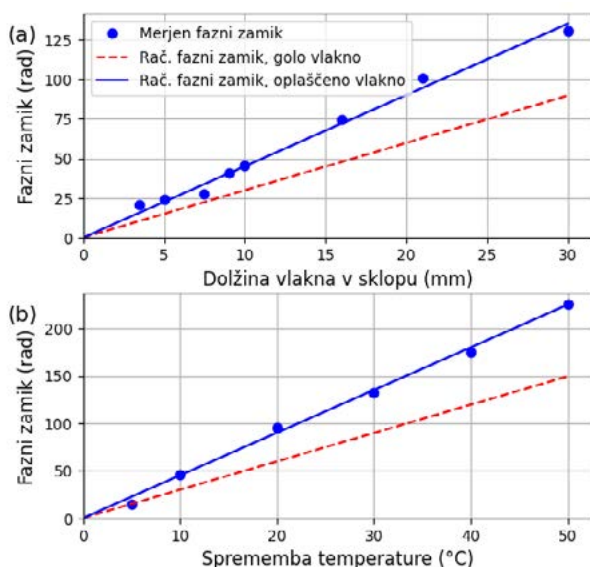
Določanje optotermičnih lastnosti vlakna. Za določanje koeficienta k_T smo vlaknu v sklopu za fazno stabilizacijo nadzorovano spreminjali temperaturo. Fazni zamik, ki ga

povzroči sprememba temperature optičnega vlakna opiše enačba:

$$\Delta\varphi = \frac{2\pi L}{\lambda} \Delta T \left(\frac{dn}{dT} + \alpha_T \right), \quad (3)$$

kjer je $dn/dT = 9,3 \times 10^{-6} \text{ K}^{-1}$ za kvarčno steklo, iz katerega je narejeno optično vlakno [5], α_T pa koeficient termičnega raztezka, ki za golo stekleno optično vlakno znaša $5,0 \times 10^{-7} \text{ K}^{-1}$ [6]. Za pravilno določitev koeficienta raztezka pa moramo upoštevati, da stekleno optično vlakno obdaja akrilatni ovoj, ki še dodatno razteguje vlakno. S tem dobimo popravljen α_T , ki znaša $4,0 \times 10^{-6} \text{ K}^{-1}$. L je dolžina optičnega vlakna v modulu za stabilizacijo, λ pa valovna dolžina laserskega vira. V našem primeru ta znaša 633 nm. Sedaj lahko z združitvijo enačb (2) in (3) izračunamo, da velja $k_T = 0,15 \text{ rad}/(\text{mm K})$.

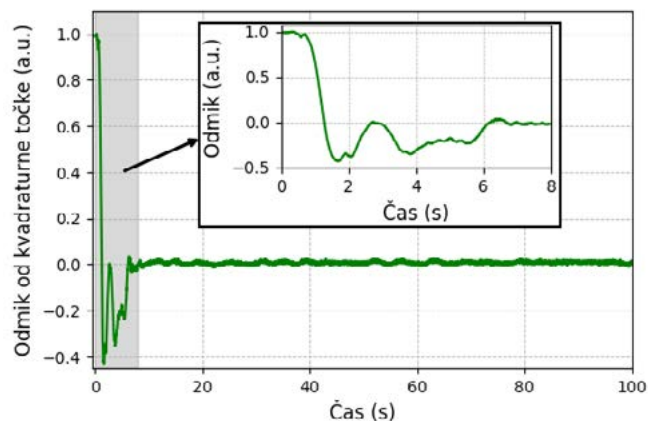
Za potrditev tega rezultata smo najprej spreminjali dolžino vlakna v sklopu za stabilizacijo faze od 3,5 mm do 30 mm, pri konstantni spremembi temperature 30°C , rezultat je prikazan na sliki 2 (a). Nato smo imeli v sklopu vedno enako dolžino vlakna (30 mm) in spreminjali spremembo temperature, od 5°C do 50°C , rezultat pa je graf na sliki 2 (b). Vidimo, da se obe meritvi ujemata z izračuni, ki upoštevajo optično vlakno z ovojem (modra krivulja).



Slika 2: (a) fazni zamik signala interferometra pri konstantni spremembi temperature 30°C in različnih dolžinah vlakna v sklopu za stabilizacijo. (b) fazni zamik pri konstantni dolžini vlakna v sklopu za stabilizacijo, enaki 30 mm, v odvisnosti od spremembe temperature

Implementacija aktivne fazne stabilizacije. Fazna stabilizacija vlakenskega MZI je bila preizkušena v daljšem časovnem obdobju, kjer se je izkazalo, da modul ustrezno stabilizira interferometer okoli kvadrature točke in kompenzira temperaturno povzročene motnje. Preizkusili smo tudi inicializacijo interferometra. V primeru, da je interferometer popolnoma izven kvadrature točke, potrebuje manj kot 8 s, da jo doseže (slika 3). Standardna deviacija odklona od kvadrature točke znaša približno 0,08 rad. Frekvenca s katero nastavljamo željeno temperaturo je bila v našem primeru 1 Hz, saj je lastni nihajni čas sistema za popravljanje faze malo več kot dve sekundi. Veljati mora, da je

frekvenca popravljanja nižja od polovice lastne nihajne frekvence, saj sicer sistem postane nestabilen. V primeru potrebe po kompenzaciji hitrejših sprememb pa bi modul za fazno stabilizacijo nadgradili še z piezzo elementom za hitrejšo popravko faze.



Slika 3: Premik interferometra v kvadrature točko iz skrajne lege in stabilizacija.

Možnosti uporabe za zaznavanje nanodelcev. V prosto polje merilne veje interferometra lahko vstavljamo različne vzorce, na primer kiveto, v kateri so zlati nanodelci suspendirani v vodi. Te lahko nato osvetljujemo z vzbujevalnim laserjem, absorpcija svetlobe na delcih pa bo povzročila spremembo lomnega količnika vode, ki ga lahko zaznamo z interferometrom. Prednost te metode proti večini ostalih, ki delujejo na principu merjenja sipanja svetlobe, je da lahko zaznamo tudi delce pod 20 nm, kjer je sipanje zanemarljivo.

Zaključek

Razvili in eksperimentalno ovrednotili smo termalno metodo za fazno stabilizacijo vlakenskega Mach-Zehnderevega interferometra. Metoda je primerna za kompenzacijo počasnih, predvsem temperaturno povzročenih motenj. Njena prednost je, da ima zelo široko delovno območje, kar bistveno zmanjša potrebo po ponastavitvi sistema za stabilizacijo faze in s tem omogoča dolgotrajne neprekinjene meritve. Poleg tega je kompatibilna s popolnoma vlakensko izvedbo interferometra. Tako fazno stabiliziran interferometer omogoča meritve širokega spektra parametrov v prostem polju.

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Snovanje in validacija električnega skiroja za preizkuse trka

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Uporaba električnih skirojev se je v zadnjem desetletju močno povečala in postala ena izmed najbolj priljubljenih oblik mestne mobilnosti. Ob hitrem razvoju in porastu priljubljenosti pa narašča tudi število nesreč in posledično poškodb, ki se zgodijo ob vožnji z električnimi skiroji. Cilj raziskovalnega dela je bil izdelati parametrični numerični model električnega skiroja, ki bo služil za izvajanje simulacij trkov z električnimi skiroji. V prvem delu smo pregledali zakonodajo, povezano z električnimi skiroji, in njihovo priljubljenost na trgu, na podlagi česar smo določili reprezentativni model kot izhodišče pri izdelavi CAD modela. Sledila je izdelava modela na osnovni metode končnih elementov (MKE) in nato nadgradnja v parametrični model, ki omogoča nastavitve vhodnih podatkov (material, dimenzije). Uspešno smo zgradili model, za katerega smo izvedli potrjevanje z izvedbo simulacij trka električnega skiroja. Izdelani model se obnaša realistično, kar smo prikazali v rezultatih z nekaj osnovnimi scenariji trčenja.

Uvod

Električni skiroji so postali široko dostopni po večini evropskih in drugih mest, ker omogočajo trajnostne rešitve za naraščajoče prometne zastoje in onesnaževanja zraku. Zaradi hitrega razvoja se pojavlja veliko raznolikih modelov, ki se ločijo po velikostih, materialih ali zmogljivostih. Pojavljajo se vedno bolj zmogljivejše baterije, lažji materiali in boljše funkcije skirojev. Posledično pa je tudi prisoten velik narast števila nesreč in poškodb, ki se zgodijo ob vožnji z električnimi skiroji. Zaradi raznolikosti modelov pa se pojavi tudi težava pri izbiri modela za analizo prometnih nesreč. [1, 2]

Namen dela je bil na podlagi pregleda trga izbrati reprezentativni model, ki bo služil kot osnovna pri izdelavi geometrijskega modela. Cilj naloge pa je bil izdelati parametrični numerični model, ki bo služil pri simuliranju nesreč z električnimi skiroji. Ta nam bo omogočili različne možnosti izbire vhodnih parametrov, kot so materiali in dimenzije, s čimer bomo zajeli raznolikost modelov.

Metode dela

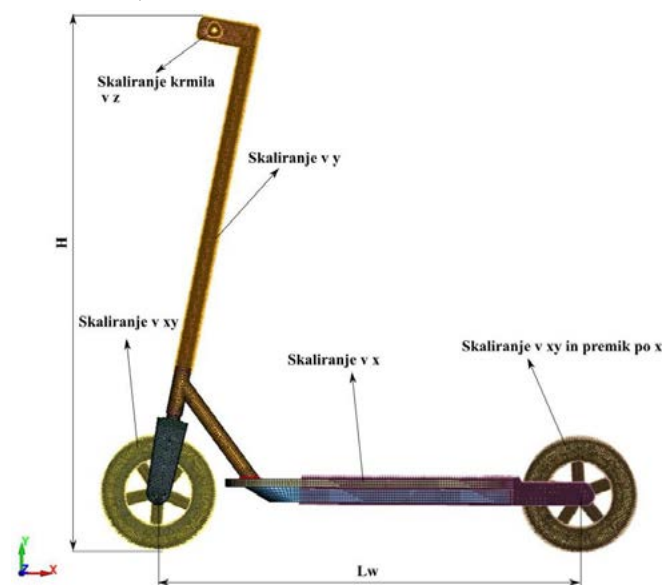
Na podlagi pregleda trga, prodaje in razširjenosti na trgu smo izbrali reprezentativni model Xiaomi Mi M365. Model nam je služil, kot osnovna pri izdelavi CAD modela. Ob pregledu trga smo še zbirali in primerjali različne modele skirojev med seboj in tako nabrali dimenzijske in materialne parametre, za uporabo pri parametričnem modelu.

Izbrali smo nekaj glavnih modelov in primerjali njihove parametre:

- Dolžina skiroja $[L]$: Merjena od začetne točke skiroja do skrajne točke. Razponi od 1070 do 1210 mm.
- Širina $[B]$: Najširši del skiroja, v večini primerov širina krmila. Razponi od 420 do 540 mm.
- Višina $[H]$: Višina skiroja, definirana do najvišje točke skiroja. Razponi od 1140 do 1260 mm.
- Premer koles $[d_{kol}]$: Razponi od 205 do 241 mm, oziroma od 8,5 do 10 colskih koles.
- Materiali: Najpogostejše uporabljena Aluminijeva zlitina 6061-T6.

CAD model je bil izdelan na podlagi geometrije in specifikacij izbranega reprezentativnega modela Xiaomi Mi M365. Geometrije manjših delov, kot so ročice, luči pri modelu nismo upoštevali, saj bi otežili nadaljnjo delo. Geometrijo smo prenesli v programsko opremo LSPrepost, kjer smo ločili vsak posamezni del skiroja na primerne oblike za izvedbo mreženja. Uporabljali smo volumnske heksaedske končne elemente in pa ploskovne tetraedske končne elemente.

Iz izdelanega numeričnega modela, smo izdelali parametrični model. Določili smo mu vhodne parametre, ki bodo imeli možnost spreminjanja. Izbrali smo 5 dimenzijskih in 5 materialnih parametrov. Vsakemu parametru smo določili relacije, ki so popisane preko enačb. Modelu smo določili možnost spreminjanja premera koles, višine krmila, medosne razdalje ter širine krmila. Dimenzije električnega skiroja se spreminjajo na podlagi skaliranja in translacije posameznih komponent. Slika 1 prikazuje označene dele, ki se transformirajo.

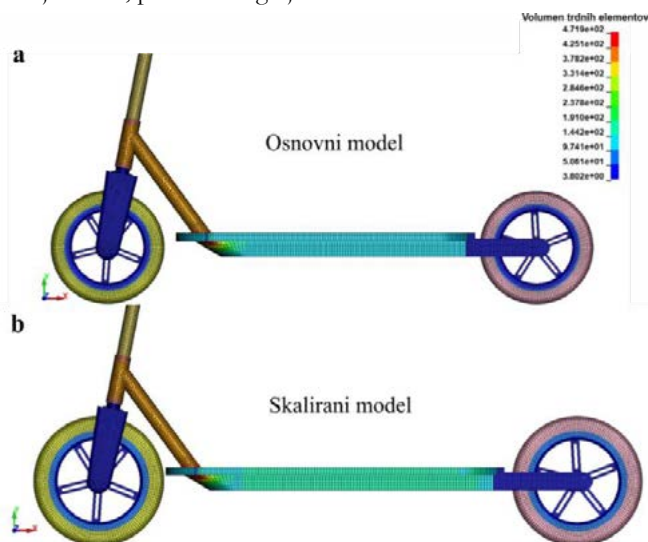


Slika 1: Parametrični numerični model.

Modelu smo tudi določili možnost spreminjanja materialov komponent, ki imajo možnost izbire preko številke materialnega modela določenega v osnovnem modelu.

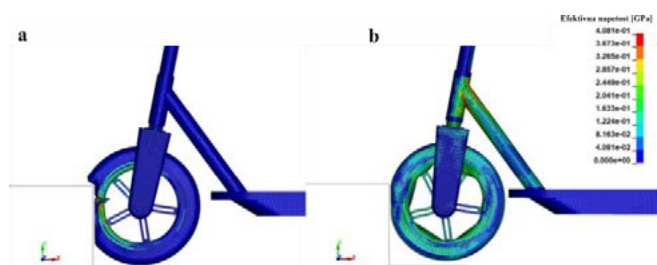
Rezultati in diskusija

Rezultat te naloge je parametrični numerični model, ki ima za osnovno numerični model sestavljen iz 23 posameznih delov. Celoten model je sestavljen iz 107 771 vozlišč in 80 920 elementov. Parametrični model ponuja možnost izbire 10-ih vhodnih parametrov. Slika 2a prikazuje osnovni numerični model in Slika 2b spremenjeni skalirani model. Vidimo, da se poveča medosna razdalja skiroja ter tudi premeri koles, mreža ostaja enaka, poveča se zgolj velikost elementov.



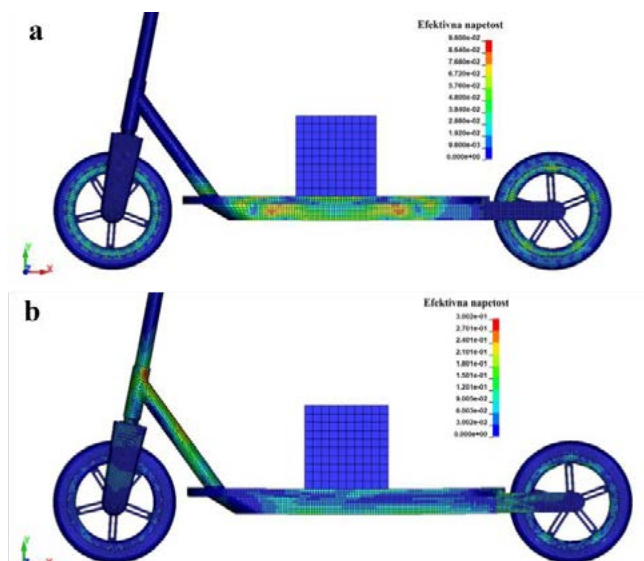
Slika 2: (a) Osnovni numerični model in (b) spremenjeni skalirani numerični model.

Izvedli smo validacijo skiroja z izdelavo treh različnih scenarijev. Izvajali smo preizkus obnašanja konstrukcije skiroja ob trčenju v pločnik. Definirali smo hitrost premikanja skiroja 90 km/h in čas trajanja simulacije 1 ms. Preizkusili smo dva različna materiala gume. Mehkejši material guma SBR privede do zelo sunkovitih deformacij, kar nam celo povzroči razpad elementov (Slika 3a). Napetosti se zaradi majhne togosti materiala gume večinoma absorbirajo in ne prenesejo v preostali del skiroja. Uporabili smo tudi bolj tog material Al6061, ki pa se deformira manj (Slika 3b). Tukaj vidimo da se elementi kolesa ob trku odzivajo boljše in se napetost prenese v povezovalno cev. Najvišje napetosti se pojavijo v stičišču povezovalne cevi in sicer do 400 MPa.



Slika 3: a) Material pnevmatike guma SBR in b) material Al6061.

Za preizkus preostalega dela skiroja smo izvedli spust kocke z maso 200 kg iz višine 2 m. To smo definirali s tem, da smo kocki predpisali začetno hitrost 6,26 m/s in definirali gostoto, da smo dosegli željeno maso 200 kg. Opazovali smo čas trajanja simulacije 1 ms. Slika 4a prikazuje potek napetosti ob času 0,3 ms, kjer se največje napetosti do 60 MPa pojavijo v deski skiroja, kjer pride do trka. V nadaljevanju trčenja ob času 0,7 ms na sliki 4b pa vidimo, da se napetosti prenesejo naprej v povezovalno cev in nosilno cev krmila, kjer znašajo nekje do 250 MPa.



Slika 4: a) Napetosti ob spust telesa na desko skiroja ob času simulacije 0,3 ms in b) ob času trajanja simulacije 0,7 ms.

Zaključki

Izdelan parametrični numerični model omogoča; nastavitve desetih vhodnih parametrov, kot so dimenzije in materiali. Ugotovimo, da se kvaliteta mreže ob spreminjanju teh parametrov ne poslabša, temveč samo spreminjanja velikost elementov. Model smo validirali s tremi različnimi scenariji trkov, največje napetosti se pojavljajo v stičiščih cevi, kjer so se pojavile vrednosti do 400 MPa. Ugotovili smo, da se odziva ustrezno, kar pomeni, da ga lahko uporabimo tako za analizo konstrukcije, kot tudi za ocenjevanje možnih poškodb voznika ob simulacijah prometnih nesreč pri vožnji z električnimi skiroji.

Za naprej vidimo nekaj možnosti nadgradnje. Modelu bi bilo potrebno dodati tlake v pnevmatikah, kar bi izboljšalo realnost odziva gume. Druga možnost je vključitev lutke človeškega telesa za bolj realistične simulacije poškodb. Nenazadnje pa bi lahko model nadgradili v okolju LS-Opt, kjer bi imeli možnost avtomatizirane optimizacije geometrije in materialov.

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Axisymmetric chiral auxetic structure – EU patent EP3970941

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A novel class of three-dimensional (3D) axisymmetric chiral structures (ACS) exhibiting negative Poisson's ratios is introduced. This structure is created by mapping the conventional 3D tetra-chiral unit cell into an axisymmetric space. A corresponding computational model was developed, validated with experimental data, and then used to explore virtual structures with graded cell architectures and optimisation. The newly designed axisymmetric structures demonstrated enhanced mechanical properties compared to existing 3D chiral structures.

Introduction

Auxetic cellular structures are novel metamaterials characterised by a negative Poisson's ratio [1,2]. This unique property—causing the structure to shrink transversely when compressed and expand when stretched—makes them highly valuable across various fields, including engineering, medicine, sport, and fashion. Their development began over three decades ago, leading to the analysis of numerous designs, predominantly 2D and orthogonal 3D geometries. Most existing auxetic structures exhibit orthotropic properties (meaning their mechanical response differs along three perpendicular axes), such as 2D honeycombs, many 3D cellular structures, and composites. However, the ultimate goal of developing truly three-dimensional isotropic auxetic structures with uniform properties in all directions has not yet been fully realised.

This work introduces a novel, fully 3D axisymmetric chiral structure (ACS), which was recently awarded an EU patent [3]. It was created by mapping regular 3D auxetic chiral unit cells into a 3D axisymmetric space. The resulting structure was fabricated, and its properties were thoroughly evaluated and optimised through experimental testing and computational modelling.

Materials and methods

The axisymmetric chiral cellular structure presented here is a cylindrical auxetic metamaterial. Its design is derived from a conventional unit cell whose shape corresponds to the 10th eigenmode of a regular cubic unit cell, as previously introduced in [4]. The three-dimensional chiral unit cell represents a lattice structure composed of curved struts joined at cube vertices (nodes), thus forming an open-cellular structure with very low structural weight. The struts take the shape of sines, whose turning points meet in the nodes and can have concave or convex curvature depending on their spatial orientation. The structure exhibits auxetic deformation behaviour upon mechanical loading with a negative Poisson's ratio in polar

(axisymmetric structure) or spherical (spherical structure) directions.

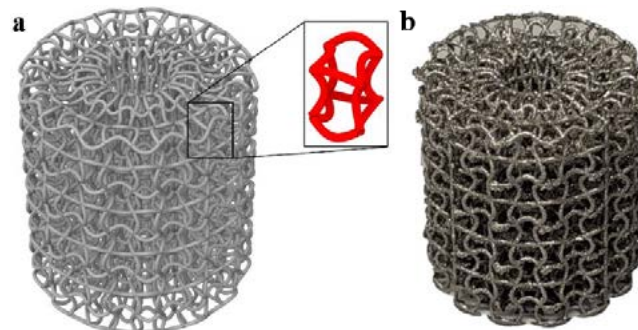


Figure 1: CAD model of ACS structure with its unit cell (a), fabricated sample (b)

Six samples of each generated structure were fabricated using the additive manufacturing machine EOS M280, based on a powder bed fusion system, from gas-atomised stainless steel 316L powder.

Uniaxial compression tests following ISO 13314:2011 standard were performed using a servo-hydraulic INSTRON 8801 testing machine with the position-controlled cross-head rate of 0.1 mm/s (quasi-static testing - QS) and 284 mm/s (dynamic testing - DYN) at room temperature of 22 °C. The testing conditions were the same for all analysed specimens. The recorded load-displacement data were converted to engineering stress-strain values, using the initial specimen's dimensions. The finite element software system LS-DYNA was used for all reported computer simulations.

Results and discussion

The mechanical testing results of axisymmetric chiral samples are given in Figure 2. The linear elastic region is followed by the plateau region of constant stress, ending in structural densification. The limited strain rate hardening can be observed when comparing the quasi-static and dynamic responses.

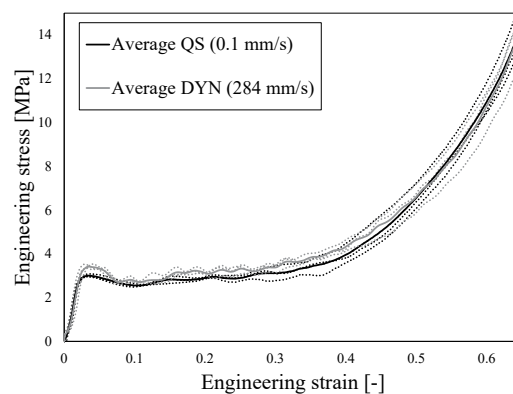


Figure 2: The mechanical responses of ACS samples at QS and DYN compression loading conditions

The deformation behaviour of ACS samples is shown in Figure 3, where it can be observed that the computed deformation pattern is very similar to the one observed in the experiments (Figure **Error! Reference source not found.**a). As observed in the experiments, the cells on the outer structure part are not extensively deformed compared to those on the inner part. Computational modelling offers the possibility of easily tracking the deformation process inside the samples. This is relevant in the studied cases where localisation results from the cell geometry, which is narrower in the structure's inner part.

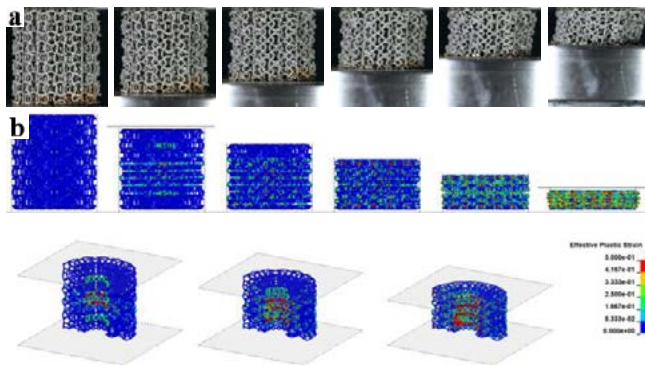


Figure 3: The deformation responses of ACS samples in experiments (a) and computational simulations (b)

The axial symmetry and the transformation of the unit cells result in a non-uniform stress field in the case of uniform ACS structures, as can be seen in Figure 3c [5]. Therefore, the computational optimisation was included to achieve a more isotropic stress field in the structure [6], which is specifically employed to mitigate the inherent mechanical anisotropy of many auxetic designs, yielding a structure with a more predictable and near-isotropic response in the plane perpendicular to the loading axis, thus ensuring uniform mechanical properties. The optACS (optimised ACS) geometry is radially graded with different thicknesses of the struts, as shown in Figure **Error! Reference source not found.**b. The specific energy absorption (SEA) values up to 40 % of deformation were calculated for the optimised design, where a 425 % increase was observed compared to the initial design (8.13 J/g compared to 1.91 J/g). This considerable enhancement of the mechanical properties confirms the superior properties of this metamaterial.

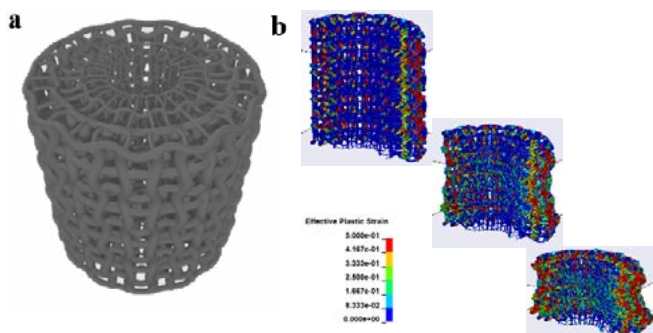


Figure 4: The optimised optACS structure (a), and deformation responses in computational simulations (b)

Conclusions

Novel **axisymmetric chiral structures (ACS)**, which exhibit a **negative Poisson's ratio**, were designed using CAD and fabricated via **additive manufacturing**. Analysis showed that these axisymmetric structures have **better mechanical properties** and **energy absorption** capabilities than their conventional (orthogonal) counterparts. Furthermore, the ACS was **optimised** by determining the optimal unit cell geometry based on the target strain energy density, finding that the structure should be **graded in the radial, circumferential, and vertical directions**. This optimisation resulted in a graded ACS with a significantly stiffer mass-normalised mechanical response, **boosting the specific energy absorption (SEA) by 4.25 times**, making it highly effective for **crash absorption** and establishing one of the **highest SEAs** in its class.

ACKNOWLEDGEMENTS. The authors acknowledge the Slovenian Research Agency's financial support of the national research programme funding No. P2-0063 and basic research project No. J2-60049.

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Printability of Al10SiMg alloys: A study of extrusion and sintering

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In this study AlSi10Mg-based feedstocks with two binder systems for material extrusion (MEX)-based 3D printing were developed. The paraffin wax (PW)-based formulation showed poor mechanical properties and failed during printing, while the low-density polyethylene (LDPE)-stearic acid (SA) system enabled successful printing and post-processing. Results highlight the importance of binder selection for effective MEX of aluminium alloys. Debinding and sintering trials under argon atmosphere were also performed.

Introduction

Material extrusion (MEX) is a widely used technique of additive manufacturing (AM) due to its low cost, low production time, minimal waste, ease of use and precise parameter control. MEX is used in the automotive, aerospace, consumer goods and biomedical industries to process neat polymer, and filled thermoplastic composites (carbon, graphene, metal, ceramic) [1]. Aluminium alloys are in high demand across all industries, but traditional AM technique such as selective laser melting (SLM) remains costly and involves complex powder handling, whereas low-cost MEX can overcome these hurdles. In addition, MEX allows designers to produce intricate, lightweight geometries such as lattice structures and internal cooling channels that were previously impractical or too expensive with SLM [2]. In this work, we developed printable AlSi10Mg feedstocks for low-cost MEX, comparing wax-based and LDPE-based binders and evaluating their rheology, printability and post-processing (debinding and sintering).

Materials and methods

AlSi10Mg powder (Renishaw Italy-AlSi10Mg-0403; $D_{50} = 45 \mu\text{m}$; $\rho = 2.68 \text{ g cm}^{-3}$) was characterized by scanning electron microscopy (SEM) (Zeiss SEM-FEG Leo Supra 35, Germany) and x-ray diffraction (XRD) (Philips X'Pert 1710, Netherlands; Cu K α , $2\theta = 20\text{--}90^\circ$, 40 kV/40 mA, 0.02° steps, 2 s/step). Two binders were formulated: B1 (97 wt.% LDPE, Merck Schuchardt OHG, Germany; 3 wt.% stearic acid, Merck Schuchardt OHG) and B2 (74 wt.% LDPE; 3 wt.% stearic acid; 23 wt.% paraffin wax, Sigma-Aldrich). Feedstocks F1 and F2 each comprised 60 vol.% AlSi10Mg powder mixed with two different multi-component binders (B1 for F1, B2 for F2). The batches (75 cm³) were compounded in a counter-rotating Brabender kneader at 170 °C, 60 rpm for 40 min, cooled, ground to 1–3 mm and dried at 50 °C for 24 h. The filaments were then extruded on a filabot EX2 extruder (1.78 mm die) and continuously spooled. Rheological measurements (150–200 °C, 1 Hz, cone-plate geometry) characterized the viscosity

of feedstocks, and the tensile tests on the filaments were performed by using a Lloyd LRX machine (500 N load cell, 5 mm min⁻¹). Cylindrical specimens were printed on a Zmorph MEX machine with identical settings: 60 °C bed, 0.6 mm nozzle, 0.3 mm layer, 100 % infill, 0/90° raster, 60 mm s⁻¹ speed and two perimeters, with nozzle temperatures of 200 °C for F1 and 180 °C for F2. The printed parts were subjected to a thermogravimetric analysis (TGA) in N₂ (50 mL min⁻¹) from 25 to 600 °C at 10 °C min⁻¹. Thermal debinding (450 °C, 90 min, 4 mbar) and sintering (570 °C, 180 min, 8.45 mbar) were carried out in a tube furnace at 5 °C min⁻¹, and the morphology of the samples was examined using SEM.

Results and discussion

Morphology of AlSi10Mg powder is shown in Figure 1a and b. Most particles show an irregularly shaped morphology, with few inclusions of spherical form. XRD (see Fig. 1c) shows only Al and Si phases (JCPDS 85-1327, 27-140), with no detectable oxide peaks, confirming the powder's chemical purity. EDS of the as-received powder showed: 89 wt.% Al, 9 wt.% Si, with traces of Mg 0.25 wt.%, Fe 0.25 wt.%, O 0.20 wt.%, Ti 0.15 wt.%, Zn 0.10 wt.%, and Ni 0.05 wt.%.

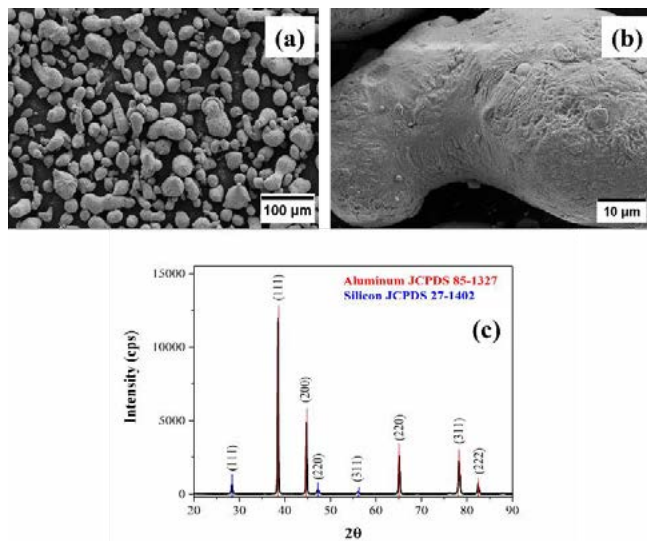


Figure 1: AlSi10Mg powder: (a) SEM, 500x, (b) SEM, 5kx, and (c) XRD diffractogram.

Feedstock F1 was less challenging to adjust the parameters as the fabricated extrudate had reasonable strength to ensure continuous automatic spooling of the filaments. In the case of F2 feedstock, filament production was quite challenging. The spooling was done manually as the strength of the manufactured filaments was not high enough for automatic performance. The viscosity of the feedstocks was measured in the range of 150–200 °C and is shown in Figure 2a. The

rheological curves clearly show that the viscosity is highly influenced by the temperature. When the temperature is low, the mobility of the polymer chains is low which inhibits material flow. As the temperature increases, the viscosity of feedstock decreases. When a metallic powder is incorporated with the polymeric binder system, a particle-particle network is created, causing limited mobility of the polymeric chains by the metallic powder, increasing particle-particle interactions, and friction [2]. As the F2 feedstock was composed of paraffin wax, the viscosity was lower than the F1 composition.

Further, the mechanical properties of the filaments were evaluated, since suitable strength and flexibility are essential to spool the filaments during extrusion and unspool it during printing. Representative stress-strain curves of filaments produced with the F1 and F2 feedstocks are shown in Figure 2b. The feedstock filament F1 exhibited high elongation at break ($\sim 2.45\%$) and maximum stress (i.e., $\sigma_{\max} = 3.17 \pm 0.17$ MPa). The mechanical properties of filament F1 are comparable with other printable filaments available in the literature [1] and good enough to feed the MEX machine. In comparison, feedstock filaments F2 resulted in shorter elongation at break ($\sim 0.95\%$) with the maximum stress value (i.e., $\sigma_{\max} = 1.9 \pm 0.35$ MPa) representing inferior mechanical properties (see Fig. 2b).

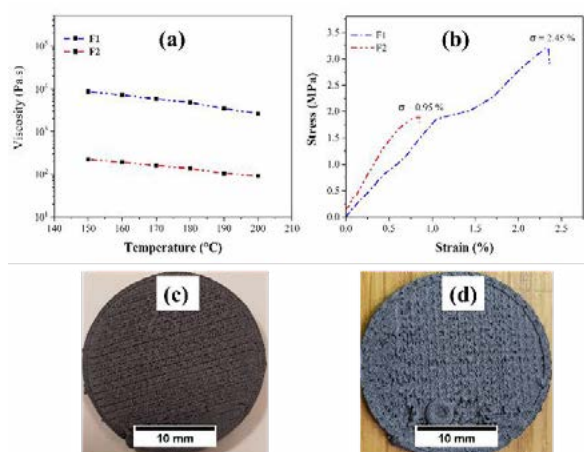


Figure 2: (a) Viscosity in temperature range of 150–200 °C for F1 and F2, (b) stress–strain curves of F1 and F2 filaments, (c) successful prints with F1, and (d) failed prints with F2 (filament breakage).

F1-based filaments enabled successful printing (see Fig. 2c), while F2-based filaments resulted in failed prints (see Fig. 2d). As the filament F2 was fragile, the feeding was done manually. Nevertheless, the filament constantly broke between the heating block and the bottom of the feeding, leading to print failures. Consequently, only F1-based printed specimens were proceeded for debinding and sintering trials. The optimal debinding thermal cycle was therefore determined by TGA only on F1-based 3D-printed specimens. TGA under the nitrogen atmosphere shows a maximum mass loss of neat polymer at temperature around ~ 487 °C and for 3D printed specimen at temperature around ~ 452 °C. As TGA results clearly show, a degrading of the polymer in the 3D-printed specimens started earlier compared to neat polymer. Due to increased particle-polymer interactions, polymer degradation inside the highly filled component started earlier due to high

heat capacity and thermal conductivity of metallic powder [3]. Considering TGA results, the thermal debinding was set at 450 °C with a heating rate of 5 °C min⁻¹ for 90 min under argon.

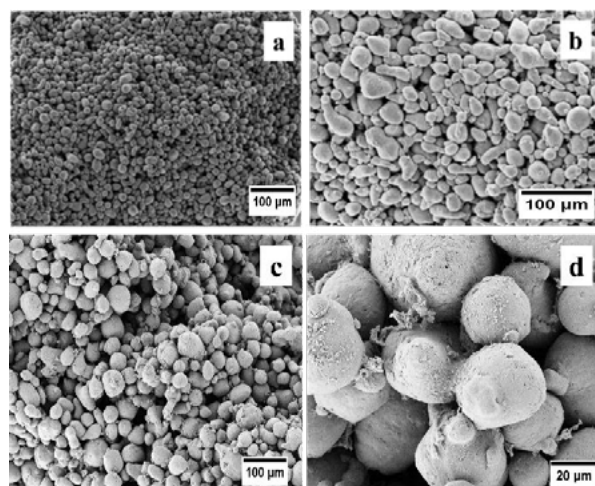


Figure 3: SEM images: (a) brown part (250x), (b) brown part (500x), (c) sintering attempt specimen (500x), and (d) sintering attempt specimen (2500x).

F1-based 3D-printed specimens were thermally debound and proceeded to sintering furnace. SEM micrograph of the debound specimen (see Fig. 3 a, b) confirmed that the binder was completely removed during the thermal treatment; moreover, pore size distribution reveals the success of the debinding process. The micrograph of the attempted sintered specimen (see Fig. 3 c, d) reported sintering failure, as only light bonding of particles and necking was formed. The shape of the individual particle was noticeable. The oxides development restricted the grain growth of the AlSi10Mg particles. There is a great chance that undesirable oxygen and carbon product formation occurs during the burning of the LDPE that sustained throughout sintering even under a controlled atmosphere. Future work should include x-ray fluorescence (XRF) to quantify oxygen and carbon in the powder. To eliminate oxidation, we should consider separate debinding in argon, pre-sintering in hydrogen, confirm contaminant removal through XRF, and complete sintering in argon.

Conclusions

A printable Al10SiMg feedstock was developed and rheologically proven to have a lower viscosity than LDPE when using paraffin wax, but the wax-rich composition resulted in mechanically weak filaments. In contrast, LDPE-based filaments were successfully printed and underwent debinding and sintering in argon, but oxidation during these steps prevented particle bonding and grain growth. Further work needs to focus on diminishing the oxide formation caused by the low melting point and high reactivity of aluminium alloys to obtain defect-free MEX components.

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Zagotavljanje najvišje ravni meroslovne sledljivosti v slovenskem nacionalnem laboratoriju za dolžino

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Prispevek opisuje vlogo Laboratorija za tehnološke meritve (LTM) kot ključnega stebra nacionalne meroslovne infrastrukture. Predstavljena je implementacija meroslovne sledljivosti dolžine, ki se vzdržuje na najvišji hierarhični ravni (He-Ne laser) in potrjuje v mednarodnem okviru (EURAMET/KCDB). Članek izpostavlja kritično meroslovno vrzel, prepoznano kot problem na globalnem meroslovnem nivoju: odsotnost zagotavljanja sledljivosti sodobnih laserskih interferometrov, ki delujejo v infrardečem spektru. V odgovor na ta izziv LTM izvaja strateški razvoj inovativnega kalibracijskega postopka v okviru tekočega raziskovalnega projekta (št. projekta: V2-24074, ARIS). Ta prizadevanja so sestavni del širše strategije širitve etalonske baze, katere cilj je krepitev meroslovnih zmogljivosti v državi.

Uvod

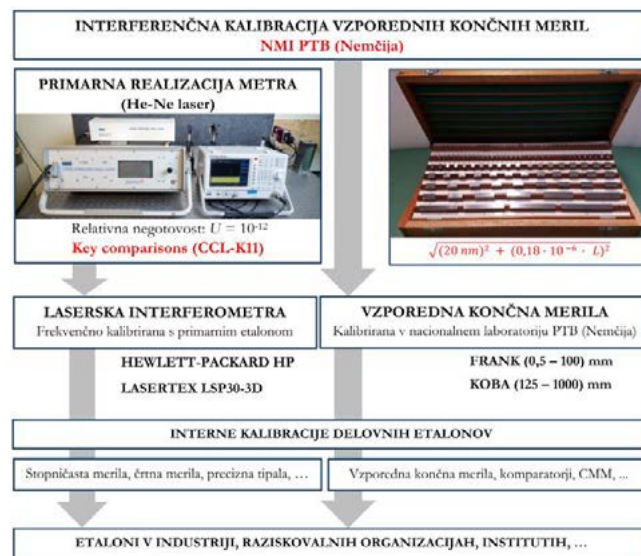
Zagotavljanje meroslovne sledljivosti ima ključno vlogo pri ohranjanju točnosti in mednarodne primerljivosti meritev. Na področju dimenzijskih meritev se ta pomen še posebej odraža, saj se industrija nenehno sooča z izzivi, ki jih prinašata napredek tehnologije in avtomatizacija. Posledično so zahteve po točnosti in kompleksnosti meritev ter doslednem upoštevanju strogih standardov kakovosti vedno višje. Za reševanje teh zahtevnih merilnih izzivov industrija potrebuje visoko napredne merilne sisteme, katerih periodično umerjanje z izjemno natančnimi fizičnimi in optičnimi etaloni je nujno. Da bi zagotovili zanesljivo sledljivost in mednarodno primerljivost merilnih rezultatov, izvajajo ta umerjanja akreditirani laboratoriji (AL), ki s svojo strokovnostjo in nepristranskostjo zagotavljajo najvišjo raven kakovosti meroslovnih storitev. AL so tako zadolženi za spremljanje potreb industrije ter izvajanje umerjanj industrijskih etalonov in merilnih sistemov na ustrezni ravni točnosti. Nosilec nacionalnega etalona je pri tem zaupana dodatna naloga: zagotavljati znanstveno-tehnološko podporo z razvojem kalibracijskih metod in širitvijo etalonske baze. Kljub tem prizadevanjem zagotavljanje meroslovne sledljivosti v praksi ni vedno preprosto, saj se zlasti na področju dimenzijske nanometrologije pojavljajo izzivi, kjer sledljivosti ni vedno mogoče zagotoviti, pogosto že na najvišji ravni.

Meroslovna sledljivost na nacionalni in mednarodni ravni

LTM deluje v okviru slovenskega distribuiranega meroslovnega sistema v koordinaciji Urada RS za meroslovje (MIRS) in je nosilec nacionalnega etalona za veličino dolžina. V okviru svoje dejavnosti zagotavlja sledljivost etalonov, ki so podlaga za realizacijo nacionalnega etalona za dolžino, v primarnem

laboratoriju Physikalisch-Technische Bundesanstalt (PTB) v Nemčiji. Etalonsko bazo sestavljajo trije seti vzporednih končnih meril (VKM): 122-delni set kratkih VKM dolžin od 0,5 mm do 100 mm ter dva seta dolgih VKM, in sicer 8-delni set dolžin od 125 mm do 500 mm in 5-delni set dolžin od 600 mm do 1000 mm. Pri primarni realizaciji nacionalnega etalona se sledljivost navezuje neposredno na etalon – frekvenčno stabiliziran He-Ne laser z valovno dolžino 633 nm (rdeča svetloba), katerega absolutna frekvenca je potrjena z mednarodno ključno primerjavo CCL-K11.

Prenos vrednosti nacionalnega etalona na nižje hierarhične ravni v Sloveniji se izvaja neposredno s primarnim etalonom (He-Ne laser) in s primerjalnim merilnim instrumentom. V slednjem se dolžina kalibriranega VKM primerja z dolžino referenčnega etalona, ki je sledljiv na primarni etalon dolžine (mednarodna raven). V ta namen se uporabljata komparatorja (do 100 mm in do 1000 mm), ki delujeta na principu diferencialnega merjenja dolžin z dvema induktivnima tipaloma z ločljivostjo 0,01 µm. Celotna sledljivostna veriga je grafično prikazana na sliki 1.



Slika 1: Sledljivost nacionalnega etalona za dolžino.

LTM je član EURAMET in ima za področje dolžina objavljene meroslovne zmogljivosti (CMC) v mednarodni podatkovni bazi KCDB pri BIPM. Sodelovanje v mednarodnih medlaboratorijskih primerjavah omogoča laboratoriju potrjevanje teh zmogljivosti, zmanjševanje merilne negotovosti ter stalno izboljševanje kakovosti meritev. Meroslovno znanje in vpogledi, pridobljeni iz mednarodnih primerjav, skupaj z vlogo nosilca nacionalnega etalona, laboratoriju omogočajo samostojen razvoj novih kalibracijskih metod in postopkov ter načrtovanje in izvajanje raziskovalnih projektov. Ti so ključni pri zagotavljanju vrhunske sledljivosti in širitvi etalonske baze,

kar se trenutno kaže v projektih, kot sta 23IND08 DI-Vision, ki rešuje problem sledljivosti sistemov strojnega vida v digitalnih industrijskih aplikacijah, in V2-24074, ki je usmerjen v razvoj fizikalnih in tehnoloških osnov za zagotovitev sledljivosti laserskih interferometrov (LI) z valovno dolžino v infrardečem področju (IR).

Meroslovni izzivi in rešitve

Na temelju vzpostavljenega sistema zagotavljanja meroslovne sledljivosti na nacionalni in mednarodni ravni se v dimenzionalnem meroslovju pojavljajo novi izzivi, med katerimi izstopa zagotavljanje sledljivosti LI, ki delujejo v IR območju. Zaradi svoje minimalistične optične zasnove in visoke prenosljivosti se takšni sistemi vse pogostejše uporabljajo neposredno v proizvodnih procesih. Enega takšnih sistemov imamo tudi v LTM (slika 2).



Slika 2: Tri-kanalni diodni laserski interferometer Picoscale.

LI tipa Picoscale deluje v IR območju, zaradi česar sledljivosti ni mogoče zagotoviti preko neposredne primerjave valovne dolžine svetlobe laserskega izvora z jedno stabiliziranim He-Ne laserjem, kot to trenutno izvajamo v našem laboratoriju (slika 3) [1] in tudi v drugih nacionalnih meroslovnih inštitutih po svetu.



Slika 3: Prikaz primerjalnega umerjanja LI.

Zaradi te meroslovne vrzeli smo se v LTM odločili za inovativen pristop: razvoj novega kalibracijskega postopka, ki bo sledljivost IR laserskih interferometrov zagotovil na obstoječ primarni etalon v RS. To rešitev želimo realizirati v okviru tekočega projekta, ki je del Ciljnega raziskovalnega programa CRP 2024. Projekt obsega celovito raziskavo globalnega meroslovnega prostora, vključno z analizo obstoječih zmogljivosti vodilnih nacionalnih meroslovnih inštitutov. S pomočjo analitičnih in eksperimentalnih analiz, ki jih izvajamo v sodelovanju z evropskimi raziskovalnimi institucijami, bomo zasnovali merilni sistem za primerjalno umerjanje omenjenih LI. Končni rezultati projekta bodo zajemali ovrednotenje merilne negotovosti, izdelavo lastnega kalibracijskega postopka ter, kot potrditev mednarodne ekvivalentnosti, organizacijo in izvedbo mednarodne medlaboratorijske primerjave. Pričakuje se, da bo rešitev te

problematike omogočila vzpostavitev sledljivostne verige na mednarodno raven, ob hkrati zadovoljivi ciljni ravni merilne negotovosti.

Pomen širitve nacionalne etalonske baze

Obravnavanje meroslovnih vrzeli, kot je npr. problem sledljivosti LI v IR območju, je neločljiv del ključne strateške usmeritve LTM: razvoja novih kalibracijskih metod in postopkov ter širitve nacionalne etalonske baze. S tem laboratorij zagotavlja sledljivost merilnih sistemov in instrumentov ter utrjuje svojo vlogo v mednarodnem meroslovnem prostoru. Razviti postopki so prilagojeni potrebam slovenske industrije, zlasti na področjih geometrijsko zahtevnih in visokotehnoloških proizvodov z visoko dodano vrednostjo, kjer je najvišja točnost meritev ključnega pomena. Hkrati se izvaja strateška širitev etalonske baze z investicijami v vrhunsko merilno opremo in prizadevanji za vzpostavitev novih referenčnih etalonov, s čimer se krepijo meroslovne zmogljivosti v državi. Te naložbe neposredno vplivajo na mednarodno primerljivost slovenskega meroslovja, saj ciljajo na doseganje, in v določenih primerih presegajo, zmogljivosti vodilnih svetovnih meroslovnih inštitutov. Posledično celotna meroslovna stroka v Sloveniji, vključno z raziskovalnimi inštituti, akreditiranimi kalibracijskimi laboratoriji in naprednimi proizvodnimi podjetji, pridobi zanesljivo znanstveno in strokovno podlago za lasten razvoj in izboljšanje meroslovnih zmogljivosti. S tem slovenski nacionalni laboratorij utrjuje svojo vlogo zanesljivega partnerja v mednarodnem meroslovnem prostoru in prispeva k globalni primerljivosti meritev na najvišji ravni.

Zaključek

Članek predstavlja vzpostavljeno sledljivost meritev, reševanje meroslovnih izzivov in pomen razvoja metod in postopkov za širitev etalonske baze v nacionalnem laboratoriju za dolžino. S tem laboratorij prispeva h globalni primerljivosti meritev, povečuje zaupanje v slovensko meroslovje ter utrjuje strateški pomen Slovenije v evropskem in svetovnem meroslovnem okolju.

ZAHVALA

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Material Engineering Addressing Industrial Challenge: Carbon-Reinforced PA66 Gears for Advanced Drivetrains

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The transition to electric mobility has increased demand for lightweight power transmission components, but traditional polymeric gears often struggle with inadequate thermal management and excessive wear. This research presents a comparative analysis of Polyamide 66 gears reinforced with 20% short carbon fibers (PA66 CF20 HT) against non-reinforced PA66 material. Comprehensive fatigue life and load-carrying capacity evaluations were conducted against a steel mating gear across various applied torques, monitoring tribological contact, temperature response, and wear behavior. The composite material drastically improved performance, yielding an 86% increase in fatigue life. The composite exhibited superior tribological characteristics, including a 39% reduction in friction coefficient and a 73% lower wear coefficient compared to the base polymer. These improvements are attributed to the carbon fibers' enhanced heat removal capacity and greater bending stiffness, validating PA66 CF20 HT as a highly durable solution for advanced drivetrain applications.

Introduction

Gears are essential machine elements for power transmission in countless applications, from household appliances to complex industrial machinery. While traditionally made from metals for strength and reliability, metal gears often have disadvantages such as high weight, noise, and production costs. Plastic gears have emerged as a popular alternative due to their lightweight nature, low noise, corrosion resistance, and ability to operate without external lubrication.

However, the application of plastic gears in demanding fields like e-mobility is limited by their inherent disadvantages, including lower mechanical strength, poor thermal conductivity, and lower temperature resistance compared to metals. Heat accumulation during operation can lead to material degradation and a shortened service life. To overcome these limitations, fillers such as carbon fibers are added to the polymer matrix. Carbon fiber reinforcement can significantly improve material properties, including strength, dimensional stability, thermal conductivity, and tribological performance [1, 2].

This study provides a systematic evaluation of the tribological performance of steel/composite gear pairs, specifically focusing on Polyamide 66 (PA66) reinforced with 20% short carbon fibers. By comparing its performance against generic PA66, this research aims to quantify the benefits of carbon fiber reinforcement and provide a comprehensive understanding of the material's suitability for high-

performance gearing applications, considering their lifetime and temperature response.

Materials and methods

Two types of plastic gears were investigated: a generic heat-stabilized Polyamide 66 (PA66 HT) and a heat-stabilized PA66 reinforced with 20% short carbon fibers (PA66 CF20 HT). Both were tested in a gear pair with a steel pinion made from 42CrMo4 alloy steel. The plastic gears were manufactured using a two-step process: injection molding of cylindrical semi-finished parts, followed by a precision CNC hobbing process to create the final involute gear profile. The geometry of the tested spur gears is detailed in Table 1 [4].

Table 1: Geometrical parameters for the tested gear pair.

	Gear geometry
Teeth number, z [-]	20
Gear width, b_w [mm]	6
Gear module, m [mm]	1
Pressure angle at normal section, α [°]	20
Tip diameter, d_a [mm]	22
Reference diameter, d [mm]	20
Root diameter, d_f [mm]	17.5
Width of the contact [mm]	6
Length of the contact line [mm]	6.2

Fatigue and lifetime evaluations were conducted on a specialized test rig designed for power transmission testing. The rig uses two 3-phase asynchronous motors, with one acting as the driving source and the other as the braking source to apply a precise torque to the gear pair. Tests were performed without lubrication at a constant rotational speed of 1400 min⁻¹ under four different torque levels ranging from 1.2 Nm to 1.5 Nm. An Optris Xi400 infrared thermal camera was used to continuously monitor the average surface temperature in the meshing zone [4].

Figure 1 presents an image of the carbon reinforced polyamide 66 gear. The microstructure was checked using SEM microscopy to evaluate the orientation and size of the carbon fibers in polyamide 66 matrix.

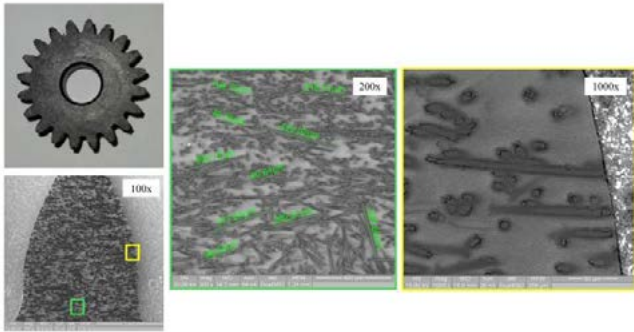


Figure 1: Schematic representation of the PA66 CF20 gear sample and SEM images of the observed microstructure at various positions with associated magnitudes.

Results and discussion

The experimental results demonstrated a dramatic improvement in the operational lifespan of the carbon-reinforced gears. Compared to the generic PA66 gears, the PA66 CF20 HT gears exhibited a fatigue life extension of up to 83% at lower torque levels. At high-load levels (1.5 Nm and 1.4 Nm), the composite gears also showed a significantly longer life and lower operating temperatures, as shown in Figure 2a and 2b.

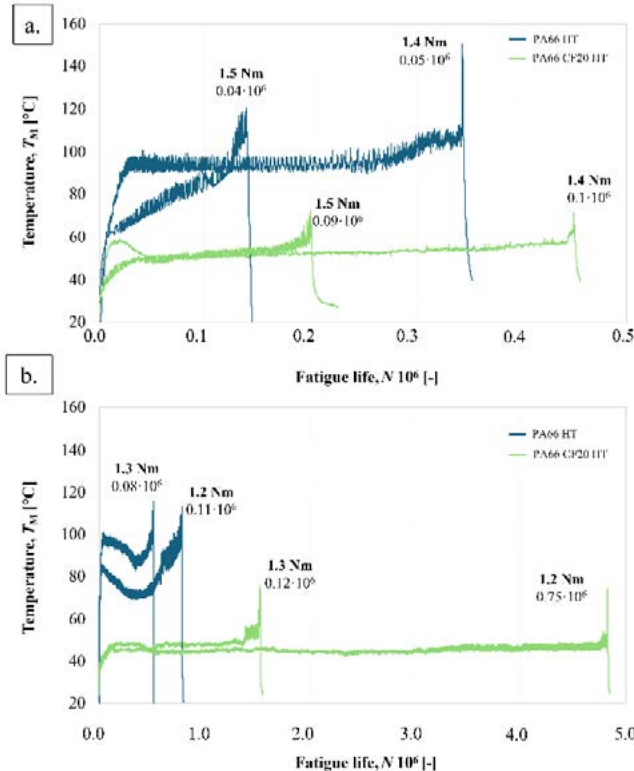
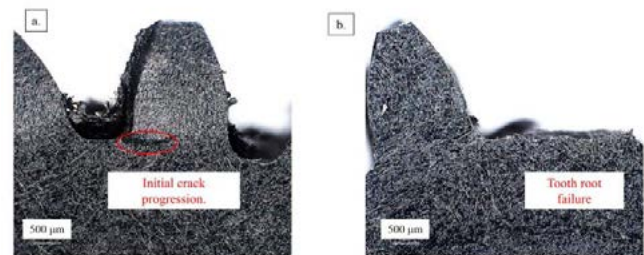


Figure 2: Meshing temperature versus lifetime in load cycles for two groups of load levels, a. 1.5 Nm and 1.4 Nm and b. 1.3 and 1.2 Nm.

The superior performance is attributed to the higher thermal conductivity of the carbon fibers, which enables more efficient heat dissipation from the meshing zone. This reduces thermal degradation of the polymer matrix and preserves mechanical properties. Furthermore, the carbon fibers provide greater

bending stiffness, leading to better dimensional stability of the teeth under load.

The failure modes differed significantly between the two materials. At high torques, the PA66 HT gears failed due to thermal overloading, which caused severe plastic deformation and localized melting of the teeth. At lower torques, the failure was characterized by micropitting and tooth root fracture due to fatigue. In contrast, the dominant failure mechanism for PA66 CF20 HT gears across all load levels was progressive fatigue and wear, without the catastrophic thermal failure seen in the unreinforced gears. The carbon fibers effectively mitigated localized heat accumulation, allowing the gear to withstand higher loads for longer durations. Figure 3 presents a typical failure mechanism (Figure 3a) and failure mode (Figure 3b) for carbon reinforced polyamide gears.



b. Failure mode of PA6 CF20 HT gear.

Conclusions

This research empirically validated the significant advantages of using short carbon fiber reinforcement in Polyamide 66 gears for demanding applications. The key conclusions are as follows:

- Carbon fiber reinforcement extended the fatigue life of PA66 gears by up to 86%, with the greatest benefits observed at lower and medium torque levels.
- The performance improvements are a direct result of the carbon fibers enhancing thermal conductivity for better heat dissipation and increasing bending strength, which leads to greater tooth stability and reduced strain.
- The results confirm that PA66 CF20 HT is a robust material solution capable of overcoming the inherent limitations of generic polymers, making it highly suitable for advanced, high-performance drivetrain systems in e-mobility and other industrial sectors.

ACKNOWLEDGEMENTS. This work was supported by the Government of the Republic of Slovenia and the European Union under the European Regional Development (C3330-18-952014). The results of this project were co-financed by the Republic of Slovenia through the EUREKA initiative (C2130-22-090023).

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Vpliv napihljive vratne blazine na poškodbene parametre vratnih vretenc v skladu s standardom CEN/TS 17342

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Napihljiva zračna blazina kot predmet pasivne zaščite, nameščena okrog vratu motorista ali kolesarja ima za cilj zmanjšanje tveganja poškodbe vratu in vratnih vretenc, do katerih pride pri trčenjih z drugimi vozili ali objekti ob cestišču. Cilj je preprečitev oziroma zmanjšanje premikov in rotacij glave napram telesu, kjer lahko pride do trajnih posledic ali smrti. Ceste so zaščitene z varnostno ograjo, ki je pritrjena v tla s stebrički. V tem prispevku je izvedena simulacija uporabe zaščitne opore za vrat in vratne vretence, kjer so primerjane razlike parametrov po standardu CEN/TS 17342, ki se uporabljajo pri tovrstnih poškodbah.

Uvod

Rast prebivalstva, pospešena urbanizacija, turizem in spletno trgovanje v svetu, so pripeljali do povečanja svetovnega prometa. Razvoj prometne infrastrukture je v preteklih desetletjih doživel velik napredek, prometni problemi pa še naprej naraščajo [1-3].

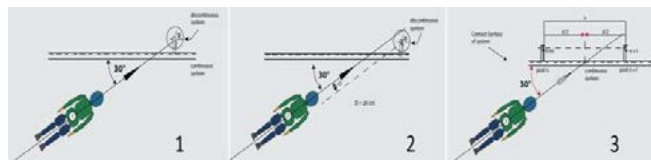
Poškodbe v cestnem prometu predstavljajo osmi najpogostejši vzrok smrti na svetovni ravni in so tudi vodilni vzrok smrti med mlajšimi odraslimi, starimi med 15 in 29 let [4]. Po podatkih svetovne zdravstvene organizacije so v več kot polovici prometnih nesreč udeleženci pešci, kolesarji in motoristi, od tega predstavljajo pešci in kolesarji (približno 26%), ter motoristi približno 28% vseh smrtnih izidov [5].

Statistika poškodb nadalje kaže da je bilo 62.2% vseh poškodb na medeničnem obroču ter poškodb glave in vratu s 27.8% deležem. Večina raziskav in študij pa nakazuje na 'šibko točko' - vratne vretence kot najpogostejši vzrok poškodbe in smrt [6]. Ker se voznik motornega kolesa pri udarci oz. Padcu loči od motornega kolesa, je bila ideja razviti zaščito, ki bi bila pritrjena neposredno nanj. Cilj je da bi se s takšno zaščito preprečili nenadni gibi glave in vratu napram telesu. Tudi v preteklosti je bilo razvitih nekaj modelov take vrste zaščite [7]. Glede na delež poškodb je bil cilj razviti zaščito s katero se ustvari trdnjša in bolj toga vez med glavo in telesom kot dvema masnima telesoma, povezanimi z vratom. Zaščita mora izpolnjevati določene pogoje. Ne sme ovirati gibanje glave napram telesu, imeti mora čim nižjo težo, delovati mora neodvisno od položaja telesa in se aktivirati v trenutku pred samim trčenjem. V nadaljevanju bo predstavljena razvita zaščita za vrat, ki je plod lastnega razvoja in simulirana z numerično simulacijo. Simulacija se izvede s pritrjeno zaščito na lutko HIBRID; enkrat s pritrjeno zaščito in drugič brez zaščite s pomočjo programa LS-Dyna.

Metode dela

Numerično testiranje

V realnih nesrečah ima lahko telo voznika različne pozicije in doseže različne položaje v času trka z oviro ali nasproti stoječim objektom. Zato je bilo numerično simuliranje izvedeno v skladu s standardom CEN/TS 17342, ki predpisuje tri različne tipe standardiziranih konfiguracij naleta lutke v nasproti stoječo zaščitno ograjo (Slika 1). Prvi dve konfiguraciji se nanašata na diskontinuirane sisteme, kjer lutka udari bodisi neposredno v stebel ali med dvema stebroma. Simulacija je bila izvedena po tretji konfiguraciji, ki simulira trčenje v zaščitno ograjo med obema podpornima stebroma (Slika 1).



Slika 1: Tipi testiranja po standardu CEN/TS 17342

Standard kot osnovo za določitev poškodb, predpisuje HIC (Head Injury Criterion) faktor, ki temelji na rezultanti smernih pospeškov. Za določevanje varnosti v skladu s standardom CEN/TS 17342 je najbolj primeren faktor HIC36 (za časovni interval do 36ms). Za prvi interval je vrednost HIC36 omejena na 650 in za drugi razred na 1000 (Tabela 1).



Slika 2: Predstavitev sil in momentov.

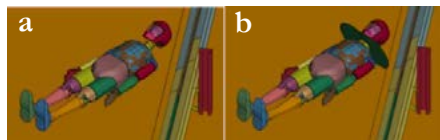
Severity level		Maximum admissible values					
		Head			Neck		
		F_x N	$F_{y,z}$ N	$F_{x,y,z}$ N	MOC Nm	MOC _{combined} Nm	MOC _{flex} Nm
I	650	Fig. 7 of TS 17342	Fig. 8 of TS 17342	Fig. 9 of TS 17342	134	42	190
II	1 000	Fig. 10 of TS 17342	Fig. 11 of TS 17342	Fig. 12 of TS 17342	134	57	190

Tabela 1: Dopustni vrednosti momentov in maksimalnih poškodbenih faktorjev na glavo in vrat.

Numerične simulacije – model opornice

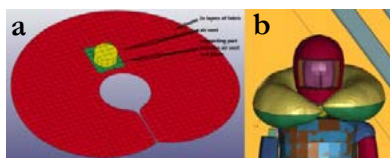
Model opornice je razvit in zasnovan za nošenje okrog vratu, (Slika 4), je elipsoidne oblike z nekoliko širšim stranskim delom, ki omogoča boljšo oporo in povezavo glava-ramena. Na sprednjem delu (pri bradi) prekinjena. Izdelana je iz dveh plasti tkanine in zračne šobe na zadnje delu. Napihovanje mora

biti simetrično (leva/desna stran). V napihnjenem stanju opornica ne sme pritiskati na vrat, glavo ali čelado.



Slika 3: (a) Lutka HYBRID III brez opornice in (b) z vratno opornico.

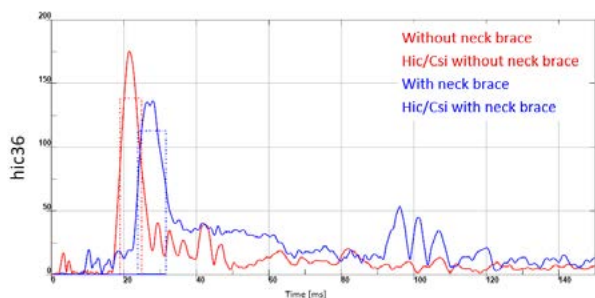
Model opornice je simuliran s pomočjo SPH (Smooth Particle Hydrodynamics) s katero se doseže bolj realistična simulacija dinamike vpihnjenega zraka med procesom napihovanja opornice. Vpihani zrak je sestavljen iz diskretnih zračnih delcev (vsak s svojo maso, tlakom in hitrostjo) med katerimi prihaja do medsebojne interakcije, kar zagotavlja ohranjanje masnega toka in momenta. Metoda je predvsem primerna za nagle in hitre ekspanzije, pretoke skozi šobe in hitre premike večjih količin plinov. Zračni SPH delci tako v interakciji z mehko tkanino bolj realistično popišejo fizični proces napihovanja tkanine in njeno obnašanje ob potiskanju zraka.



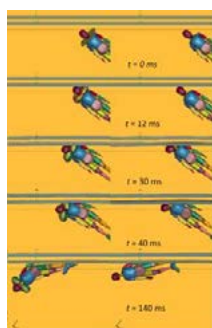
Slika 4: (a) Model opornice v neaktiviranem stanju in (b) model nameščen na lutko HYBRID III.

Rezultati in diskusija

Numerični rezultati modela opornice so pokazali očiten zaščitni vpliv na glavo in vrat. Vratna opornica kaže na znižanje faktorja HIC36 za 23% (Slika 5), in do trikratno znižanje kompresijske sile F_z in momenta okrog x osi - M_x , kar ima za posledico znižanje upogibnih momentov.



Slika 5: HIC36 faktor z uporabo in brez vratne opornice.



Slika 6: Vizualna primerjava časovnega poteka naleta lutke v zaščitno ograjo z in brez opornice.

Zaključki

Numerična simulacija vratne opornice na lutki HYBRID III (Slika 5), je pokazala predvsem znižanje poškodbenih parametrov HIC36 in upogibnih momentov okrog x in y osi (M_x in M_y), medtem ko so sile v x smeri ostale skoraj nespremenjene. Rezultati analize se skladajo z raziskavami, ki kažejo na vratni del hrbtenice kot pogosto mesto resnih poškodb pri nesrečah z motorji [8]. Pozitivni učinki uporabe vratne opornice pa se skladajo z varnostnimi cilji, opredeljenimi v standardu CEN/TS 17342, kjer se uporaba vratne opornice smatra kot učinkovit ukrep k zmanjšanju tveganja za poškodbo, hkrati pa ti učinki povečujejo potencial in možnosti za nadaljnji razvoj, testiranja in bolj podrobne eksperimente na področju implementacije takšne vrste zaščitne opreme v promet.

ZAHVALA. Javni agenciji za raziskovalno dejavnost RS, ki je delno financirala raziskavo sklopu raziskovalnega programa "Modeliranje v tehniki in medicini (P2-0109).

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Karakterizacija utrujanja in obrabe PEEK polimernih zobnikov s ta-C in a-C:H DLC prevlekami

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DLC prevleke predstavljajo potencialno rešitev za izboljšanje življenjske dobe polimernih zobnikov. Raziskava ovrednoti utrujanje in obrabo PEEK polimernih zobnikov, prevlečenih s ta-C in a-C:H DLC prevlekami z debelino 5 μm . Zobniki so podvrženi ubiranju v zobniškem paru pri navoru 1,8 Nm v klimatsko nadzorovani okolici.

Mehanizmi poškodb zobnikov vključujejo iniciacijo in rast bočnih in korenskih razpok do loma, z manjšo stopnjo obrabe bokov. Kljub temu, da se DLC prevleke obrabijo relativno zgodaj, v primerjavi z osnovnim materialom izkazujejo prevlečeni PEEK polimerni zobniki povprečno dvakrat daljšo življenjsko dobo. DLC ta-C in a-C:H prevleke torej znatno izboljšajo zmogljivost PEEK polimernih zobnikov in njihov potencial za zahtevne inženirske aplikacije.

Uvod

Zobniki v naprednih pogonskih sistemih zahtevajo lahke in robustne materiale. To je v zadnjih desetletjih vodilo v vse pogostejšo uporabo polimernih zobnikov kot nadomestek za jeklene zobnike, kljub kompromisom v zmogljivosti. Istočasno so napredki v znanosti površin vodili v razvoj prevlek, ki izboljšujejo zmogljivost polimernih in kovinskih komponent. Razvite prevleke so dokazale sposobnost znižanja trenja in izboljšanja obrabne odpornosti, kar je vodilo v podaljšanje življenjske dobe inženirskih komponent [1]. Posebno znane so postale DLC prevleke (ang. Diamond-Like Carbon), ki izkazujejo znatno odpornost v okoljih, kjer se pojavlja intenzivna obraba strojnih delov [2].

Številne raziskave DLC prevlek so se primarno osredotočile na kovino kot osnovni material, kljub temu pa so določene študije razširile uporabo DLC prevlek na visokozmogljive termoplaste, kot je npr. PEEK [3]. Raziskave, ki preučujejo polimerne zobnike s prevlekami pa so relativno redke [4,5].

Cilj obstoječe raziskave je zato preučiti zmogljivost in življenjsko dobo PEEK polimernih zobnikov s ta-C in a-C:H prevlekami, ki bi se lahko uporabili v naprednih zobniških pogonskih sistemih.

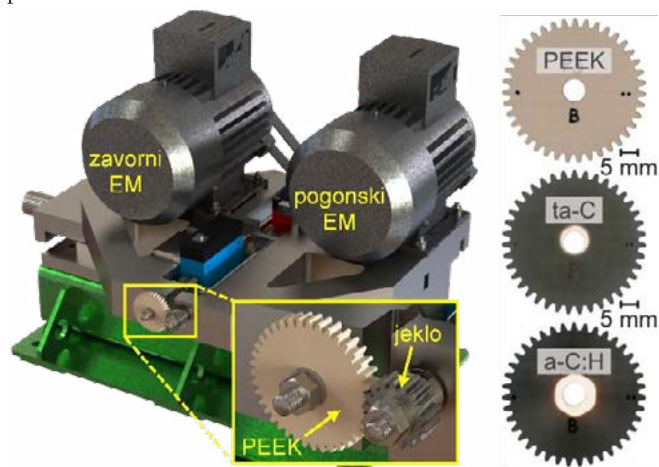
Materiali in metode

Kot osnovni material zobnikov je bil izbran delno kristalinični SustaPEEK polimer. Gre za visokozmogljivi termoplast, ki nudi visoko trdnost, žilavost in odlično obrabno odpornost. Polimerni zobniki so bili izdelani s postopkom odvalnega rezkanja iz okrogle palice s premerom 50 mm. Geometrija zobnikov je bila določena v skladu s priporočili VDI 2736 Part 4, ki določajo pogoje preizkušanja termoplastičnih zobnikov. Izbrana je bila 'Size 1' geometrija zobnikov.

Prevleke so bile na PEEK polimerne zobnike nanešene v debelini 5 μm . Prevleka ta-C je bila nanešena s tehnologijo fizičnega parnega nanosa (PVD), prevleka a-C:H pa s tehnologijo kemijskega parnega nanosa s pomočjo plazme (PACVD). Prevleka ta-C je primarno sestavljena iz sp^3 strukture ogljika, ki nudi visoko trdoto in odlično obrabno odpornost. Prevleka a-C:H izkazuje mešano sp^2/sp^3 strukturo ogljika, vključno z vodikom, kar rezultira v nekoliko nižji trdoti in obrabni odpornosti.

Referenčni testi zobniških dvojic so bili izvedeni na posebnem preizkuševališču, ki je bilo zasnovano v laboratoriju LeCAD, UL FS. Preizkuševališče zobnikov je prikazano na Sliki 1. PEEK polimerni zobniki in zobniki s prevlekami so ubirali v paru z referenčnim jeklenim zobnikom iz jekla 42CrMo4, ki je bil termo-kemijsko obdelan s plazmanitriranjem do visoke trdote površine. Ker pride na polimernih zobnikih do porušitve zob preden se na jeklenemu zobniku pojavijo znatne poškodbe, se variacije v življenjski dobi polimernih zobnikov lahko pripiše razlikam v lastnostih osnovnega materiala in ta-C ter a-C:H prevlek.

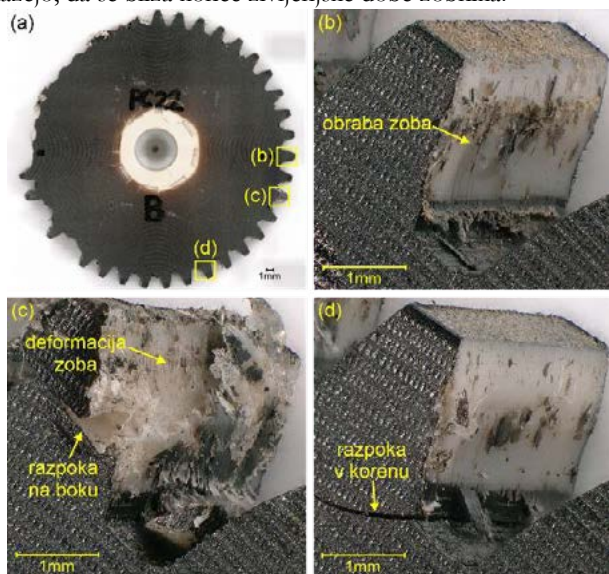
Zobniki so bili testirani pri navoru 1,8 Nm. Opravljene so bile tri ponovitve za polimerne zobnike iz osnovnega materiala, in za zobnike, prevlečene s ta-C in a-C:H prevlekami. Vsi preizkusi so potekali brez mazanja. Pogonski jekleni zobnik je obratoval pri 1592 obr/min, gnani polimerni zobnik pa pri 694 obr/min, kar rezultira v okvirno 10^6 ciklov na 24 h za polimerni zobnik. Preizkusi so bili izvedeni v klimatski komori s temperaturo $18 \pm 2^\circ\text{C}$ in z relativno vlažnostjo zraka $50 \pm 10\%$. Posamezen test se je zaključil, ko so tri zaporedne meritve navora padle pod 15 % nominalne vrednosti 1,8 Nm, kar je nakazovalo nezmožnost nadaljnjega prenosa bremena zaradi porušitve zob.



Slika 1: LeCAD preizkuševališče polimernih zobnikov in vzorci iz osnovnega materiala ter s ta-C in a-C:H prevlekami.

Rezultati in diskusija

Mehanizmi porušitve polimernih zobnikov so odvisni od lastnosti materiala in od obremenitve na širino zoba. Tipične poškodbe preizkušancev so prikazane na Sliki 2(a)-(d). Poškodbe so podobne za PEEK polimerne zobnike in za zobnike z DLC prevlekami. Zobniki iz osnovnega materiala primarno izkazujejo bočne lome zob, zobniki z DLC prevlekami pa izkazujejo bolj enakomerno razporejeno kombinacijo bočnih in korenskih lomov zob. Kot je razvidno iz Slike 2(b), je obraba zob relativno nizka, z akumulacijo ostankov prevleke na boku zob. Glavni mehanizem porušitve zob preizkušancev je utrujenostni lom. Do iniciacije razpok na boku zob pride zaradi visokih kontaktnih napetosti s superpozicijo strižnih in upogibnih napetosti. Razpoke rastejo do loma zoba, čemur lahko sledi tudi deformacija zoba, kot je prikazano na Sliki 2(c). Na Sliki 2(d) je prikazana razpoka v korenu zoba, ki nastane zaradi visokih upogibnih napetosti in vodi v korenski lom zoba. Polimerni zobnik lahko nosi breme tudi z nekaj manjkajočimi zobmi, vendar lomi posameznih zob kažejo, da se bliža konec življenjske dobe zobnika.



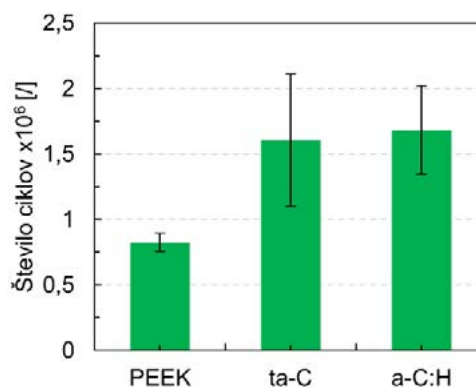
Slika 2: PEEK polimerni zobnik z A-C:H prevleko po porušitvi pri $1,48 \cdot 10^6$ ciklih (35,5 h).

Število ciklov do porušitve PEEK polimernih zobnikov in zobnikov z DLC prevlekami je prikazano na Sliki 3. Zobniki s ta-C in a-C:H prevleko izkazujejo okvirno dvakrat daljšo povprečno življenjsko dobo ($1,61 \cdot 10^6$ in $1,68 \cdot 10^6$ ciklov), kot zobniki brez prevlek ($0,82 \cdot 10^6$ ciklov).

Zobniki brez prevlek izkazujejo relativno nizko standardno deviacijo števila ciklov do porušitve, ki pa se poveča pri zobnikih s ta-C in a-C:H prevleko. V splošnem daljšo življenjsko dobo spremljajo večje deviacije življenjske dobe. Zobniki, ki odpovejo relativno hitro, običajno odpovejo zaradi utrujanja in nastanka lomov. Pri zobnikih z daljšo življenjsko dobo pa je bolj izrazita obraba zob. Poleg tega na število ciklov do porušitve močno vplivajo variacije v kakovosti in enakomernosti nanosa prevleke. Lokalne nepravilnosti v prevleki na vsaj enem zobu lahko služijo kot mesta iniciacije poškodb, kar učinkovito izniči prednosti prevlek. Zob z defektno prevleko je šibka točka in na njem lahko pride do iniciacije razpok in loma pri podobnem številu ciklov, kot pri zobu brez prevleke. Zgodnji lom zoba nato poveča

obremenitve na sosednjih zobeh, kar v končni fazi vodi v nove lome in odpoved zobnika.

Numerične analize polimernih zobnikov s prevlekami kažejo, da prevleke z večjo debelino in z visokim modulom elastičnosti zmanjšujejo deformabilnost zob med ubiranjem [6]. Glede na to, da je bil utrujenostni lom glavni mehanizem porušitve preizkušancev, so ta-C in a-C:H prevleke znatno prispevale k povišanju povprečne življenjske dobe zobnikov. Prevleke so zelo verjetno povišale togost zob in odpornost na rast utrujenostnih razpok, vendar pa so za končno potrditev potrebni dodatni eksperimenti glede deformacije zob.



Slika 3: Število ciklov do porušitve za PEEK polimerne zobnike in za zobnike z DLC prevlekami.

Zaključki

Raziskava je analizirala zmogljivost PEEK polimernih zobnikov s ta-C in a-C:H DLC prevlekami. Zobniki so bili preizkušeni v referenčnem paru z jeklenim zobnikom pri navoru 1,8 Nm. Vsi preizkušanci so izkazovali podobne mehanizme porušitve, to je bočne in korenske lome z manjšo stopnjo obrabe bokov. Obrabna odpornost DLC prevlek je bila relativno omejena, saj so prevleke v zahtevnih kontaktnih pogojih drsenja in kotaljenja razpadle zgodaj v življenjski dobi zobnika. Kljub temu so DLC prevleke okvirno podvojile življenjsko dobo zobnikov iz osnovnega materiala PEEK.

Polimerni zobniki s ta-C in a-C:H prevleko so izkazali podobno življenjsko dobo. Zobniki s prevleko a-C:H so povzročili znatno manjšo obrabo na referenčnih jeklenih zobnikih in s tem izkazali svojo prednost. Za praktične aplikacije polimernih zobnikov s prevlekami je treba zagotoviti visoko kakovost adhezije in enakomerno debelino prevlek, saj lahko lokalne napake na posameznih zobeh znatno skrajšajo življenjsko dobo zobnikov z DLC prevlekami. Za oceno obrabne odpornosti prevlek pri nizkih obremenitvah zobnikov pa so potrebne dodatne raziskave.

ZAHVALA. Raziskavo je delno financirala Javna agencija za znanstvenoraziskovalno in inovacijsko dejavnost Republike Slovenije (ARIS) v okviru raziskovalnega programa P2-0425: Decentralizirane rešitve za digitalizacijo industrije ter pametnih mest in skupnosti.

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The Effect of Contact Area Between Uncoated/Anodised Aluminium Alloy 6082 and Copper on Galvanic Corrosion in Chloride Medium

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Galvanic corrosion between AA6082 and copper accelerates aluminium degradation in corrosive environments, which is influenced by the cathode-to-anode area ratio. This study assessed anodisation's effectiveness in minimising this issue through exposure tests in NaCl solution and salt spray chamber (ASTM B117). For uncoated AA6082, increasing the cathode size from ½ to 2 reduced aluminium volume retention from 90 % to 88 % and mass retention from 91 % to 89 %, confirming the importance of cathode area. In contrast, anodised AA6082 exhibited stable behaviour independent of cathode size, maintaining more than 95 % of its volume and mass with minimal damage. These results demonstrate that anodisation significantly reduces galvanic corrosion but also eliminates the influence of cathode size, thereby enhancing material durability.

Introduction

Galvanic corrosion is a significant challenge in engineering applications with dissimilar metals such as aluminium alloys and copper [1]. Wrought aluminium alloys (AA), such as 6082, are particularly susceptible due to their heterogeneous microstructure and microgalvanic coupling between phases [2]. In corrosive environments, aluminium, as the less noble metal, corrodes preferentially, reducing structural integrity. A specific factor influencing the severity of galvanic corrosion is the cathode-to-anode area ratio, which significantly intensifies corrosion in uncoated aluminium–copper couples [3]. Mitigation strategies include breaking the electrical connection or protecting the anodic surface with coatings or treatments [4]. Among these, anodisation is effective, as it forms a stable (Al₂O₃) oxide film that shields the metal and reduces galvanic interaction. The successful protective effect of anodising has also been confirmed in a previous study [5].

Materials and methods

Aluminium alloy (AA)6082 and a high-purity copper (99.9 wt.%), both provided by Ludwig Leiner KG, were employed as a substrate. The cylinders of AA6082 measured 13.1 mm × 9.4 mm. Copper cylinders representing half the volume had dimensions 13.1 mm × 6.8 mm, while those representing double the volume had dimensions 13.1 mm × 11.4 mm. The contact surfaces of the specimens were mechanically ground with silicon carbide papers of 1200, 2400,

and 4000 grit to obtain a uniform surface. Grinding residuals were removed by ultrasonic cleaning in ethanol, followed by rinsing and drying under compressed nitrogen. AA6082 specimens were anodised (carried out in sulfuric acid solution and sealed in hot water), producing a ~10 µm thick oxide film. Accelerated corrosion testing in salt spray was performed in a KÖHLER HKT 750 BASIC-LINE salt spray chamber (0.750 m³), operated in accordance with ASTM B117-22 (a NaCl solution (50 ± 1 g/L) and maintenance at 35 ± 1 °C). Three-dimensional surface characterisation was carried out using a Zeiss METROTOM 800/225kV HR X-ray system.

Results and discussion

Figure 1 presents optical images obtained after 1000 hours of salt spray testing, providing a clear comparison between (a, b) untreated and (c, d) anodised AA6082 coupled with copper.

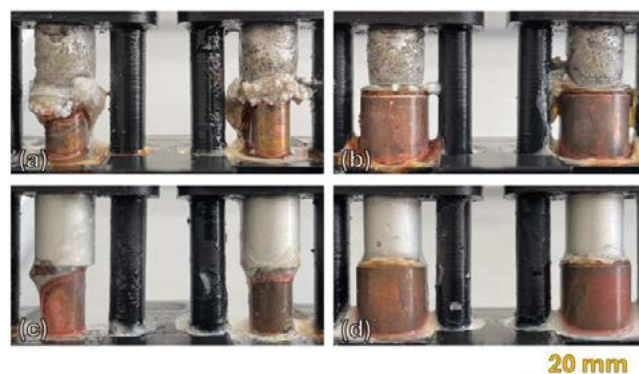


Figure 1: Results of corrosion testing after 1000 hours in a salt spray chamber (ASTM B117). Untreated AA6082 coupled with copper with (a) half, (b) with double cathode size and anodised AA6082 coupled with copper with (c) half and (d) with double cathode size.

Figure 1 shows the formation of a large amount of corrosion products on unprotected pairs: (a) with the cathode being half the size, and also on (b) with the cathode being doubled. On the other hand, for the pairs protected by anodisation, where the cathode is (c) half the size and (d) twice as large, much less corrosion products were observed after exposure in the salt spray chamber for 1000 hours.

After removal of corrosion products, the optical images of the corrosion testing in a salt spray environment (after 1000 hours) are presented in Fig. 2. The results reveal significant differences between untreated and anodised AA6082 when coupled with

THE EFFECT OF CONTACT AREA BETWEEN UNCOATED/ANODISED ALUMINIUM ALLOY 6082 AND COPPER ON GALVANIC CORROSION IN CHLORIDE MEDIUM

copper, with the variation also clearly influenced by the cathode size. Figure 2 (a,b) shows the AA6082 alloy coupled with copper. Due to galvanic corrosion, the cylinder diameter was reduced from 13.1 mm to 7 and 8 mm. Corrosion progressed laterally up to 9 mm, while the twice the cathode area showed a 12 mm depth. The copper diameter remained unchanged, confirming that AA6082 serves as the anode. Figure 2 (c,d) presents coupling anodised aluminium with copper. The anodised alloy retained a diameter of about 7 mm, but corrosion had progressed to a depth of 1.5 mm. The anodised pair with twice the cathode area showed a smaller diameter (6 mm) and similar corrosion progression (2 mm). The diameter of copper again remained unchanged.

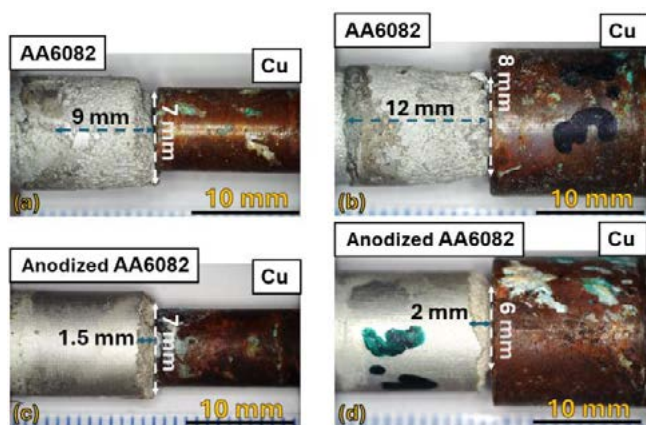


Figure 2: Results of corrosion testing after 1000 hours in a salt spray chamber (ASTM B117). Untreated AA6082 coupled with copper with (a) half, (b) with double cathode size and anodised AA6082 coupled with copper with (c) half and (d) with double cathode size.

Additionally, the cylinder volumes were evaluated using Computed Tomography (CT), as shown in Figure 3.

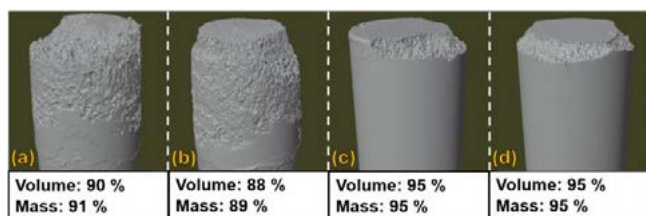


Figure 3: 3D scanning results of volume retention: untreated AA6082 coupled with copper with (a) half, (b) with double cathode size and anodised AA6082 coupled with copper with (c) half and (d) with double cathode size.

The untreated AA6082, coupled with copper covering half the cathode area, retained 90% of its volume and 91% of its mass. For pairs coupled with copper twice the cathode area, the untreated AA6082 retained 88 % of its volume and 89 % of its mass. On the other hand, the anodised pair retained 95 % of its volume and 95 % of its mass, regardless of the size of the copper cathode. In all cases, the copper volume, despite aluminium corrosion, remained unchanged.

The galvanic corrosion mechanism between AA6082 and copper in a Cl^- environment involves anodic and cathodic reactions. Figure 4 illustrates the scheme of galvanic corrosion

for anodised AA6082 coupled with copper. The protective oxide (Al_2O_3) film formed by anodisation uniformly covers the aluminium surface (including intermetallic particles), preventing their direct exposure to the electrolyte and thus preventing localised dissolution. Corrosion mainly develops at the interface regions where the passive (anodised) films (marked with x and z) are less protective.

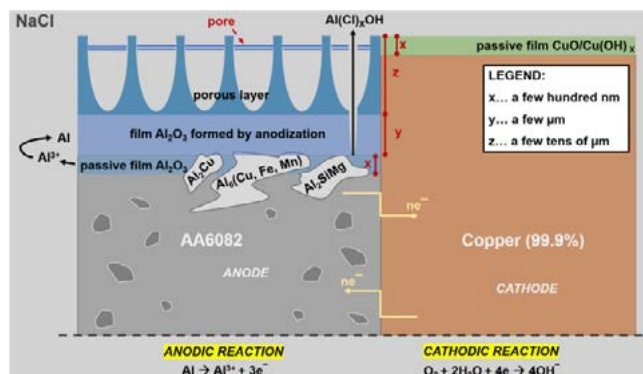


Figure 4: The scheme of the galvanic corrosion between anodised AA6082 and copper in corrosive medium ($\text{NaCl}_{(\text{aq})}$).

Conclusions

The galvanic connection between AA6082 and copper results in aluminium acting as the anode and copper as the cathode. The main conclusions are:

- The influence of cathode size is evident only in the uncoated Al–Cu couple, where a larger cathode accelerates aluminium corrosion.
- In anodised AA6082, this effect is reduced, as the anodised oxide layer minimises the electrochemical potential difference at larger cathode-to-anode ratios.
- 3D scanning confirmed that anodised AA6082 retained more than 95% of its volume and mass after 1000 hours, regardless of cathode size.

The results demonstrate that anodising AA6082 is highly effective at minimising the galvanic corrosion with copper (almost independent of cathode area) and preserving the integrity of the aluminium alloy.

ACKNOWLEDGEMENTS

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Determining the environmental impact of electricity generation on an hourly basis using life cycle assessment methodology

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Electricity use significantly contributes to the environmental impact of products and processes. Due to variation in the shares of electricity production sources in countries, there are significant variation in their environmental impact profile if hourly composition is taken into account. Relying on annual averages of electricity sources composition can lead to over- or underestimation of environmental impact. Croatia has a significantly higher share of wind generation and a lower share of photovoltaics electricity generation compared to Slovenia. Life cycle assessment studies using hourly electricity production profiles are still not common. Such studies can contribute towards implementing strategies for off-peak emissions charging in the case of battery electric vehicles. A considerable variation in the impact category of climate change throughout the average year can be observed in analyzed countries. The study shows that the highest daily values of GHG emissions can vary depending on the electricity mix composition and are country-specific.

Introduction

The use of electricity is a factor that significantly contributes to the environmental impact of products and services. Recently, the number of life cycle assessment (LCA) studies on electricity systems has increased [1]. LCA studies have focused on the composition of energy sources in the electricity systems of Italy, Spain, Portugal, the United Kingdom, Ecuador, and Slovenia, as well as modeling the increase in the share of renewable energy sources (RES) in the system [2]. The results showed that scenarios with higher shares of RES had a lower impact on global warming [2]. Most studies are still focused on the average annual composition of the shares of individual sources in the electricity system. Relying on annual averages can lead to inaccurate assessments of environmental impact [3], [4].

Since electricity is typically generated using different production technologies, variations in hourly emissions depend not only on the technologies used but also on their shares within a given time unit. Because technologies have very different emission factors, the potential for large variations in the emissions of generated electricity is high [2]. Since the use of electricity often stands out as the largest contributor to the environmental impact of a system, research has shown that the electricity mix heavily influences the LCA of BEVs. For example, it has been shown that greenhouse gas (GHG) emissions per kilometre driven in a BEV could decrease by 50% due to the expected

reduction in the carbon intensity of the European electricity mix [5]. For Slovenia and Croatia, information on the environmental impacts of electricity mix scenarios is still scarce and requires further research. Recently, in a study published by [6], the increase in the share of photovoltaics (PV) in Slovenia led to a 30.3% reduction in the global warming potential (GWP) impact category by 2050. Green scenarios, which also included a phase-out of coal, led to even greater reductions. The results showed that the reduction in the GWP impact category was 80.5% compared to the baseline scenario. PV systems have minimal environmental impact during operation. However, their growing share in electricity generation has led to higher values in the mineral resource scarcity impact category. Hourly data would enable emission-based load shifting, offering greater potential for reducing GHG emissions. Data on the environmental impact of electricity are particularly important for policy planning, as they provide the basis for assessing how national generation portfolios align with sustainability targets [2].

Materials and methods

In a recent study [2], methodology from Nauman et al. was used to determine the global warming potential of Slovenia and Croatia electricity production system on an hourly basis for the 2020 – 2024 period. Time-resolved data on an hourly basis were used for a dynamic retrospective approach to the LCA of electricity generation [3]. Methodology from Nauman et al. was used to determine the global warming potential of Slovenia and Croatia electricity production system on an hourly basis for the 2020 – 2024 period [2], [3]. The data were downloaded from the publicly available ENTSO-E Transparency platform which provides information on generation, load, transmission, and balancing data for European countries [7].

For the LCA studies of electricity generation most common functional unit used is 1 kWh of electricity produced [8]. Environmental Footprint (EF) method was used [2], [3]. Time series data were generated and linked to the appropriate datasets of Ecoinvent 3.11. LCI database (see Fig 1). When available, country-specific datasets were applied for Slovenia (SI) and Croatia (HR) [2].

For illustration purposes, the climate change (CC) impact category are shown. They are supported with the average, minimum, and maximum values, as well as the standard deviation (SD) and relative standard deviation (RSD), on an hourly basis across the year to assess the range of values and identify trends in the variability of the results [2], [3].

DETERMINING THE ENVIRONMENTAL IMPACT OF ELECTRICITY GENERATION ON AN HOURLY BASIS USING LIFE CYCLE ASSESSMENT METHODOLOGY

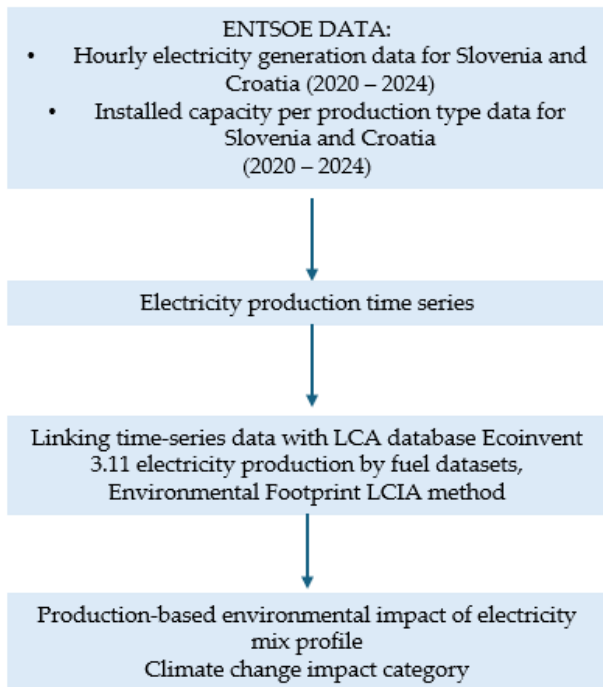


Figure 1: Methodological steps used in a recently published study [2].

Results and discussion

Slovenia's electricity mix is characterized by a high share of nuclear and hydro energy, while Croatia relies more on natural gas and hydro energy, with seasonal fluctuations linked to the availability of hydro resources and an increasing share of renewable energy sources. These differences result in unique hourly impact profiles within the climate change impact category, as illustrated for Slovenia and Croatia in Fig. 2. The lowest value for Slovenia was 0.096 kg CO₂ eq., with the highest being 0.474 kg CO₂ eq. The lower values in the impact category can be associated with a higher share of RES in the electricity mix, consistent with the available data for other countries [3].

The shift towards a higher share of renewable energy sources is considered one of the key strategies for decarbonizing the sector; however, solar and wind electricity generation exhibit significant inter-annual variations and inflexibility [9]. Variations are observed in the differences between the peak generation periods of wind and photovoltaic (PV) systems. Wind power generation is typically more productive in winter, while PV systems perform better in summer [3]. In the case of intermittent RES, Croatia has a significantly higher share of wind generation and a lower share of electricity generation than Slovenia [10]. Although the Krško Nuclear Power Plant (NEK) is jointly owned by Slovenia and Croatia [11], it is not included in the Croatian production profile, as NEK is geographically located in Slovenia [2]. Similar to the results in a study [2], a study by Naumann et al. showed that the lowest values for the climate change category coincided with the highest share of renewable production [3]. The daily variability in the climate change categories of a typical winter and summer day can also be observed and was shown in a recently published study [2].

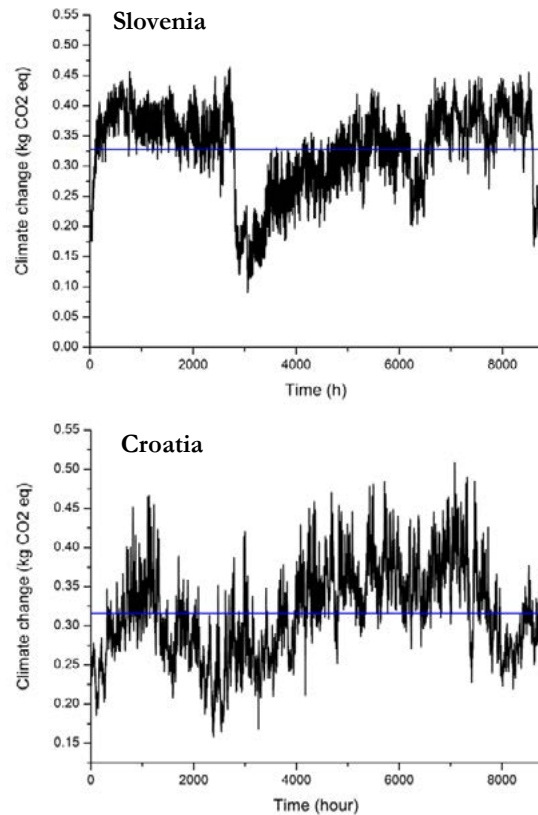


Figure 2: Time series of environmental impact categories of climate change in Slovenia (above) and Croatia (below). The average value is indicated by a blue line [2].

Conclusions

The climate change impact analysis showed that the highest value was 0.47 kg CO₂ eq. for Slovenia during times of low RES production. A similar pattern was observed in Croatia, with the highest observed value being 0.51 kg CO₂ eq [2]. Integrating dynamic profiles into the optimization of EV charging, demand response, and long-term capacity expansion highlights the importance of temporal electricity profiles [2].

ACKNOWLEDGEMENTS. The research was co-funded by the Slovenian Research and Innovation Agency (ARIS) through the annual work program of Rudolfovo.

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Eksperimentalna analiza učinkovitosti F9 filtrov in razvoj izboljšanega prototipa za napredne filtracijske sisteme

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V raziskavi je predstavljena eksperimentalna analiza učinkovitosti standardnih F9 filtrov, skladnih s standardom EN ISO 16890, ter razvoj izboljšanega prototipa za uporabo v sodobnih prezračevalnih sistemih. Uporabljena je bila merilna linija z laserskim spektrometrom GRIMM 11-D, razredčevalniki TOPAS, merilnikom tlaka ALMEMO in anemometrom TESTO. Rezultati kažejo razlike v učinkovitosti filtracije PM1 delcev in padcu tlaka med različnimi komercialnimi filtri. Na podlagi analiz je bil razvit izboljšan prototip filtra proizvajalca 3, ki je dosegel boljše ravnoesje med visoko učinkovitostjo in manjšim padcem tlaka, kar prispeva k višji energetski učinkovitosti celotnega sistema.

Uvod

Zrak v notranjih prostorih ima pomemben vpliv na zdravje in produktivnost uporabnikov, zato je filtracija trdnih delcev eden ključnih elementov prezračevalnih sistemov. Standard EN ISO 16890 omogoča klasifikacijo filtrov glede na učinkovitost pri zajemu delcev različnih velikosti (PM10, PM2.5, PM1) [1]. Filtri razreda F9, ki so namenjeni odstranjevanju finih delcev, morajo zagotavljati visoko učinkovitost in hkrati omejen padec tlaka zaradi vpliva na porabo energije ventilatorjev [2]. Namen raziskave je bil primerjalno preizkusiti standardne F9 filtre treh proizvajalcev ter razviti izboljšano konstrukcijo, ki bi omogočala povečano učinkovitost filtracije pri nižji tlačni razliki.

Raziskovalne metode

Eksperimentalni del raziskave je bil zasnovan za primerjalno analizo učinkovitosti treh standardnih F9 filtrov in razvoj izboljšanega prototipa po standardu EN ISO 16890. Meritve so bile izvedene na merilni liniji, ki omogoča natančno spremljanje padca tlaka, koncentracije delcev in vpliva pretoka zraka na učinkovitost filtracije.

Merilni sistem je vključeval generator aerosolov TOPAS ATM 226 kot vir delcev, dva razredčevalnika TOPAS pred merilnikom koncentracije aerosolnih delcev anemometer TESTO za določitev pretoka ter laserski spektrometer GRIMM 11-D, ki omogoča merjenje koncentracije delcev velikosti od 0,25 μm do 32 μm , ter merilnik tlaka ALMEMO za zajem tlačne razlike [3, 4].

Vsa tega od filtrov, treh proizvajalcev smo testirali, pri dveh različnih hitrostih pretoka, kar je omogočilo oceno vpliva pretoka na tlačno razliko in učinkovitost filtracije delcev PM1. Meritve so bile izvedene pri sobni temperaturi in ob spremljanju relativni vlažnosti. Podatki so bili zajeti v intervalih

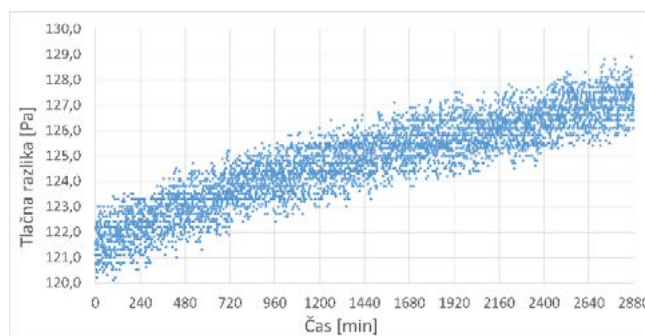
po 10 sekund, povprečeni ter obdelani v programskem okolju Excel.

Rezultati in diskusija

Raziskava je pokazala, da se med testiranimi filtri pojavljajo izrazite razlike v padcu tlaka in učinkovitosti filtracije.

V prvem deli raziskave so bili preizkušeni trije standardni F9 filtri različnih proizvajalcev. Posebna pozornost je bila namenjena primerjavi padcev tlaka, učinkovitosti filtracije aerosolnih delcev ter razliki v aktivnih filtracijskih površinah. Cilj meritev je bil določiti, kateri filter ima največji potencial za nadaljnjo optimizacijo.

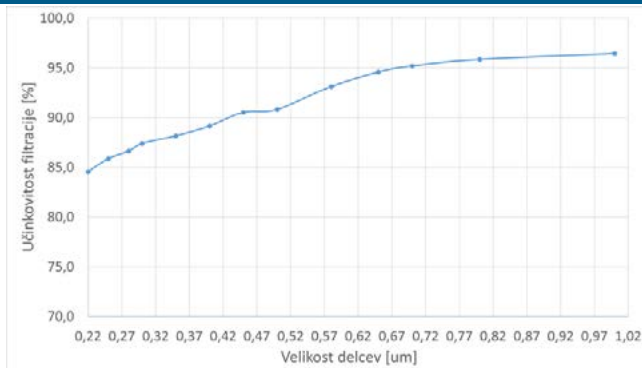
Slika 1 prikazuje potek tlačne razlike skozi čas za filter proizvajalca 3 z globina filtra 220 mm pri pretok 1150 m^3/h . V primerjavi z ostalimi filtroma je ta filter izkazal nekoliko višje tlačne razlike – med 121 in 129 Pa – kar je posledica večje gostote in debelejšje zložitve filtrirnega medija. Kljub temu je njegova aktivna filtracijska površina bistveno večja, kar omogoča izjemno visoko učinkovitost odstranjevanja finih delcev. Trend grafa kaže enakomerno rast padca tlaka v času, brez nenadnih odstopanj, kar potrjuje stabilno filtracijo in homogeno nalaganje delcev.



Slika 1: Tlačna razlika filtra proizvajalca 3 [5].

Slika 2 prikazuje učinkovitost filtracije glede na velikost delcev za isti filter proizvajalca 3. Dosežene so bile učinkovitosti 91 % za delce PM1, kar potrjuje skladnost z razredom F9 po standardu EN ISO 16890. V primerjavi z filtri ostalih proizvajalcev, je imel filter proizvajalca 3 najvišjo stopnjo filtracije PM1 delcev, kar je bil tudi ključni razlog, da je bil izbran za nadaljnjo razvojno nadgradnjo.

Zaradi svoje velike aktivne površine ponuja dobro osnovo za konstrukcijske spremembe, s katerimi bi bilo mogoče znižati padec tlaka in s tem povečati energijsko učinkovitost brez poslabšanja filtracijske zmogljivosti.



Slika 2: Učinkovitost filtracije glede na velikost filtriranih delcev za filter proizvajalca 3 [5].

Rezultati meritev so pokazali, da se pri vseh filterih z večanjem pretoka zraka pričakovano povečuje tlačna razlika.

Filtra proizvajalca 1 sta izkazala stabilno in enakomerno rast padca tlaka, s povprečno spremembo med 3 % in 5 %, kar potrjuje dober konstrukcijski dizajn in homogeno nalaganje delcev. Filtra proizvajalca 2 sta imela nekoliko nižjo spremembo tlaka (okoli 2 %), vendar pri tem ni bilo doseženih zahtev razreda F9. Filter proizvajalca 3 je kljub nekoliko višjim absolutnim tlakom (okoli 120–130 Pa) ohranjal enakomerno rast padca tlaka v času, kar kaže na stabilno delovanje in počasno mašenje filtrirnega medija.

Učinkovitost filtracije PM delcev se je pri vseh filterih gibala znotraj razreda F9, razen pri filterih proizvajalca 2, kjer so bile vrednosti nižje. Filtra proizvajalca 1 sta dosegala dobro ravnovesje med učinkovitostjo in padcem tlaka, medtem ko je filter proizvajalca 3 izstopal z najvišjo učinkovitostjo filtracije PM1 delcev, nad 91 %.

Sprememba hitrosti zraka v merjenem območju (750–1400 m³/h) ni imela izrazitega vpliva na učinkovitost filtracije, je pa povzročila pričakovano povečanje tlačne razlike. To potrjuje, da testirani filtri delujejo v območju optimalnega pretoka, kjer učinkovitost ostaja stabilna, energetska obremenitev pa narašča predvsem zaradi povečane hitrosti zraka skozi filtrirni medij.

Izboljšave filtrirnega sistema smo se lotili z optimizacijo obstoječega filtra proizvajalca 3, ki se je v predhodnih meritvah izkazal kot najbolj primeren za nadgradnjo. Cilj izboljšave je bil razviti energetsko učinkovitejši filter, ki bi ohranil visoko učinkovitost zajemanja aerosolnih delcev PM1, hkrati pa zmanjšal začetne tlačne izgube. Optimizacija je zajemala dve smeri: preučitev spremembe filtracijskega materiala in zmanjšanje aktivne filtracijske površine. V sodelovanju s proizvajalcem smo izdelali štiri prototipe filtrov – dva z materialom tipa 1 in dva z materialom tipa 2 – pri dveh različnih filtracijskih površinah (8,8 m² in 7,0 m²). Vse meritve so bile izvedene na enaki merilni liniji kot v prejšnjih testiranjih, pri konstantnem pretoku zraka 1200 m³/h.

Iz rezultatov lahko ugotovimo, da je bil z uporabo filtracijskega materiala tip 1 dosežen najboljši kompromis med padcem tlaka in učinkovitostjo filtracije. Zmanjšanje filtracijske površine z 14 m² na 8,8 m² je povzročilo znižanje padca tlaka za približno 28 % (s 157,9 Pa na 113,6 Pa), ob tem pa se je učinkovitost filtracije PM1 povečala na več kot 91 %. Natančnejše podatke lahko vidimo v preglednici 1.

Preglednica 1: Primerjava osnovnega in izboljšanih filtrov različnih materialov.

	Dolžina filtra	Filtracijska površina	Povprečni padec tlaka	Povprečne učinkovitosti filtracije delcev PM1
	[mm]	[m ²]	[Pa]	[%]
Prvotni filter - material tip 1	200	14	157,9	89,2
Filtracijski material tip 1	142	8,8	113,6	91,3
Filtracijski material tip 1	110	7	116,2	91,5
Filtracijski material tip 2	142	8,8	98,8	72,5
Filtracijski material tip 2	110	7	98,2	73,0

Potrjeno je bilo, da je mogoče z ustrezno izbiro materiala in optimizacijo geometrije filtra doseči znatno zmanjšanje tlačnega upora, ne da bi pri tem poslabšali kakovost filtracije. Filtri z materialom tipa 2 so sicer imeli najnižji padec tlaka (okoli 98 Pa), vendar je bila njihova učinkovitost filtracije prenizka (<75 %), zato niso primerni za uporabo v sistemih razreda F9.

Povzamemo lahko, da je filter z materialom tip 1 in filtracijsko površino 8,8 m² najprimernejša konfiguracija za nadaljnjo uporabo, saj združuje:

- visoko učinkovitost filtracije aerosolnih delcev PM1 (91 %),
- nižji padec tlaka (113,6 Pa) v primerjavi z izhodiščnim filtrom (157,9 Pa),
- ter izboljšano energetsko učinkovitost sistema ob ohranjeni kakovosti filtracije.

Zmanjšanje padca tlaka ob enaki učinkovitosti filtracije potrjuje, da lahko že z optimizacijo geometrije in strukture medija bistveno vplivamo na delovanje filtrirnih sistemov. Takšni rezultati pomenijo pomemben prispevek k razvoju trajnostno zasnovanih prezračevalnih sistemov z nižjo porabo energije.

Zaključki

Eksperimentalna analiza je pokazala, da se F9 filtri različnih proizvajalcev razlikujejo tako po učinkovitosti filtracije kot po padcu tlaka. Filter proizvajalca 3 se je izkazal kot najprimernejši za optimizacijo, saj združuje visoko učinkovitost filtracije in stabilno obratovanje.

Z razvitimi prototipi smo dokazali, da je mogoče z ustrezno izbiro filtracijskega materiala in geometrije filtra zmanjšati padec tlaka za približno 10 %, ob tem pa ohraniti visoko učinkovitost filtracije PM1 delcev. Rezultati potrjujejo, da optimizacija strukture filtrirnega medija bistveno poveča energetsko učinkovitost prezračevalnih sistemov, kar je ključno za njihovo dolgoročno trajnost.

V prihodnje bo raziskava usmerjena v spremljanje zamašitve filtrov in preučevanje njihove življenjske dobe v realnih pogojih obratovanja.

- [1] EN ISO 16890:2016. Air filters for general ventilation – Part 1: Technical specifications, Geneva (2016).
- [2] EN 779:2012. Particulate air filters for general ventilation – Determination of the filtration performance, Brussels (2012).
- [3] GRIMM Aerosol Technik. Portable Aerosol Spectrometer 11-D, Operating Manual (2020).
- [4] TOPAS GmbH. Aerosol generator ATM 226 and diluter series, Technical data sheet (2021).
- [5] Frumen, Ž. Eksperimentalna analiza učinkovitosti standardnih F9 filtrov in razvoj izboljšane prototipa, Magistrsko delo (2025).

Estimation of an Equivalent Excitation Model for a Dishwasher During Operation

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The purpose of virtual acoustic prototyping (VAP) is to evaluate a product's acoustic and vibration behaviour in a virtual environment before physical production. By simulating different design solutions and analysing their virtual dynamic responses, engineers can identify an optimal configuration early in the development process. This approach minimizes the need for multiple physical prototypes, thereby reducing both development time and costs.

A prerequisite for obtaining the response of the prototype in the virtual environment is knowing the excitation force provided by the source during operation. Real-like sources are notoriously difficult to model or measure directly. As an alternative, transfer path analysis (TPA) proposes an alternative force set that fully reproduces the effect of the operating source on the connected receiver structures. In this work, an equivalent force set is estimated for a Gorenje dishwasher (DW).

Introduction

The analysis of structural dynamics is an essential step in the development of high-tech mechanical systems. This requires the creation of experimental or virtual dynamic models of the system components, which are then assembled to evaluate the dynamic properties of the complete product. For modelling critical paths for the transmission of sound and vibration in an assembly, transfer path analysis is a reliable and effective tool. TPA replicates the source excitations using a set of equivalent forces between the source and the receiver structure of the assembly. Equivalent forces are an inherent property of the source and as such, are transferable to any assembly with a modified receiver, which makes them suitable for VAP.

This paper presents a workflow for estimating the equivalent excitation source for a Gorenje dishwasher (Fig. 1) during operation. The DW represents a complex vibroacoustic system with multiple excitation mechanisms, primarily due to the running pump and the water impact on the tub walls from the diverters. Given the source complexity, the operational forces cannot be directly measured or modelled. This work proposes an equivalent source applied to the DW tub that can substitute the original operational excitation. The approach combines measured operational responses with a numerically obtained response model of the DW. Measured responses provide the system's output during operation, while numerical response model describes how applied forces produce such responses;

using both enables the estimation of the unknown excitation forces that act as the equivalent source. The required workflow, challenges, and consistency of the estimation are discussed.



Figure 1: Gorenje dishwasher.

Theoretical background and notation

Vibroacoustic operational response of an assembly in a virtual environment is obtained as:

$$\mathbf{u}_3 = \mathbf{Y}_{31} \mathbf{f}_1, \quad (1)$$

where $\mathbf{u}_3$ is the response vector of the virtual prototype at the locations of interest (e.g. sound pressure next to the user's ear), $\mathbf{f}_1$ is the excitation force provided by the source in operation and $\mathbf{Y}_{31}$ is a matrix of transfer functions for the virtual prototype that relate responses $\mathbf{u}_3$ to the excitation $\mathbf{f}_1$.

However, dishwasher (or any complex source) in operation generates an input force $\mathbf{f}_1$ that is impossible to measure or model directly. Hence Eq. (1) cannot be directly applied to obtain the virtual assembly response. Instead, a quantity is needed that enables a complete description of the source for a given operating condition. A set of equivalent forces $\mathbf{f}_2^{\text{eq}}$ is introduced [1]:

$$\mathbf{f}_2^{\text{eq}} = (\mathbf{Y}_{42})^+ \mathbf{u}_4, \quad (2)$$

where $\mathbf{u}_4$ are the responses at the receiver side of the assembly (side without an active force in operation) measured while the assembly is in operation and $\mathbf{Y}_{42}$ is the matrix of transfer functions that relate $\mathbf{u}_4$ to the arbitrary excitation locations at the source denoted with subscript $(\star)_2$. The latter serves as equivalent excitation set. Eq. (2) estimates magnitude of the forces $\mathbf{f}_2^{\text{eq}}$ so they fully replicate $\mathbf{u}_4$.

Virtual responses at the locations of interest can now be expressed as:

$$\mathbf{u}_3 = \mathbf{Y}_{32} \mathbf{f}_2^{\text{eq}}. \quad (3)$$

Methodology

The object of this study is the Gorenje DW (Fig. 1) in operation, where the two main excitation sources can be attributed to the running pump and water hitting the DW tub from the lower and upper diverter. Due to the latter, the equivalent source is distributed all over the DW tub, which implies that the equivalent excitation acts in a large number of degrees of freedom (DoFs). This leads to a significant measurement effort in obtaining $\mathbf{Y}_{42}$ for all $(\star)_2$. Therefore, we decided to adopt $\mathbf{Y}_{42}$ from a validated numerical model of the DW, while $\mathbf{u}_4$ was measured using a scanning laser vibrometer.

Since the equivalent force set is a property of the source only and is invariant to any receiver substructure attached to it, the DW assembly was first simplified. All components not required to be attached to the DW for it to operate were physically decoupled from the source. This significantly improved accessibility for $\mathbf{u}_4$ measurement and reduced the effort required to obtain the validated numerical model.

The latter was validated against the experimentally obtained frequency response function (FRF) of the physical assembly. Fig. (2) demonstrates good agreement between the experimental and numerical FRFs, confirming the validity of the numerical model.

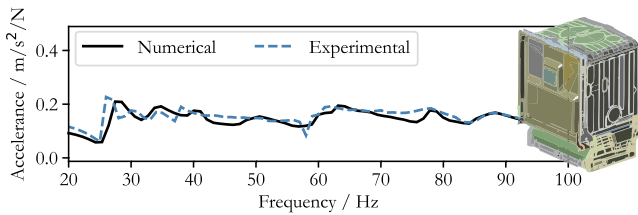


Figure 2: Comparison between numerical and experimental frequency response of the DW.

Spatial density of the equivalent force distribution on the DW tub was estimated from the numerical modal analysis results. Since the frequency of interest lies between 20 – 600 Hz, modes close to 600 Hz were visually inspected to estimate the minimum necessary number of DoFs to avoid spatial under-sampling. It was decided that the spatial resolution on all DW tub panels should be at least 2 cm in both vertical and horizontal directions. This resulted in 2942 equivalent source DoFs.

At these DoFs, responses during operation were measured using scanning laser vibrometer. Pump rotation speed was set at 2800 RPM, while lower and upper diverter were activated. Measurement time was adjusted to the diverter rotation speed, so that multiple diverter rotations were observed within one measurement block. To smooth the presence of random errors, 20 measurement blocks were averaged for each measured DoF. An example of the operational deflection shape is presented in Fig. (3).

DoFs measured with scanning laser should also serve as output DoFs $(\star)_4$ in $\mathbf{Y}_{42}$. Therefore, their locations and directions were defined in a numerical model. To simplify the process of obtaining $\mathbf{Y}_{42}$, the same DoFs were also considered as inputs $(\star)_2$, resulting in $\mathbf{Y}_{42}$ being a square matrix (2942×2942) with

perfectly collocated input/output DoFs. Here, input DoFs represent the locations where the equivalent source acts.

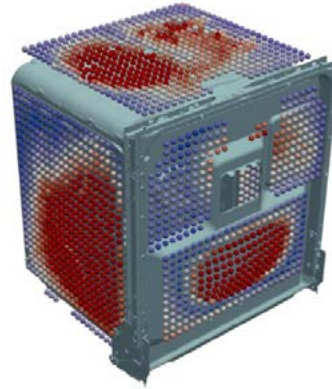


Figure 3: Operational deflection shape of the DW tub at 47 Hz measured using scanning laser vibrometer.

Results

Having obtained the admittance matrix $\mathbf{Y}_{42}$ and responses $\mathbf{u}_4$ for a given operational regime, equivalent force set was estimated using Eq. (2).

Using Eq. (3), equivalent force set can be applied to predict the responses at arbitrary DoFs $\mathbf{u}_3$ not considered in the source characterization (Eq. (2)). Given that this response can also be measured during operation, a visual comparison between the predicted and measured responses highlights the possibility of using equivalent force set to reconstruct passive-side responses. This is presented in Fig. (4) which demonstrates that the estimated equivalent source is a suitable source substitution.

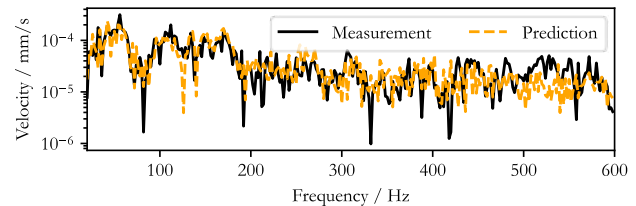


Figure 4: Comparison between measured and predicted operational responses at the receiver side of the DW.

Conclusions

In this work, a workflow for estimating an equivalent source for a Gorenje dishwasher in operation is presented. The purpose of the equivalent source is to replicate the effect of the operating source on the connected receiver structures; therefore, it can be treated as its full substitution. The procedure to characterize a source composed of a running pump and water hitting the DW tub from the lower and upper diverter is proposed in this work. Results indicate that the proposed equivalent source is a valid excitation for the purpose of virtual acoustic prototyping. In the future, these equivalent forces are intended to be used to determine suitable bitumen distribution on the DW tub without the need for physical prototypes.

[1] van der Seijs et al. *Mech. Syst. and Signal Process.* **68** (2016): 217-244.

Analiza modelov ET za vključitve v algoritme pametnega namakanja ozelenjenih sten

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V raziskavi smo analizirali deset modelov evapotranspiracije (ET) in ocenili njihovo ustreznost za določanje potreb po vodi pri modularnih ozelenjenih stenah. Meritve smo izvedli na eksperimentalnem sistemu, opremljenem s tehniko visoke ločljivosti in meteorološko postajo. Modela Penman-Monteith (FAO-56 in ASCE) sta izkazala najboljše ujemanje z merjenimi vrednostmi, medtem ko sta se sevalna modela Priestley-Taylor in Abtew po kalibraciji izkazala kot primerni alternativni. Pametno namakanje, zasnovano na izračunu ET, omogoča zmanjšanje porabe vode do 25 %, dodatno upoštevanje napovedi padavin pa še za dodatnih 10 %. Rezultati potrjujejo, da lahko napovedno upravljanje namakanja, na osnovi modelov ET, pomembno prispeva k učinkovitejši rabi vode pri ozelenjenih stenah.

Uvod

Hitro širjenje mest povečuje učinek toplotnega mestnega otoka, kar vodi v višje temperature grajenih površin in povečano rabo energije. Ozelenjene stene (ang. *living walls*) predstavljajo enega izmed učinkovitejših ukrepov blaženja mestnega toplotnega otoka in izboljšanja kakovosti bivanja v urbanem okolju. Zaradi vertikalne zasnove so še posebej primerne za gosto pozidana območja, kjer primanjkuje prostora za zelene površine na tleh. Njihova učinkovitost temelji na mehanizmih senčenja, ET in izboljšane izolativnosti ovoja stavb.

Kljub številnim okoljskim koristim ozelenjene stene zahtevajo stalno oskrbo z vodo, kar lahko predstavlja omejitev z vidika trajnostne rabe vodnih virov. Natančno poznavanje procesov ET je zato ključno za učinkovito načrtovanje in upravljanje sistemov namakanja. Ker je bila večina modelov ET razvita za horizontalne površine ali kmetijske kulture, njihova uporaba pri vertikalnih sistemih ni samoumevna. Namen raziskave je bil eksperimentalno ovrednotiti uporabnost najpogostejše uporabljenih modelov ET in preučiti možnost njihove vključitve v algoritme pametnega namakanja ozelenjenih sten.

Metodologija

Sistem smo postavili na zunanjem preskuševališču Laboratorija za okoljske tehnologije v zgradbah – LOTZ (Slika 1). Modul ozelenjene stene dimenzij $0,5 \times 0,6 \text{ m} \times 0,08 \text{ m}$ je vseboval substrat iz mineralne volne in 5 različnih vrst rastlin. Nameščen je bil na precizni tehnični za kontinuirno spremljanje sprememb mase zaradi izhlapevanja in transpiracije. Z meteorološko postajo ter dodatnimi merilniki smo merili temperaturo in relativno vlažnost zraka, hitrost vetra ter sončno in dolgovalovno sevanje.

Analizirali smo deset modelov ET, ki se delijo v štiri skupine:

- modela na podlagi temperature: Trajkovic, Ivanov,
- modela na podlagi sevanja: Priestley-Taylor, Abtew,
- modela na podlagi prenosa snovi: Penman, Lungeon,
- kombinirani modeli: Penman-Monteith FAO-56, ASCE, Djedjig in Shuttleworth-Wallace.

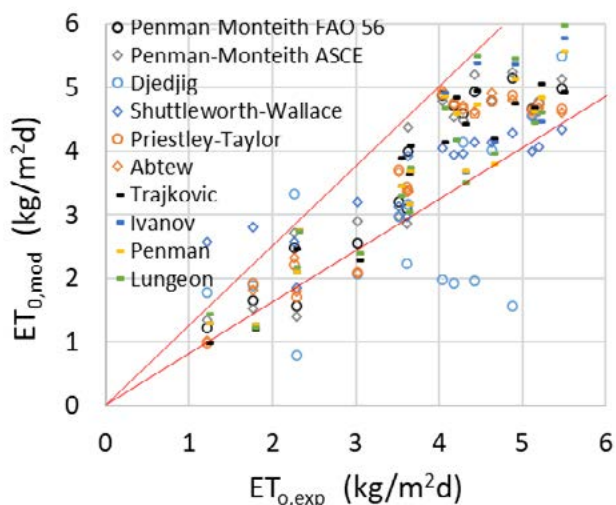
Modele smo najprej verificirali z izračunom referenčne evapotranspiracije ter nato analizirali oz. validirali na podlagi meritev ET v pogojih zadostne vlažnosti in zmernega pomanjkanja vode v substratu. Parametre modelov smo kalibrirali na podlagi statistične analize tako za primer izračuna urne kot tudi dnevne ET.



Slika 1: Zunanje preskuševališče LOTZ v Gamelnah z ozelenjeno steno sistema Urbanscape® (levo) in modul ozelenjene stene na tehnični za določanje urne ET (desno).

Rezultati in razprava

Primerjava modelov ET. Na Sliki 2 je prikazana primerjava dnevne ET ozelenjene stene, izmerjene in izračunane z izbranimi urnimi in dnevnimi modeli ET. Kombinirani modeli Penman-Monteith FAO-56 [1] in ASCE so dosegli najboljše ujemanje z meritvami (RMSE približno $0,4 \text{ kg/m}^2 \text{ d}$). Modela na osnovi sevanja Priestley-Taylor [2] in Abtew [3] sta po kalibraciji dosegla primerljivo natančnost, kar potrjuje, da neto sevanje gonilna sila izhlapevanja in transpiracije. Modela Djedjig in Shuttleworth-Wallace najbolj odstopata, sta zelo občutljiva na vrednosti temperature vegetacije, in praviloma potrebujeta izračun z numeričnim modelom [4-5]. Modeli na osnovi temperature in prenosa snovi so manj natančni vendar uporabni v primerih, ko so meteorološki podatki omejeni.



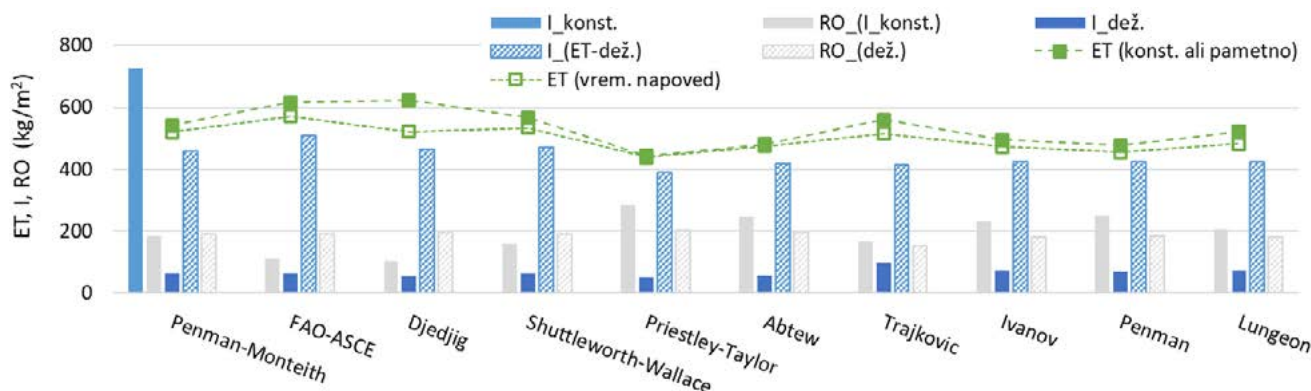
Slika 2: Primerjava dnevne evapotranspiracije (ET) ozelenjene stene, izmerjene in izračunane z izbranimi urnimi in dnevnimi modeli ET.

Vpliv pomanjkanja vode. Meritve so pokazale, da se ET začne zmanjševati po dveh do treh dneh brez namakanja. V modelih smo izboljšali napoved ET z vključitvijo linearnega koeficienta stresnih pogojev. Dnevi z zmanjšano ET zaradi pomanjkanja vode so tudi vključeni v analizi prikazani na Sliki 2.

Analiza učinkovitosti pametnega namakanja. Analizirali smo tri načine namakanja v poletnem obdobju za podnebne podatke mesta Koper:

- konstantno namakanje – dnevno 6 kg/m^2 ,
- pametno namakanje – količina vode enaka izračunani ET in
- pametno namakanje z napovedjo padavin – namakanje se prekine, če so v treh dneh predvidene padavine; upoštevan je prispevek deževnice s strehe za namakanje.

Na Sliki 3 so prikazani rezultati analize. Analiza je pokazala, da v poletnih mesecih s konstantnim namakanjem (*I*) porabimo 720 kg oz. litrov vode za vsak m^2 površine ozelenjene stene, pri čemer jo $15\text{--}30\%$ odteče (*RO*). S pametnim namakanjem z dnevno količino, ki je enaka izračunani ET porabo vode manjšamo na $440\text{--}620 \text{ kg/m}^2$, z upoštevanjem napovedi



Slika 3: Primerjava rezultatov različnih ET modelov uporabljenih v treh scenarijih namakanja.

padavin pa še za dodatnih 10% . S pametnim navlaževanjem lahko tako prihranimo okvirno 25% pitne vode. Ker razmeroma veliko deževnice iz sistema odteče, bi bila za večje

prihranke pitne vode smiselna vgradnja zalogovnika. Rezultati analize so tudi pokazali, da se z modeli napovedana ET za celotno obdobje razmeroma veliko razlikuje.

Pomen rezultatov. Rezultati potrjujejo, da lahko fizikalno utemeljeni modeli ET dovolj zanesljivo napovejo potrebo po vodi ozelenjenih sten. Modela Penman-Monteith FAO-56 in ASCE sta najprimernejša, modela na osnovi sevanja pa predstavljata učinkovito alternativo, če ni na voljo celoten nabor meteoroloških podatkov. Vgradnja teh modelov v krmilne sisteme pametnega namakanja omogoča učinkovitejšo rabo vode in zmanjšuje obremenitev urbane vodne infrastrukture.

Zaključki

- Penman-Monteith FAO-56 in ASCE sta najnatančnejša modela za napoved evapotranspiracije ozelenjenih sten.
- Modela na osnovi sevanja Priestley-Taylor in Abtew po kalibraciji dosegata primerljive rezultate.
- Modela Djedjig in Shuttleworth-Wallace sta občutljivejša na napake vhodnih podatkov.
- Poenostavljeni modeli na osnovi temperature in prenosa snovi so primerni za okolja z omejenimi podatki.
- Pametno namakanje na osnovi modelov ET zmanjša porabo pitne vode do 25% , dodatno upoštevanje padavin pa poveča prihranek pitne vode na več kot 30% .

V prihodnje želimo modele validirati v različnih podnebjih in jih povezati s senzorji vlažnosti, napovednimi algoritmi in strojnimi učenjem, da bi razvili popolnoma samodejen sistem namakanja.

ZAHVALA. Avtorji se zahvaljujejo Javni agenciji za znanstvenoraziskovalno in inovacijsko dejavnost Republike Slovenije (ARIS) za finančno podporo v okviru aplikativnega raziskovalnega projekta [št. L7-4495 (C)], programa temeljnega raziskovalnega financiranja [št. P2-0223 (C)], temeljnega raziskovalnega projekta – Programa dr. Aleša Debeljaka [št. J2-50222] ter interdisciplinarnega projekta Univerze v Ljubljani: Zelene urbane skupnosti prihodnosti (I. faza: pripravljana faza). Delo je bilo finančno podprto tudi v okviru programa Mladi raziskovalec, ki ga sofinancira ARIS.

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Optimizing Drum Speed to Minimize Fiber Shedding During Tumble Drying

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Mechanical stress during tumble drying accelerates fabric degradation and fiber release. This study investigates how drum speed influences fiber shedding, drying time, and energy consumption in a heat-pump tumble dryer. Experiments were performed at constant and phased drum speeds ranging from 5 to 70 rpm using cotton textiles. Both very low (10 rpm) and high (70 rpm) speeds significantly reduced fiber mass relative to the nominal 58 rpm regime but increased drying time and energy use. Phased drum operation combining nominal and reduced speeds achieved up to 50 % lower fiber shedding with moderate penalties in drying performance.

Introduction

Microfiber emissions from domestic dryers are gaining attention as a relevant contributor to environmental fiber pollution. Mechanical and thermal loads inside the drum promote textile wear, with the severity largely governed by drum speed and textile motion pattern [1, 2]. Tumble dryers typically operate in the cataracting motion regime (Figure 1), which offers the best drying performance but also imposes higher mechanical stress on textiles compared to cascading or centrifuging patterns. This leads to increased fibers shedding, especially during the later stages of drying [3]. Building on these findings, this study explores how controlled variation of drum speed, including phased regimes, can minimize fiber shedding while maintaining acceptable drying performance.

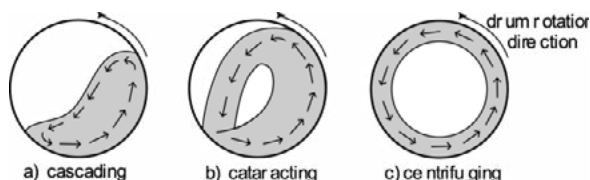


Figure 1: Basic textile motion patterns encountered in a tumble dryer drum; grey areas represent space occupied by textiles

Materials and methods

Drying experiments were carried out in a modified 9 kg heat-pump tumble dryer equipped with an external air-filtration system capable of capturing sub-micron fibers. The cotton load (6 kg) consisted of worn bed sheets, pillowcases and towels, initially wetted to $60\% \pm 1\%$ moisture. Drum speed was controlled between 5 and 70 rpm, while the fan speed was kept constant by employing an external drive. Two experimental sets were performed:

(1) **Constant-speed tests** at 5–70 rpm to establish baseline relationships. At 70 rpm the textiles were moving in centrifuging motion, while speeds of 30 rpm and lower produced cascading motion.

(2) **Phased regimes R1, R2 and R3**, combining nominal (58 rpm) and reduced-speed (10 rpm) operation with periodic reversals of rotation direction. These regimes typically started with nominal speed and continued at 10 rpm as the textiles became drier and more prone to damage.

Results and discussion

Energy–time relation (Figure 2). A strong linear correlation was observed between energy consumption and drying time for constant drum speeds (5–58 rpm, excluding 70 rpm), with $R^2 = 0.9988$. Both parameters increased as textile motion shifted away from the nominal cataracting pattern (58 rpm). Phased regimes aligned closely with this trend, while regime R3 operated slightly below the line, indicating improved energy efficiency per unit time.

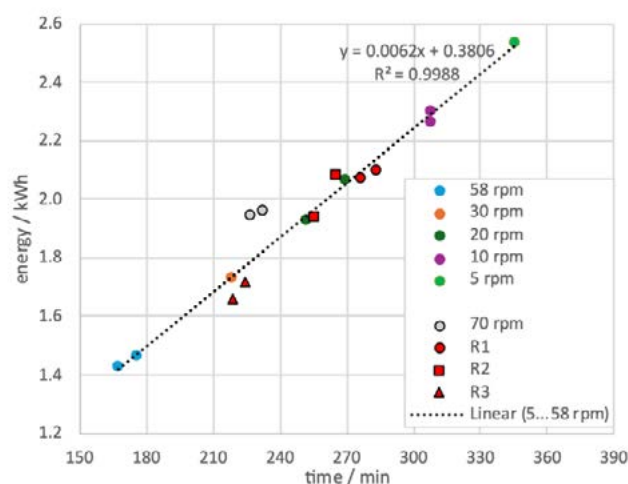


Figure 2: Energy consumption as a function of drying time

Drying time vs. drum speed (Fig. 3). Reducing drum speed below 30 caused an almost proportional increase in drying time. The lowest drying times were achieved at the nominal drum speed, while increasing the speed to 70 rpm again led to longer drying. Phased regimes R1-R3 did not deviate significantly from the trends observed at constant speeds.

Fiber mass vs. drum speed (Fig. 4). Total total mass of shed fibers showed a non-linear dependence on average drum speed. The highest shedding occurred near 58 rpm, while both lower and higher speeds produced substantially less fiber release. A quadratic model fitted to constant-speed tests (5–70 rpm) as

achieved $R^2 = 0.901$. The phased speed tests, which alternated between cataracting and cascading motion, were not included in the regression. These results confirm that controlling drum speed and adjusting textile motion patterns can effectively mitigate fiber shedding.

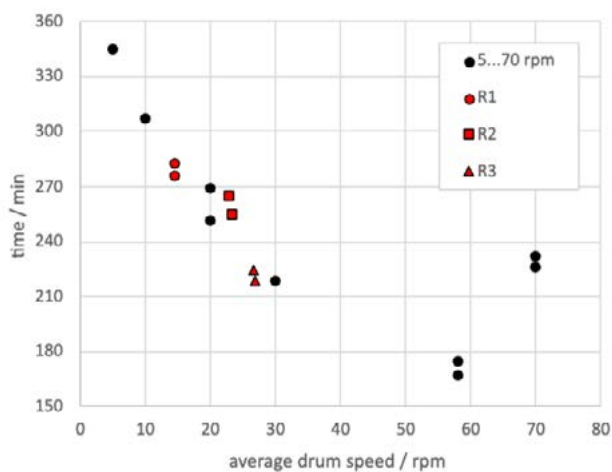


Figure 3: Total drying time as a function of average drum speed

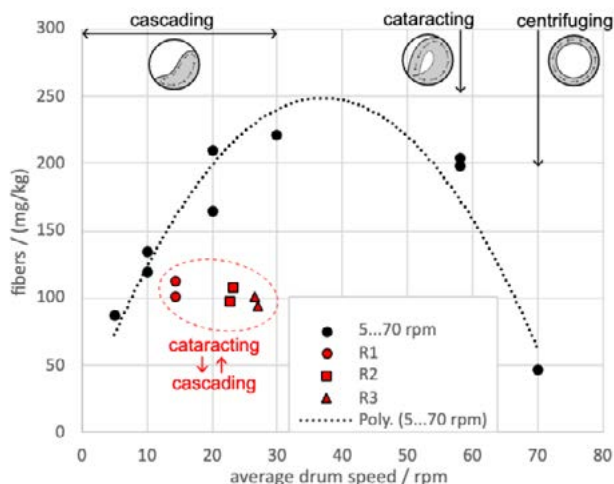


Figure 4: Total mass of fibers per mass of load as a function of average drum speed

Phased operation effects. Regimes R1–R3 balanced tumbling duration and intensity during the drying cycle. The most advanced regime R3, starting with one hour at nominal-speed followed by reduced-speed phases, reduced total fiber mass by $\approx 50\%$ relative to nominal operation while increasing drying time and energy consumption by only 29 % and 17 %, respectively. Further optimization of phased regimes could yield even better results. Incorporating periods of increased speed (70 rpm) appears promising, however, high-speed operation is prone to uneven drying and may require more frequent alterations in drum speed and direction.

Regression analysis. Fiber mass was further analysed to develop predictive empirical models. Using the total number of drum rotations (N), the product of average speed and drying time, yielded the strongest correlation with fiber mass, indicating that cumulative mechanical action governs shedding

intensity. The developed model showed good predictive power ($R^2 = 0.962$) with a simple quadratic relation (Eq. 1):

$$m_{fib}/m_l = -2.911N_{1000}^2 + 48.967N_{1000} + 9.16 \quad (1)$$

where N_{1000} is the total number of drum rotations, expressed in units of 1000 rotations and m_{fib}/m_l represents fiber mass per mass of load. The model and data are presented in Figure 5. Evidently, alignment of points to the model is improved compared to Figure 4, also for phased speed tests, despite their exclusion from the regression sample.

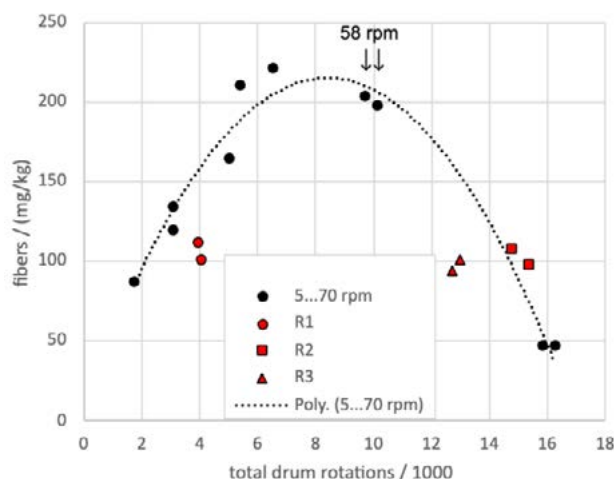


Figure 5: Total mass of fibers per mass of load as a function of total drum rotations

These results suggest that strategic modulation of drum speed, informed by the moisture-dependent mechanical sensitivity of textiles, can meaningfully reduce microfiber emissions without major efficiency losses.

Conclusions

- Fiber shedding peaks at nominal drum speed (≈ 58 rpm) corresponding to energy efficient cataracting motion.
- Both lower (10 rpm) and higher (70 rpm) speeds markedly reduce fiber mass but increase drying time and energy.
- Phased drum operation combining nominal and reduced speeds (R3) achieved $\approx 50\%$ fiber reduction with only 29 % longer drying and 17 % more energy use.
- The total number of drum rotations proved a reliable single predictor of fiber loss and energy consumption, integrating both mechanical intensity and duration.
- Drum-speed control is a practical pathway for sustainable textile care and microfiber emission reduction.

ACKNOWLEDGEMENTS. This work was supported by the Slovenian Research Agency under projects L2-3174 and TN-02-0782.

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Digital Feedback Loop for SMEs via ETL

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Small and Medium-sized Enterprises (SMEs) struggle to fully utilize production data. This causes errors and suboptimal decisions. Expensive Manufacturing Execution System (MES) are often unaffordable for them. This research developed a cost-effective digital feedback loop, by using the Action Design Research method (ADR). The Extraction, Transformation and Load (ETL) process relied on Power Query and Python/Pandas. It connected diverse, heterogeneous production data in real-time. The system successfully calculates actual material consumption and measures yield. It thus provides key MES functionality using accessible tools. Solution is functional and transferable within different production fields.

Introduction

In contemporary competitive manufacturing environment, digitalization and automation are key for optimization. Despite this, companies often fail to fully utilize the generated data. This leads to manual work and consequently to errors, and bad decision-making. Incomplete digitalization overloads operators. Key problems include information being dispersed and separated (information silos), operators lacking application skills, poor data literacy of operators etc. Traditional, slow feedback methods are being replaced by Continuous Feedback Loops (CFLs). These dynamic mechanisms constantly capture, analyse, and respond to real-time events, allowing users to make prompt, data-driven adjustments and proactively increase agility [1]. In real-time systems, data quality is the most critical success factor. Incomplete data leads to inaccurate predictions and operational inefficiency. Quality assurance must be continuous [2].

While large companies use expensive Manufacturing Execution System (MES), Small and Medium-sized Enterprises (SMEs) ask: *How can we establish a digital feedback loop without major investment?* Underutilized data causes delays in production, higher material consumption, and increased costs. Business Intelligence (BI) systems are key to this, transforming raw data into actionable knowledge. Affordable platforms like Microsoft Power BI enable the creation of real-time dashboards for tracking Key Performance Indicators (KPIs), which is crucial for SMEs [4]. Establishing a digital feedback loop requires a robust ETL (Extraction, Transformation, Load) process. In modern systems, static ETL pipelines evolve into dynamic, two-way feedback infrastructures. These support continuous learning by supplying data for training (Forward Flow) and capturing feedback from model outputs (Backward Flow) [3]. Power Query, integrated into Power BI and Excel, is a valuable tool for ETL, as it addresses issues related to employees' insufficient digital literacy and simplifies data preparation [6].

This article explores alternative, accessible solutions for data capture and processing. We focus on standard tools like Power Query and open-source solutions such as Python, specifically for performing the ETL process. Using a case study of production with CNC and Nesting machines, we will show how to effectively capture, transform, and connect heterogeneous data sources. The goal is to establish a digital feedback loop. This enables material consumption optimization and accurate utilization measurement. We focus on converting diverse data into key information for decision-making. The Action Design Research (ADR) methodology is often used to develop such solutions in real-world contexts [4, 6].

Materials and methods

The primary objective of this research was to establish a digital feedback loop system. This system was designed for the real time capture and processing of actual production data. The goal was the optimization of existing material consumption norms and measuring yield. The data utilized for the analysis originated from more CNC machines. They had heterogeneous digital formats, including PDF, TXT, CSV, and Excel files (Fig. 1). The organization and structure of the data varied significantly across sources. Therefore, we made a thorough preliminary cleaning. This included removing redundant introductory lines in some files that did not contain measured values.

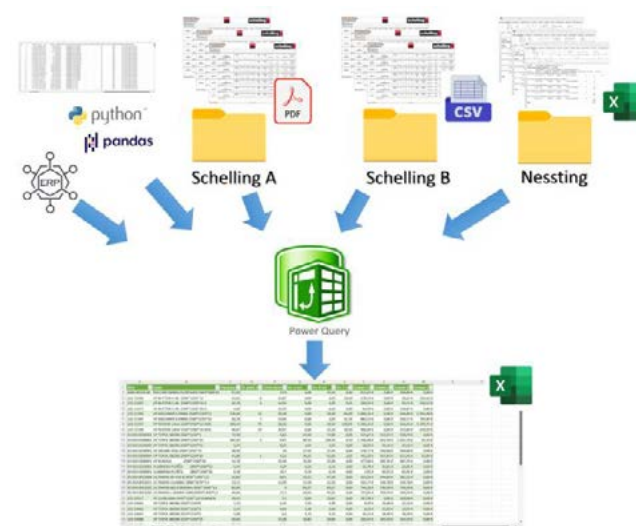


Figure 1: Overview of the Data Sources, File Types, and the established Data Processing Pipeline.

A combination of standard and open-source tools was used to execute the ETL process. The primary tool employed for capturing and structuring most data sources was Microsoft Excel with its integrated Power Query (M language) module. Additionally, for data acquisition from one specific, more

complex source, the Python programming language was used together with the Pandas library, ensuring automated data processing and normalization.

An important part of the methodology was carrying out ETL transformations to combine and align the data. This meant connecting data sources in a way like joining tables in a relational database (Fig. 2). The main challenge was finding and matching the right linking keys, since one system often used a numeric code and the other a descriptive name for the same item. In addition, text values had to be converted into numbers, which required solving problems caused by different regional settings. Finally, for optimization and yield analysis, new columns were added. For example, material consumption and utilization rate (yield %).

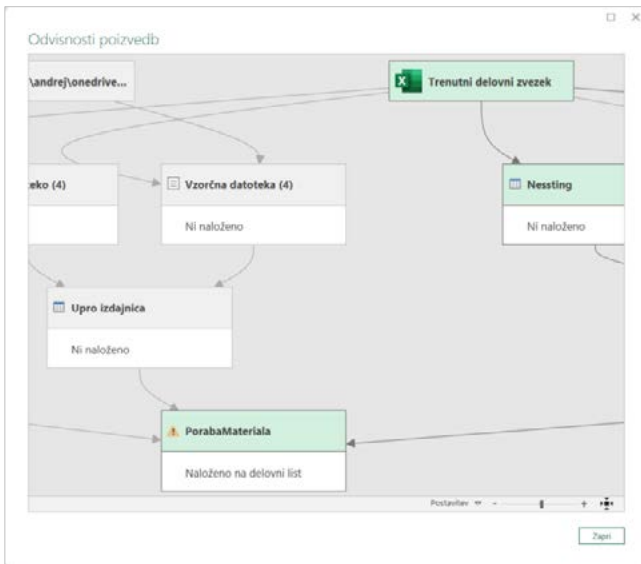


Figure 2: Diagram showing the linking of various data tables within Power Query.

Results and discussion

We developed the digital feedback loop following the Action Design Research (ADR) framework, combining practical intervention with systematic evaluation. The process consisted of four main stages: (1) identification of data sources, (2) integration and transformation of data, (3) creation of a consolidated data model, and (4) validation and visualization of results.

The main result of the research was the successful implementation of a functional digital feedback loop (Fig. 3). The system was comprised of 10 source data inputs, which were logically combined in the ETL process (involving over 70 transactions) into a scheme that generated 7 additional transformed tables. The final product of the data processing is an Excel table that contains aggregated data for each work order, structured for analysis using pivot tables.

The consolidation and subsequent processing of data from all work orders enables the calculation of actual material consumption, which provides a key input for the correction of the norm in the ERP system or the product's Bill of Materials (BOM). The developed solution demonstrates that a digital feedback loop, implemented using accessible standard and

open-source tools, is functional and transferable to similar manufacturing sectors, such as the metal or wood industry. By ensuring the capture and analysis of actual material consumption, the solution successfully covered one of the key functionalities typically provided by expensive MES (Manufacturing Execution System) systems.

The greatest technical challenge in the project was the processing of PDF files. Even though these files were digitally generated, they presented the most difficulties due to the occasional misalignment of columns during the extraction and transformation phase.

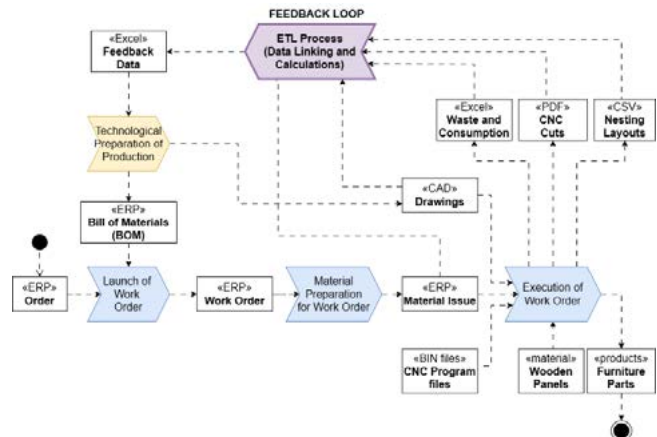


Figure 3: The blue arrows represent the core working process, while the upper arrow (purple) illustrates the digital feedback loop. The yellow arrow highlights the user utilizing the feedback data for decision-making.

Conclusions

In this research, we built a cost-effective digital feedback loop tailored for SMEs. It enables real-time use of diverse production data to optimize norms and measure yield. Using Power Query and Python (Pandas), we addressed complex ETL tasks. These included linking data from multiple sources and resolving issues caused by different local settings.

The solution demonstrates that operational excellence is possible even with simple, accessible tools. In the future, automating the transfer of calculated norms into the ERP system is recommended. This would further enhance the process's responsiveness and reliability.

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Optična zaznava in ustvarjanje nanomehurčkov v vodi

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Raziskava preučuje obstoj in nastanek nanomehurčkov v vodi, ki kljub pričakovani nestabilnosti vztrajajo v nekaterih pogojih. Z uporabo laserskega vzbujanja in podtlačnih valov so avtorji iskali dokaze o naravno prisotnih nanomehurčkih v ultra čisti, deionizirani in pitni vodi, ter preiskovali mehanizme nastanka nanomehurčkov. Rezultati so pokazali, da v vodi prosti nanomehurčki, večji od 10 nm, niso prisotni. V vodi z nečistočami so nanomehurčke po laserskem vzbujanju zaznali, saj nečistoče delujejo kot jedra za njihov nastanek in začasno povečano stabilnost nanomehurčkov. Prisotnost nečistoč je torej ključna za nastanek lasersko vzbujenih nanomehurčkov in nudi možno razlago mehanizma povečane stabilnosti nanomehurčkov.

Uvod

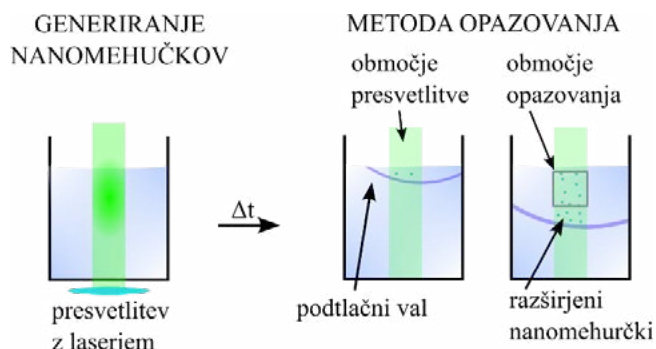
Nanomehurčki v vodi, plavajoči plinasti mehurčki v premeru manjši od mikrometra, se že uporabljajo v industriji, kmetijstvu, pri čiščenju odpadnih voda in kot kontrastna sredstva v medicinskem slikanju. Zaradi svoje majhnosti lahko dolgo časa ostanejo v vodi, saj naključno Brownovo gibanje premaga silo vzgona. Kljub vse širši uporabi pa še vedno ne razumemo povsem, kako nanomehurčki nastanejo, kako med seboj interagirajo in ali so prosti nanomehurčki v vodi sploh dolgoročno stabilni. Večina raziskav doslej se osredotoča predvsem na njihove praktične koristi, manj pa na temeljna fizikalna vprašanja.

Obstoj stabilnih nanomehurčkov v vodi se zdi paradoksalen, saj splošna termodinamika namreč pravi, da majhni mehurčki ne morejo doseči stabilnega ravnovesja in se raztopijo [1]. Kljub izmuzljivosti prostih nanomehurčkov v primerjavi s površinsko vezanimi, predvsem zaradi bistveno okrnjenih možnosti zaznave prvih, v zadnjem času to področje eksperimentalnih raziskav doživlja veliko aktivnost. Razvija se vse več metod za ustvarjanje in zaznavo nanomehurčkov. Ena bolj razširjenih tehnik ustvarjanja je s periodičnim spreminjanjem tlaka, pri čemer tlačne spremembe povzročijo nastanek plinastih nanomehurčkov velikosti od približno 40 nm do 1000 nm, kar lahko zaznamo in določimo z uporabo dinamičnega sipanja svetlobe. Druge tehnike ustvarjanja vključujejo elektrolizo, kavitacijo, obsevanje z ultrazvokom in nenazadnje z lasersko svetlobo. Prav ustvarjanje nanomehurčkov z laserjem se kaže kot ena bolj obetavnih metod za natančne aplikacije in osnovne raziskave [2]. Hkrati predstavlja odskočno desko za vpogled v obstoj povsem prostih nanomehurčkov v vodi.

Materiali in metode

Za opazovanje nanomehurčkov smo uporabili poseben pristop: skozi vodo smo poslali podtlačni val, ki za kratek trenutek močno zmanjša tlak v tekočini. Zaradi tega se nanomehurčki na hitro napihnejo in postanejo dovolj veliki, da jih lahko posnamemo s hitro kamero in mikroskopom. Tako plinaste mehurčke lahko jasno ločimo od trdnih delcev ali drugih nečistoč v vodi. Prednost metode je še, da ne ustvarja novih mehurčkov ali vnaša nečistoč v vodo, temveč zgolj razkrije že obstoječe mehurčke. Podtlačni val smo ustvarili s kratkim in močnim laserskim pulzom, ki je v vodi povzročil nastanek plazme. Nastanek plazme v vodi spremlja hitra rast kavitacijskega mehurčka do velikosti nekaj mm in ob nastanku mehurčka še udarni tlačni val. Slednji se radialno širi iz mesta preboja in se odbije od proste vodne površine, kjer se zaradi razlike v akustičnih impedancah zraka in vode faza vala obrne in dobimo potujoči podtlačni val. Ko podtlačni val doseže območje opazovanja (na Sliki 1 desno in na Sliki 2 zgoraj), lahko začnemo opazovati razpenjanje mehurčkov. Območje ustvarjanja podtlačnega vala je odmaknjeno od območja opazovanja, da ne zmoti meritve.

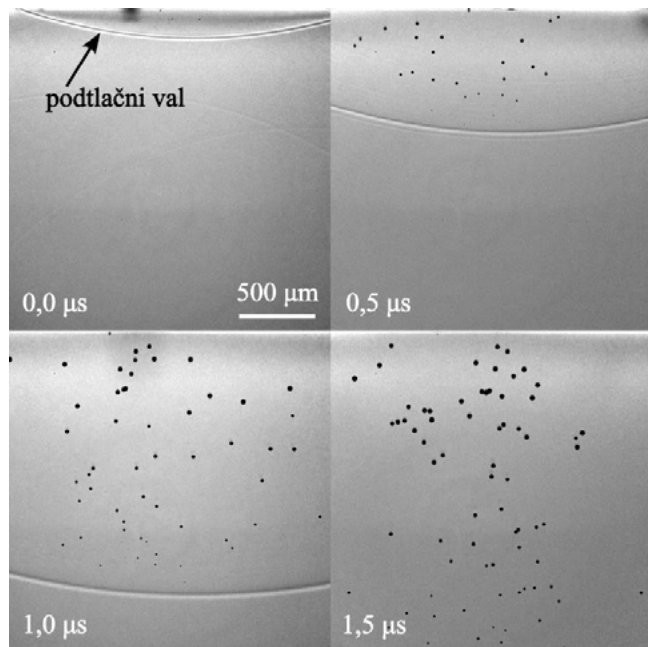
Poleg morebitnih naravno prisotnih nanomehurčkov smo v vodi opazovali tudi lasersko vzbujene nanomehurčke. Lasersko ustvarjene nanomehurčke lahko najdemo v stožcu fokusiranega laserskega žarka v vodi, v območju dovolj visokih intenzitet svetlobe [3, 4]. Za doseganje visokih intenzitet svetlobe smo uporabili nanosekundni laserski vir, za zagotavljanje ponovljive detekcije pa smo omejili območje vzbujanja v vodi z uporabo cilindrične leče. Opazovano območje znotraj steklene kivete je pri uporabi laserskega vzbujanja veliko približno 1,0 x 1,0 x 0,1 mm, pri čemer je globina območja omejena tako z obliko vzbujevalnega laserskega snopa kot z optičnimi lastnostmi objektiva kamere.



Slika 1: Poenostavljena shema laserskega generiranja nanomehurčkov v stekleni kiveti in metode njihove zaznave kratek čas kasneje.

Rezultati in diskusija

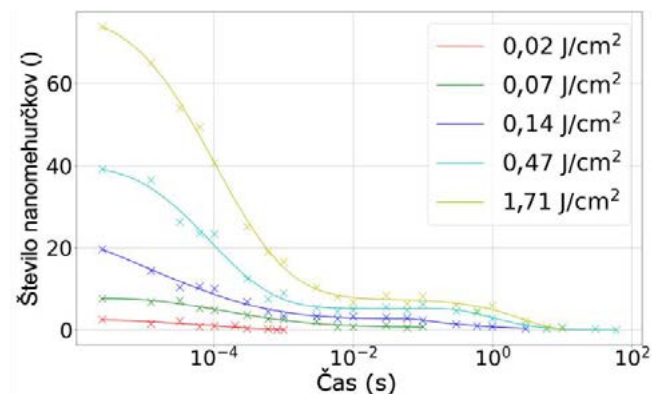
Da bi preizkusili metodo, smo najprej uporabili ultra čisto vodo, ki predstavlja kontrolni eksperiment. V ultra čisti vodi pričakujemo le do 3000 delcev manjših od mikrometra na liter vode. V opazovanem območju bi bilo v tem primeru v povprečju prisotnih manj kot 0,0003 delca oziroma največ en vsakih 3000 poskusov, če bi vmes dobro premešali vzorec. Iz tega lahko sklepamo, da bi bil po aktivaciji metode zaznave nanomehurčkov brez uporabe laserskega vzbujanja praktično vsak opažen nanomehurček nujno prosto plavajoč in naravnega izvora. Rezultat naših meritev je bila popolna odsotnost nanomehurčkov. Podoben preizkus smo ponovili tako v deionizirani kot običajni pitni vodi, kjer je v obeh primerih prisotnost delcev bistveno večja. Naravno prisotnih mehurčkov nismo zaznali v nobenem primeru, kar nakazuje na odsotnost dolgoživih nanomehurčkov. Območje opazovanja po prehodu podtlačnega vala je prikazano na Sliki 2. Omeniti velja, da je opisana metoda omejena na zaznavo nanomehurčkov s premerom okoli 10 nm ali večjim. Po drugi strani smo z uporabo laserskega vzbujanja nanomehurčkov v deionizirani in pitni vodi zaznali prisotnost nanomehurčkov. Tekom razpenjanja jih lahko opazimo na slikah hitre kamere kot črne pike, kar je prikazano na sekvenci na Sliki 2. Zanimivo, v ultra-čisti vodi niti lasersko vzbujanje nanomehurčkov ni bilo uspešno in do tvorbe mehurčkov ni prišlo.



Slika 2: Območje opazovanja, slikano v časovnem zaporedju po aktivaciji metode opazovanja, s predhodnim laserskim vzbujanjem nanomehurčkov. Opazimo razpenjanje lasersko ustvarjenih nanomehurčkov v vodi za prehodom podtlačnega vala. Skala velja za vse slike.

V literaturi obstajajo različne razlage za prisotnost nanomehurčkov v tekočinah in njihovo podaljšano stabilnost v primerjavi s termodinamskimi omejitvami prosto plavajočih nanomehurčkov. Nekateri raziskovalci menijo, da se tvorijo okrog delcev, ki delujejo kot seme za njihov nastanek. Princip je podoben znanim mehanizmom stabilizacije mehurčkov ob površinah. Drugi predlagajo, da bi se lahko stabilizirali tudi v popolnoma čisti vodi, česar pa naši rezultati ne potrjujejo.

Rezultati naših meritev po eni strani kažejo na odsotnost naravno prisotnih nanomehurčkov, tako povsem prostih v ultra čisti vodi, kot morebitnih vezanih na v vodi prisotne nečistoče. V nasprotju z izmuzljivimi naravnimi nanomehurčki smo jih z laserskim vzbujanjem uspeli ustvariti, vendar zgolj v vodnem okolju z nečistočami. V kolikor bi z laserjem ustvarili v vodi prosto lebdeče mehurčke, bi glede na njihovo začetno majhnost v skladu s fizikalnimi modeli pričakovali, da se bodo raztopili že v nekaj milisekundah. Takšno raztapljanje oz. življenjska doba bi bila skladna s tisto, ki jo napoveduje Epstein-Plessetov model raztapljanja za proste plinaste mehurčke v vodi. Vendar smo te mehurčke opazili tudi še kasneje po ustvarjanju. Zanimiva je primerjava življenjske dobe nanomehurčkov, lasersko ustvarjenih z različnimi energijami laserskega pulza v deionizirani vodi (Slika 3). Pri višjih energijah laserskega pulza, ki ustvarja nanomehurčke, najdemo neraztopljene nanomehurčke še več sekund po ustvarjanju, čeprav so v začetku zagotovo manjši od 1 μm , saj bi jih v nasprotnem primeru opazili na posnetku hitre kamere. Epstein-Plessetov model raztapljanja prostih mehurčkov v vodi napove, da šele več kot 5 μm veliki mehurčki potrebujejo več kot 1 s do raztopitve. Glede na to ostaja edina smiselna razlaga, da pride do stabilizacije nanomehurčkov ob površini – ob nečistočah v vodi.



Slika 3: Število nanomehurčkov v opazovanem območju pada s pretečenim časom od laserskega vzbujanja.

Zaključki

Naši nanomehurčki so torej obstajali dlje, kot bi napovedovali fizikalni modeli, a vseeno niso bili trajno stabilni. Glede na opaženo smo postavili hipotezo, da nečistoče v vodi lasersko svetlobo absorbirajo in okoli sebe tvorijo nanomehurčke.

Prav tako so naše raziskave pokazale, da v čisti vodi ni naravno prisotnih prostih nanomehurčkov večjih od 10 nm, niti jih v ultra čisti vodi ni mogoče ustvariti z laserjem, saj so za njihov nastanek potrebne primesi. Metoda, ki smo jo uporabili, omogoča zanesljivo razlikovanje nanomehurčkov od drugih delcev. Pokazala je, da imajo nečistoče ključno vlogo pri njihovem nastanku in začasni povečani stabilnosti nanomehurčkov. To odkritje ponuja pomembne nove vpoglede v razumevanje nanomehurčkov in razrešuje del uganke o njihovem obstoju v vodi.

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Fusion of Optical Flow and Depth Data for Real-Time Motion Correction in Medical Robotics

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Accurate motion tracking is crucial in medical robotics, where involuntary patient movements can affect treatment precision and safety. We present a real-time motion-correction method based on the fusion of optical flow and depth data acquired by a time-of-flight (TOF) camera. The approach converts 2D pixel displacements into 3D body-surface motion, enabling adaptive correction of robotic trajectories. Seven optical-flow algorithms were compared under controlled motion conditions. The Farneback algorithm achieved the best compromise between speed and accuracy, operating at 140 FPS with a trajectory error of 8 mm over a 2250 mm long path. Results confirm that optical-flow–depth fusion provides reliable 3D motion estimation for real-time compensation in robotized medical procedures.

Introduction

Modern robotized medical systems enable high precision, repeatability, and automation of complex therapeutic procedures [1]. However, involuntary patient motion—caused by breathing or minor body shifts—remains one of the most critical challenges. Such movements can defocus the laser or misalign the robot trajectory, potentially reducing treatment quality or causing unwanted tissue exposure.

Previous research on motion compensation focused mainly on imaging modalities such as magnetic resonance imaging (MRI), optical coherence tomography (OCT), or thermography, whereas real-time 3D surface tracking over larger body regions [2] has received little attention. Optical flow methods, which estimate apparent motion from image intensity changes, offer a computationally efficient approach [3] but are typically limited to 2D image planes.

To address this limitation, we developed a Fusion Flow approach that combines dense optical flow with point-cloud data from a TOF camera to reconstruct full 3D motion. The goal is to achieve real-time body-surface tracking with millimetre-scale accuracy, suitable for adaptive robot control in laser-based skin treatments.

Materials and methods

Figure 1 shows the laboratory setup. A TOF camera (pmd flexx2, PMD Technologies, Germany) was mounted on a linear actuator (LEFS32A, SMC, Japan) positioned approximately 140 mm above the human torso. The actuator provided precise, repeatable motion along the x-axis (± 0.02 mm accuracy). The camera recorded synchronized grayscale and depth frames (224×172 pixels, 30 FPS).

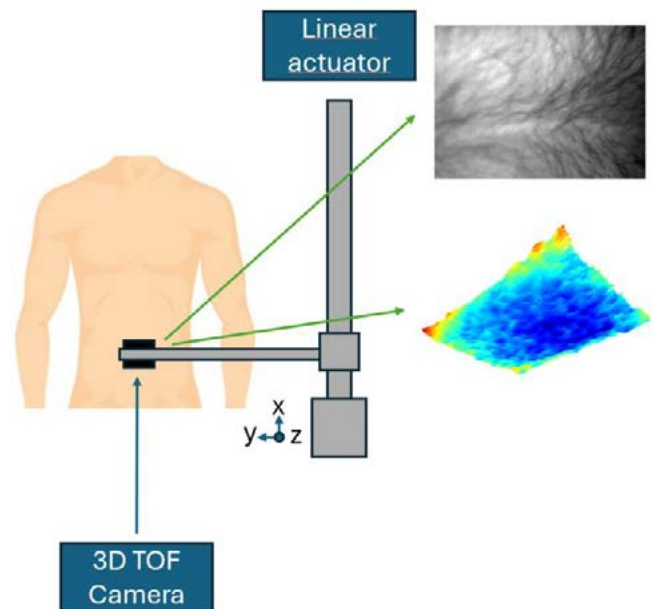


Figure 1: Experimental setup for 3D body motion measurement using a TOF camera mounted on a linear actuator.

Each measurement sequence was analyzed in four steps:

1. **Preprocessing** (illumination correction and optional filtering);
2. **Optical-flow estimation** using one of seven algorithms (DeepFlow, DenseRLOF, DualTVL1, Farneback, PCAFlow, SimpleFlow, and SparseToDense) implemented in OpenCV [4];
3. **Fusion with 3D data**, where pixel displacements were mapped into real-world coordinates;
4. **Post-processing and integration** to obtain the camera trajectory and compare it with actuator encoder data.

The Farneback algorithm [5] was identified as the most robust for real-time operation. Accuracy, precision, and computational speed were evaluated at camera velocities between 20 mm/s and 200 mm/s.

Results and discussion

Figure 2 compares the optical-flow-based trajectories with encoder reference data for various motion speeds. At low speeds (20–60 mm/s), the trajectories almost completely overlap, indicating negligible systematic error. At higher speeds, small deviations occur, primarily due to motion blur and reduced frame overlap between consecutive images.

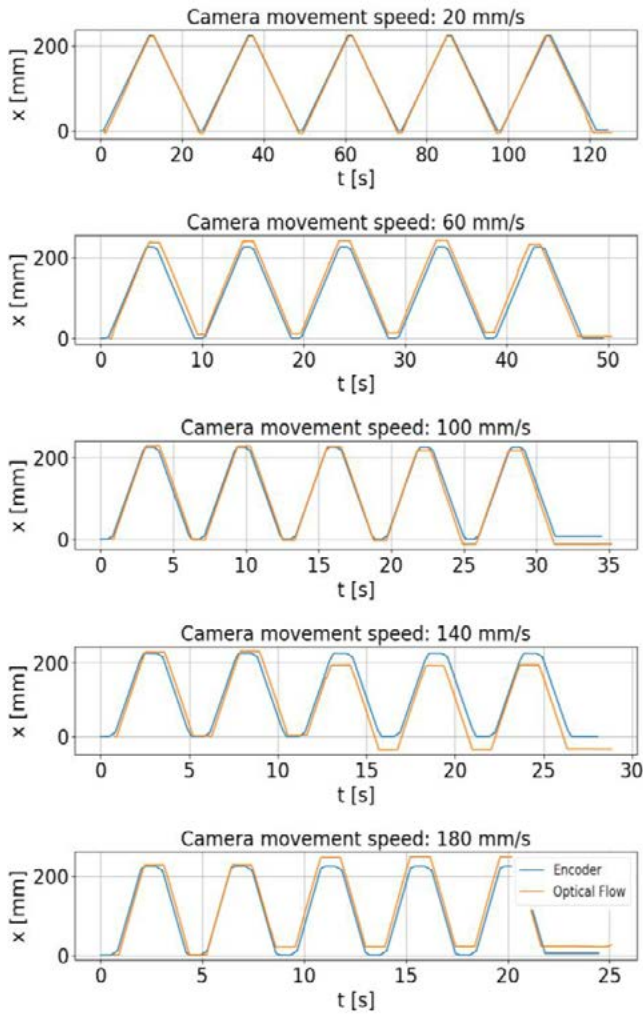


Figure 2: Comparison of measured (orange) and reference (blue) trajectories for different camera movement speeds.

Quantitatively, the Farneback method achieved a root-mean-square error (RMSE) of approximately 8 mm over a 2250 mm translation, while operating at 140 frames per second—well above the minimum 30 FPS requirement for real-time control. Figure 3 shows that precision, expressed as the mean standard deviation of displacement along the motion direction across all frames (σ_x), degrades approximately linearly with increasing motion speed. Applying a Sobel kernel prior to optical-flow computation proved to be the most effective preprocessing strategy, maintaining $\sigma_x < 0.5$ mm up to 100 mm/s.

These findings demonstrate that the Fusion Flow approach provides sufficient accuracy for on-the-fly motion correction in robotized procedures. Further improvement can be achieved through Kalman filtering [6] or visual Simultaneous Localization and Mapping (SLAM) [7] trajectory stabilization to reduce cumulative drift during prolonged motion.

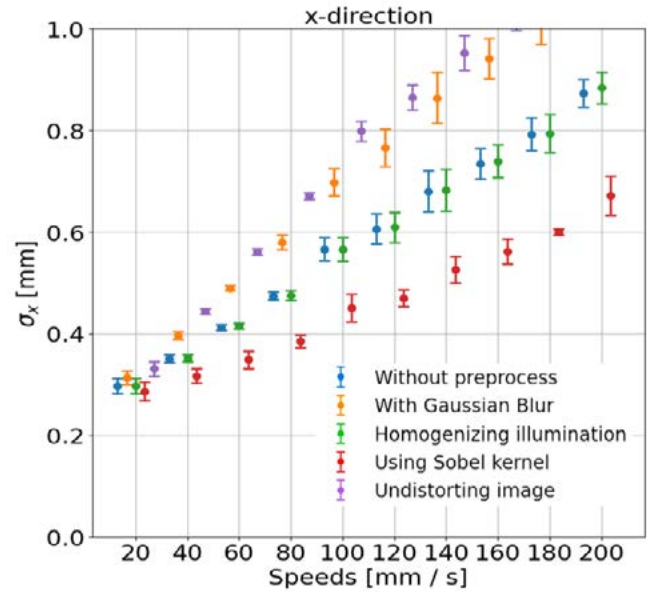


Figure 3: Precision of motion estimation (σ_x) as a function of camera speed for various preprocessing methods.

Conclusions

- A real-time 3D motion-correction framework based on fusion of optical flow and depth data was developed.
- The Farneback algorithm provided the best compromise between speed and accuracy (140 FPS, RMSE $\approx$ 8 mm).
- The method enables precise monitoring of patient movement and can be integrated into robot-controlled laser systems to enhance treatment safety and reliability.

ACKNOWLEDGEMENTS.

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Vizualizacija in analiza turbulentnega curka zraka z uporabo psihoakustičnih značilk

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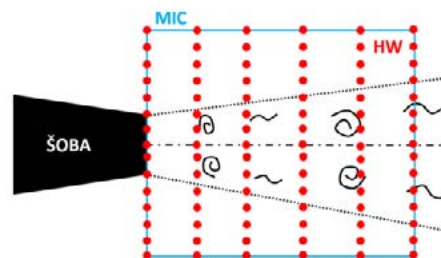
V prispevku je predstavljena nova metoda vizualizacije turbulentnega curka zraka, ki temelji na uporabi psihoakustične značilke hrapavost (R). Značilka je bila izračunana iz tlačnih signalov, posnetih z mikrofonom, in omogoča prostorsko identifikacijo značilnih območij curka. Rezultati kažejo dobro ujemanje z meritvami hitrosti, izvedenimi z anemometrom na vročo žico, ter s teoretičnimi predpostavkami o razvoju curka. Predlagani pristop predstavlja stroškovno učinkovito alternativo konvencionalnim merilnim metodam in odpira možnosti za uporabo psihoakustičnih značilk pri analizi turbulentnih tokov.

Uvod

Hrup turbulentnega curka zraka že desetletja predstavlja enega izmed najzahtevnejših problemov v aeroakustiki, z izrazitim pomenom za inženirske in okoljske aplikacije. Kljub več kot sedemdeset letom raziskav, ki segajo od Lighthill-ove akustične analogije [1], osnovni mehanizmi pretvorbe turbulentnih fluktuacij v zvočno sevanje ostajajo le delno pojasnjeni. Zapletenost izhaja iz narave turbulentnega curka, kjer kaotični tokovi povzročajo tlačne fluktuacije, od katerih le majhen delež prispeva k širjenju zvoka v okolje. Strukturo turbulentnega curka lahko v grobem razdelimo na potencialno jedro, strižno plast in območje zajema [2]. V potencialnem jedru hitrost ostaja konstantna, medtem ko v strižni plasti nastajajo intenzivne turbulentne strukture, ki uravnavajo proces mešanja in zajem okoliškega zraka. V območju zajema prevladuje irrotacijski tok, katerega povprečna meja s strižno plastjo se pojavi pod kotom približno 10°. Interakcije teh struktur povzročajo nastanek vrtincev in posledično hidrodinamičnih ter akustičnih fluktuacij. Hidrodinamične komponente, imenovane tudi psevdovzrok, so lokalne in ne sevajo v okolje, medtem ko akustične fluktuacije predstavljajo pravi zvok, ki se radialno širi iz vira. Vidimo lahko, da je tako nastanek zvoka ob iztekanju zraka, močno povezan s turbulentnimi strukturami. Psihoakustika je področje akustike, ki omogoča opis hrupa z vidika človeškega poslušalca. Namen pristopa je bil oceniti, ali lahko psihoakustične značilke, zasnovane za zaznavo človeškega sluha, prispevajo k boljšemu razumevanju zvočnega polja v bližini turbulentnega toka. Analiza značilke hrapavosti je omogočila identifikacijo in prostorsko predstavitev značilnih območij curka, kot so potencialno jedro in strižna plast, ter s tem ponudila nov način interpretacije interakcije med turbulenco in akustičnim sevanjem. Takšen pristop v obstoječi literaturi doslej še ni bil opisan in predstavlja nov prispevek k razumevanju generacije zvoka v nizko hitrostnih zračnih curkih.

Metodologija

Osnovne ideje psihoakustike in psihoakustične značilke sta predstavila Fastl in Zwicker [3] v 1960-ih. Danes se psihoakustični pristopi uporabljajo predvsem v avtomobilski industriji, diagnozi napak v strojih, v industriji gospodinskih aparatov in pri spremljanju okoljskega hrupa. Ena izmed psihoakustičnih značilk za vrednotenje zvokov je tudi hrapavost R. Hrapavost je slušni občutek, povezan z modulacijami glasnosti pri frekvencah, ki so previsoke, da bi jih lahko ločeno razločili, torej višje od 30 Hz. Značilka je implementirana po standardu ECMA-418-2:2024 [4]. Značilka je bila uporabljena za analizo časovnih signalov tlaka v notranjosti in okolici turbulentnega toka zraka, iztekajočega iz šobe s izstopnim premerom 50 mm. Signale smo posneli z mikrofonom, vpetim na 3-o osni traversirnik, ki nam je omogočal natančno pozicioniranje in opravljanje meritev v 25x17 mreži točk z medsebojno razdaljo 10 mm. Skupaj je bilo zajetih 425 tlačnih signalov. Ob obdelavi smo jih uporabili za izračun ravni zvočnega tlaka (L_p) in vrednosti značilke hrapavost (R). Poleg tlačnih signalov smo z uporabo anemometra na vročo žico zajeli tudi signale hitrosti v preseku curka na šestih oddaljenostih od šobe. Celotna postavitev šobe, curka in merilnih mest je predstavljena na Sliki 1. Uporabljen je bil 1/2" Superlux EMC888B mikrofoni v kombinaciji z merilno kartico Motu Stage B-1, za meritve hitrostnega polja pa Dantec 55P11 1D anemometer in A/D konverterjem Data Translation DT9837. Oba signala sta bila vzorčena s frekvenco vzorčenja 96 kHz.



Slika 1: Uporabljen eksperimentalni sistem in lokacije merilnih mest – rdeče točke predstavljajo merilna mesta kjer je bilo vzorčeno hitrostno polje z anemometrom (HW) v modrem pravokotniku pa so bila postavljena merilna mesta tlačnega polja zajeta z mikrofonom (MIC).

Zajeti signal iz vroče žice je bil v hitrost pretvorjen preko King-ovega zakona. Iz celotnega časovnega signala je bila izračunana srednja vrednost $\bar{u}$ [m/s] in efektivna vrednost fluktuacije hitrosti u'_{RMS} , ki smo jo za lažje razumevanje pretvorili v logaritemsko skalo z enačbo 1.

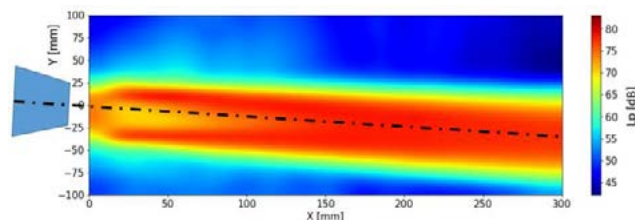
$$u'_{RMS} = 20 \log_{10} \left(\sqrt{u'(t)^2} \right) \quad (1)$$

Šoba in iztek iz nje sta bila vmeščena v brezodmerno sobo. Preko za zvok porozne cevi je bila šoba povezana s centrifugalnim puhalom zunaj sobe, ki je zagotavljalo konstantni masni pretok zraka $m_{pika} = 0.04 \text{ kg/s}$, kar je zadostovalo za produciranje curka zraka z izhodno hitrostjo 0.05 Mach-a. Konec potencialnega jedra curka lahko zaznamo s spremembo statističnih parametrov sploščenosti in asimetrije hitrostnega signala, slednja izračunamo z uporabo enačbe 2.

$$S = \frac{\overline{w(t)^3}}{\overline{w(t)^2}^{3/2}}, \quad F = \frac{\overline{w(t)^4}}{\overline{w(t)^2}^2} \quad (2)$$

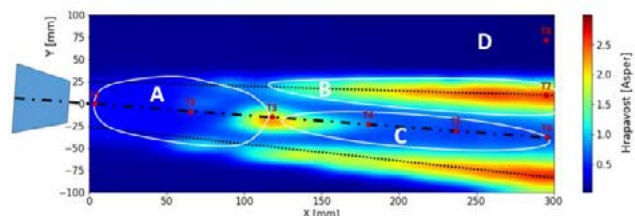
Rezultati in diskusija

Na Sliki 2 je predstavljena raven zvočnega tlaka (L_p) izračunana iz tlačnega signala, posnetega z mikrofonom na vsakem merilnem mestu.



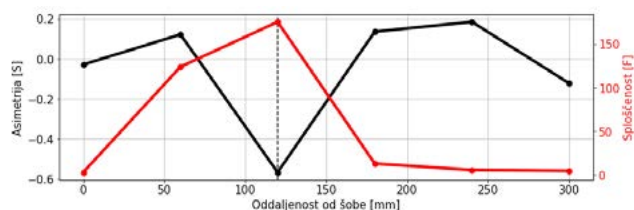
Slika 2: Karta ravni zvočnega tlaka iz šobe iztekajočega curka zraka.

Jasno je razviden curek, ki izteka iz šobe. Višja raven zvočnega tlaka v območju curka je posledica dominantnega hidrodinamskega dela tlačnih fluktuacij, moder del pa predstavlja izsevani akustični del. Opazimo hitro razširitev curka ob izteku iz šobe, ter kasneje rahlo razširjanje vzdolž curka. Posameznih delov curka ni mogoče ločiti. Na Sliki 3 pa lahko vidimo enak tlačni signal obdelan preko značilke hrapavost. Ponovno temno moder del predstavlja mirujoč fluid. Z višjimi vrednostmi značilke pa je povezano območje curka, oz. iztekajočega zraka. Opazno je rdeče območje na osi curka (B), ki predstavlja konec stabilnega potencialnega jedra curka in začetek turbulentno razvitega območja (C). Konec potencialnega jedra identificirata tudi skoka v značilkah sploščenosti in asimetrija hitrostnih fluktuacij, kot je razvidno na Sliki 3, ravno na enaki oddaljenosti od konca šobe.



Slika 3: Karta vrednosti hrapavosti. Rdeče pike so merilna mesta, kjer je bila izračunana raven fluktuacije (Tabela 1). A – potencialno jedro, B – strižna plast, C – razvito turbulentno območje, D – mirujoči fluid.

Opazne sta tudi dve simetrični strukturi v obliki trikotnikov (B), ki zajemata širše območje, kot je za razliko omejeno na Sliki 2.



Slika 4: Vrednosti sploščenosti in asimetrije hitrostnih fluktuacij na osi curka. Preloma na razdalji 120 mm nakazujejo na porušitev potencialnega jedra curka.

Območje nakazuje tudi vrednosti fluktuacije hitrosti izračunane z enačbo 1, ki so predstavljene v Tabeli 1. Opazimo lahko, da vrednost fluktuacije v potencialnem jedru vzdolž osi narašča, ob prehodu v razvito turbulentno območje pa ostaja na enaki ravni. Opazno pa je tudi močno povečanje ravni fluktuacije na točkah, ki se nahajajo na strižni plasti (B), ter potem močan padec v območju mirujočega fluida (C).

Tabela 1: Vrednosti ravni fluktuacije hitrosti na posameznem merilnem mestu označenem na sliki 3.

Merilno mesto	Raven fluktuacije hitrosti [dB]	Območje
T1	0	A
T2	3.8	A
T3	10.5	A
T4	21.6	C
T5	22.0	C
T6	21.8	C
T7	26.2	B
T8	2	D

Zaključek

V prispevku je bila predstavljena nova metoda vizualizacije turbulentnega curka zraka, ki temelji na uporabi psihoakustične značilke hrapavost (R). Analiza prostorske porazdelitve hrapavosti, izračunane iz tlačnih signalov, je omogočila jasno identifikacijo značilnih območij curka, kot so potencialno jedro in strižna plast. Dobljeni rezultati se dobro ujemajo s teoretičnimi predpostavkami o zgradbi curka ter z meritvami hitrostnega polja. Hrapavost se je izkazala kot občutljiv pokazatelj prehoda med stabilnim jedrom in razvito turbulentno regijo, kar potrjuje njeno uporabnost pri analizi turbulentnih struktur. Nova metoda uporablja le mikrofoni in ustrezno obdelavo signalov, kar predstavlja bistveno cenejšo in enostavnejšo alternativo konvencionalnim anemometrih z vročo žico ali optičnih sistemih. Rezultati kažejo, da psihoakustični pristopi lahko nudijo dragoceno orodje za raziskave aeroakustike in odpirajo možnosti za nadaljnji razvoj metod za analizo in vizualizacijo turbulentnih tokov na osnovi zvočnih meritev.

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Analiza dinamike odboja kapljice na superhidrofobni površini z uporabo strojnega učenja

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Trk kapljice s površino predstavlja kompleksen pojav, ki je odvisen od več medsebojno povezanih dejavnikov, kot so lastnosti površine, kapljevine in okolice. V študiji smo z uporabo strojnega učenja na obširni zbirki podatkov o odboju kapljic binarne zmesi glicerina in vode na lasersko-strukturiranih hidrofobiziranih aluminijastih površinah razvili napovedne modele ključnih parametrov popisa trka kapljice s površino in analizirali doprinos vplivnih faktorjev. Pokazali smo, da ima na dinamiko širjenja in odboja kapljice največji vpliv njena hitrost in termofizikalne lastnosti, medtem ko lastnosti površine pomembneje vplivajo predvsem pri odcepitvi kapljice od podlage.

Uvod

Sposobnost odboja kapljic superhidrofobnih površin ima pomembno vlogo v aplikacijah, kot so samočistilnost ter zakasnitev zmrzovanja in korozije, kjer je bistveno skrajšanje kontaktnega časa med kapljico in površino. Zaradi kompleksnega prepletanja vplivov lastnosti površine, kapljevine in okolice pa dinamika trka kapljice še vedno ostaja nerazjasnjena. Z namenom razjasnitve vloge posameznih vplivnih dejavnikov smo z uporabo strojnega učenja na obsežni bazi podatkov razvili napovedne modele ključnih parametrov popisa odboja kapljice in analizirali njihove doprinose k izidu trka.

Metodologija dela

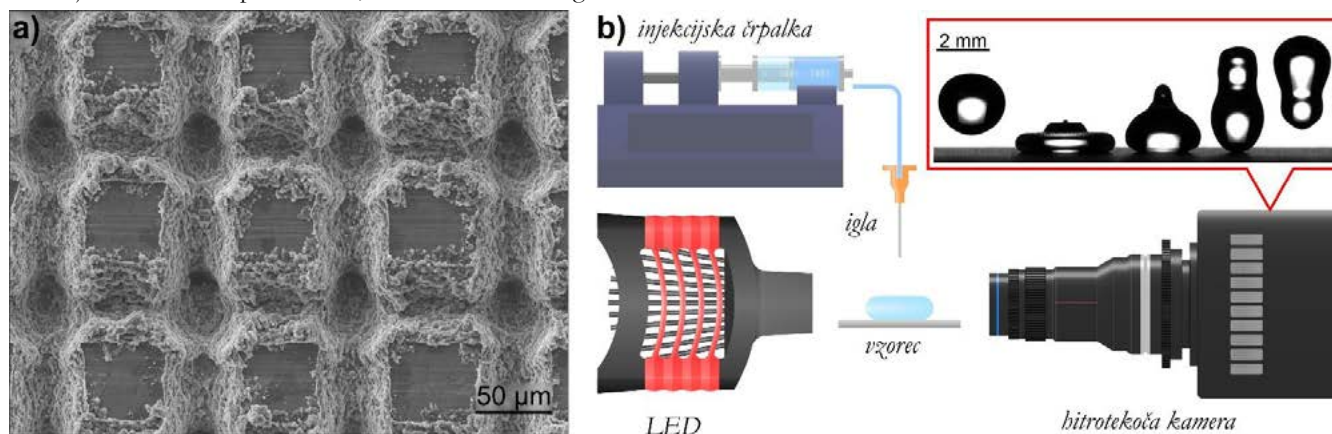
Priprava vzorcev. Superhidrofobne površine smo izdelali na aluminijastih ploščicah (1050A H24, $\geq 99,5\%$) s kombinacijo laserskega strukturiranja in hidrofobizacije površine. Z nanosekundnim bliskovnim vlakenskim laserjem (FL Mark-C with JPT Opto-electronics "M7 30 W" MOPA source) smo z variacijo obdelovalnih parametrov, ki so navedeni v Preglednici

1, na površinah izdelali mikrokanele globine ~ 6 in ~ 25 μm z razmaki 50, 100, 200, 400, 600 in 800 μm med središči kanalov. Slika 1a prikazuje primer lasersko-strukturirane površine z globokimi kanali z razmakom 100 μm pri 350-kratni povečavi. Strukturirane površine smo hidrofobizirali s kapljičnim nanosom 3 mM raztopine 1H,1H',2H,2H'-perfluorododecil-1-fosfonske kisline (FDPA) v 2-propanolu. Po obdelavi so vse površine izkazovale superhidrofobne lastnosti s kotom omočenja nad 160° in kotom zdrsa pod 1° .

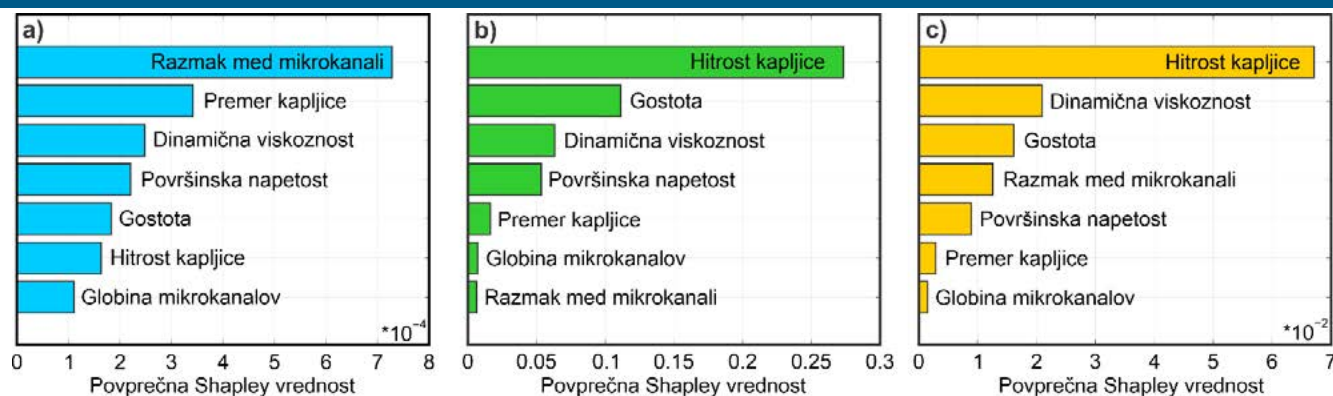
Preglednica 1: Obdelovalni parametri laserskega sistema.

Parameter obdelave	Globoki kanali	Plitvi kanali
Hitrost skeniranja [mm s^{-1}]	400	1650
Frekvenca bliskov [kHz]	80	110
Dolžina bliska [ns]	100	45
Fluena [J cm^{-2}]	45,8	33,3

Merilni protokol. Meritve odboja kapljic smo izvedli z binarno zmesjo glicerina in vode z masnim deležem glicerina 0, 20, 60, 78 in 91 % na merilni progi, shematsko prikazani na sliki 1b. Kapljice kontrolirane velikosti smo izdelali z injekcijsko črpalko (Harvard Apparatus PHD 2000) in iglo z ravno konico ter jih na površine spuščali s pet različnih višin. Odboje smo zajeli s hitrotekočo kamero (Photron FASTCAM Mini UX100) pri hitrosti zajema 5000 fps z ločljivostjo ~ 12 $\mu\text{m px}^{-1}$. S strojno obdelavo slik smo iz posnetkov meritev določili glavne parametre za popis interakcije kapljice s površino: (i) premer kapljice D_0 , (ii) hitrost kapljice pred trkom v_0 , (iii) kontaktni čas τ , (iv) maksimalno radialno razširitev kapljice D_{max} in (v) višino odboja kapljice h_{max} , ter izračunali maksimalni koeficient širjenja ($\beta_{\text{max}} = D_{\text{max}}/D_0$) in izkoristek odboja η , ki predstavlja razmerje med potencialno energijo kapljice v najvišji točki po odboju in kinetično energijo pred trkom. Eksperimentalni podatki so objavljeni kot zaključena znanstvena zbirka raziskovalnih podatkov na prosto dostopnem repozitoriju [1].



Slika 1: Metodologija dela meritev odboja kapljic na superhidrofobni površini: (a) površina z globokimi kanali z razmakom 100 μm med središči mikrokanalet pri 350-kratni povečavi in (b) shema merilne proge.



Slika 2: Povprečne Shapley vrednosti za: (a) kontaktni čas, (b) maksimalni koeficient širjenja in (c) učinkovitost odboja.

Strojno učenje. Rezultate meritev odboja kapljice smo prestrukturirali v nabor napovednih (vhodnih) in napovedovanih (izhodnih) spremenljivk. Izhodne spremenljivke zajemajo parametre, ki opisujejo izid trka kapljice s površino (τ , $\beta_{\max}$ in η), medtem ko vhodne spremenljivke vključujejo parametre popisa lastnosti kapljice pred trkom (D_0 in n_0), termofizikalne lastnosti kapljevine (gostota ρ , površinska napetost γ in dinamična viskoznost μ) ter topološke značilnosti površine (razmak in globina mikrokanalov d in b). Za vsako izhodno spremenljivko smo v razvojnem okolju MATLAB Regression Learner razvili večvhodni model strojnega učenja. Kot najbolj točen se je izkazal izotropni eksponentni model Gaussove procesne regresije (IE GPR), ki smo ga nato dodatno optimizirali z Bayesovo optimizacijo.

Rezultati in diskusija

Z naučenim IE GPR modelom lahko za interpretacijo prispevka posameznih vhodnih spremenljivk pri določeni napovedi izračunamo Shapley vrednosti. Če to storimo za vse podatkovne točke in rezultate povprečimo, dobimo povprečno pomembnost vsakega napovednega parametra na izhodno spremenljivko za celoten set podatkov. Povprečne Shapley vrednosti za kontaktni čas, maksimalni koeficient širjenja in učinkovitost odboja so prikazane na sliki 2.

Pri napovedi dolžine kontaktnega časa model največji pomen pripisuje razmaku med mikrokanali. Velikost razmaka neposredno vpliva na adhezijo med kapljico in površino, saj je ta na nestrukturirani površini večja, zato na površinah z manjšo gostoto mikrokanalov opazimo daljši čas odcepitev kapljice. Presenetljivo je, da model kaže relativno neodvisnost dolžine kontaktnega časa od termofizikalnih lastnosti kapljice in njene velikosti, čeprav je njihova povezava splošno uveljavljena $\tau \sim (\rho R_0 / \gamma)^{1/2}$ [2]. Slednje lahko pripišemo omejenemu raztrosu eksperimentalno izmerjenih vrednosti kontaktnega časa, ki so bile uporabljene za razvoj napovednega modela, kar zmanjšuje zanesljivost napovedi.

V nasprotju s kontaktnim časom model pri napovedi maksimalnega koeficienta širjenja topološkim značilnostim površine pripisuje najmanjši pomen izmed vseh vhodnih parametrov, medtem ko kot glavni vplivni faktor izpostavlja hitrost kapljice ob trku. Ob trku kapljice s površino se ta prične horizontalno raztezati po površini, pri čemer se njena kinetična energija pretvarja v površinsko energijo, do točke maksimalnega raztezka, v kateri je kinetična energija kapljice

enaka 0. S spremembo hitrosti kapljice dosežemo povečanje oz. zmanjšanje njene kinetične energije in s tem tudi maksimalnega raztezka, kar pojasnjuje opaženo odvisnost med parametroma. Poleg hitrosti kapljice model velik pomen pripisuje tudi njenim termofizikalnim lastnostim. Sprememba gostote kapljevine podobno kot hitrost botruje k povečanju oz. zmanjšanju kinetične energije kapljice pred trkom, medtem ko viskoznost in površinska napetost zavirata deformacijo kapljevine oz. širjenje kapljice po površini. Presenetljivo model ne kaže korelacije med maksimalnim koeficientom širjenja in velikostjo kapljice, ki sicer prav tako vpliva kinetično energijo pred trkom, vendar je vredno izpostaviti, da je bila med eksperimenti velikost kapljice konstanta.

Tako kot pri maksimalnem koeficientu širjenja, tudi za učinkovitost odboja napovedni model največji pomen pripisuje hitrosti kapljice pred trkom, le da je v tem primeru njuna odvisnost obratno sorazmerna. Kot že rečeno, višja hitrost kapljice ob trku botruje k večjemu maksimalnemu raztezku, zaradi katerega pa prihaja do večje viskozne disipacije energije, kar se odraža v nižji učinkovitosti odboja. Na učinkovitost odboja pomembno vplivajo tudi termofizikalne lastnosti kapljevine, saj s povečanjem njene viskoznosti in površinske napetosti dosežemo večjo izgubo energije. V primeru učinkovitosti odboja model kot vplivni faktor izpostavlja tudi razmak med mikrokanali, kar potrjuje razlago o povečanju adhezije na površinah z manjšo gostoto mikrokanalov in nakazuje na to, da adhezija površine ne igra bistvene vloge pri širjenju kapljice na površini.

Zaključki

V študiji smo z uporabo strojnega učenja razvili napovedne modele kontaktnega časa, maksimalnega koeficienta širjenja in učinkovitosti odboja. Pokazali smo, da na dinamiko odboja kapljice najbolj vpliva njena hitrost pred trkom, sledijo njene termofizikalne lastnosti, topološke lastnosti površine pa vplivajo le na odcepitev kapljice od površine.

Zahvala

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Aerodynamics of a tumble dryer with a novel drum design

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A redesign of a tumble dryer demonstrates how flow path geometry alone can improve aerodynamic performance and energy efficiency. A drum with a laterally perforated wall eliminates the need for front and rear ducts, reducing aerodynamic losses by up to 20% and allowing an 18% increase in drum volume without increasing the dryer footprint.

Introduction

Tumble dryers are among most common household appliances, used to dry laundry. Their operation relies on the circulation of hot, dry air through a rotating drum containing wet laundry. In modern heat-pump dryers, the process air circulates in a closed loop: when it leaves the drum, it first passes through the cold evaporator, where water from the moist air condenses, and then through a condenser, where the air is reheated before returning to the drum. The heat-pump configuration is versatile but compact, allowing efficient heat recovery within tight spatial constraints.

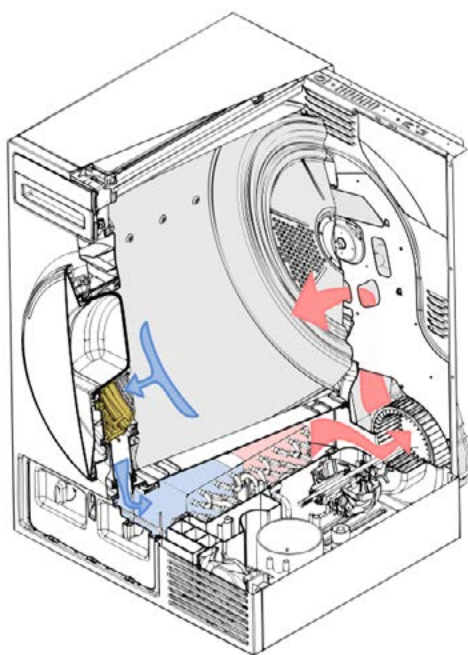


Figure 1: Conventional heat-pump tumble dryer flow tract.

Most domestic dryers use a drum where air enters through a perforated rear wall and exits through the opening at the front. In this arrangement, air must enter and leave the drum along the drum rotation axis, requiring additional ducting at both ends. These channels occupy valuable space, reducing the maximum drum length and forcing the flow to change direction twice: first, from the radial fan outlet to axial flow

through the drum, and second, from the axial drum-front outlet to radial flow towards the filter. Such abrupt turns generate pressure losses and increase fan power demand, while the additional ducting reduces the effective drum length and volume. In compact domestic appliances, the trade-off between aerodynamic efficiency and available space is therefore unavoidable.

Materials and methods

To address these limitations, a new concept featuring a drum with laterally perforated wall was proposed and investigated. In this configuration, drying air enters the drum radially through its lateral wall, eliminating the need for both rear and front ducts and resulting in a shorter airflow path with fewer turns. The prototype retained the standard drum diameter of 575 mm but extended its length from 465 mm to 550 mm, increasing the internal volume by 18% (from 121 L to 143 L) without altering the external dimensions.

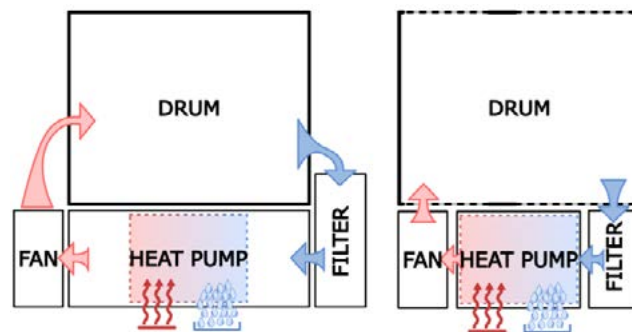


Figure 2: Conventional dryer (left) and novel dryer with perforated drum (right) — schematic of the airflow path.

To evaluate the concept, the aerodynamic characteristics of the perforated-drum dryer were compared with those of a conventional design under identical operating conditions. The airflow rate was determined indirectly from the pressure drop across the condenser [1]. Its pressure–flow rate characteristic was obtained in a separate experiment, in which the dryer was disassembled and the section of the channel housing the heat exchangers was attached to an apparatus used to set and measure the flow rate and pressure drop across the condenser. Subsequently, during in situ operation, the pressure drop measured across the condenser was used to calculate the flow rate. The aerodynamic properties were evaluated for 4 kg, 6 kg, and 8 kg cotton loads while fan speed was varied to generate different flow rate conditions. Measurements were carried out under steady-state conditions without heating to eliminate the influence of temperature and humidity. The total system pressure drop was measured between the fan outlet and inlet, encompassing the drum, ducts, and heat exchangers.

Results and discussion

The perforated-drum configuration exhibited lower system resistance than the conventional design. The pressure–flow curve aligns well with the theoretical second-order dependence of pressure drop on velocity. At the nominal flow rate of $280 \text{ m}^3 \text{ h}^{-1}$, the overall pressure drop decreased from approximately 740 Pa to 620 Pa – a reduction of approximately 20%. From an aerodynamic standpoint, the fan power demand scales approximately linearly with pressure drop when the airflow rate is held constant. Hence, the pressure drop reduction translates directly into lower fan power consumption. Assuming a combined fan–motor efficiency of 50%, the electrical input required to maintain the same flow rate decreases from roughly 150 W to 125 W. Over a 150-minute drying cycle, this equates to an energy saving of about 0.06 kWh, or roughly 4% of the total heat-pump dryer energy demand [2]. Although modest in absolute terms, such savings are significant for an appliance in which the fan operates continuously throughout the entire cycle. Moreover, reduced aerodynamic resistance allows for operation at lower fan speeds, thereby lowering noise emissions and further improving system efficiency.

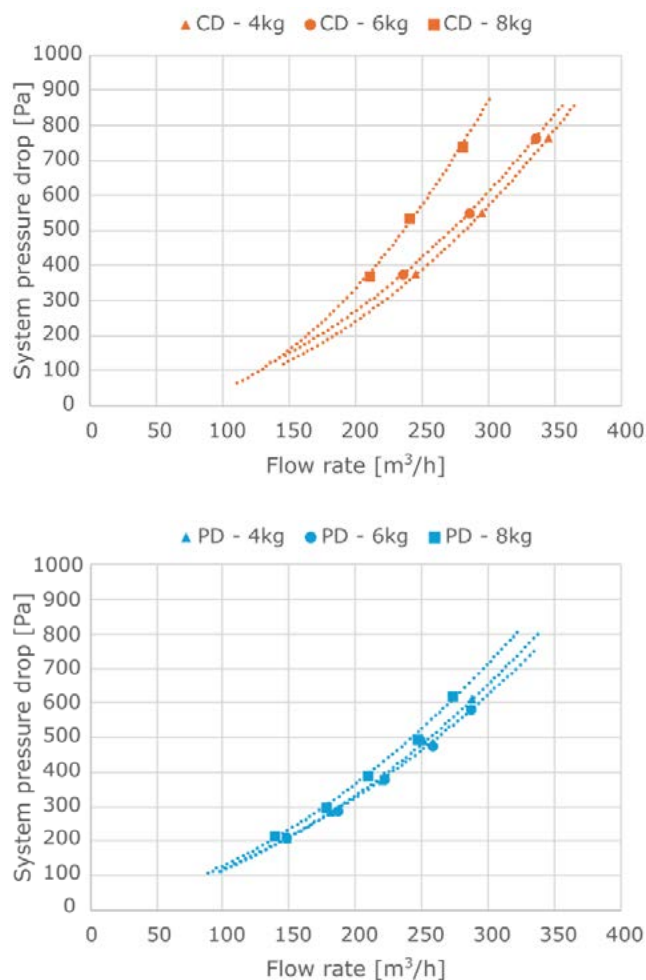


Figure 3: System pressure drop characteristics of the conventional (top) and novel, perforated drum dryers (bottom).

Load mass also influenced the airflow behaviour. In the conventional dryer, partial loads of 4 kg and 6 kg produced unexpectedly low pressure drop compared with the fully loaded drum. This behaviour indicates the formation of void regions within the laundry mass that create aerodynamic short-circuits, allowing air to bypass parts of the fabric surface. Although such bypassing reduces the overall pressure drop, it simultaneously decreases the effective air–fabric contact area, thereby lowering convective heat and mass transfer efficiency.

The laterally perforated drum behaved differently. Because air enters through the lateral wall, it is forced to pass through the fabric layers regardless of load mass. This radial inflow prevents the formation of bypass voids, which is indicated by the consistent pressure drop across the entire load range. The forced passage of the drying air also promotes more homogeneous temperature and humidity distribution inside the drum, improving drying uniformity and reducing local overheating or under-drying. Furthermore, it allows operation at lower drum rotational speeds, which helps to reduce fabric fibre emissions [3].

Conclusions

The experimental comparison shows that a significant modification of the flow tract geometry is required to achieve a measurable improvement in the dryer’s aerodynamic performance. The laterally perforated drum reduced total pressure drop by about 20% at nominal flow rate, corresponding to a proportional decrease in fan power demand. In practical terms, this represents up to 4% of the total electrical energy consumed by the dryer. More importantly, removing the front and rear ducts allows for an 18% larger drum volume within the same device footprint. Hence, increasing the load capacity without enlarging the appliance. The radial inflow through the lateral drum wall also prevents aerodynamic short-circuiting at lower loads, maintaining predictable performance across varying load conditions.

Although the present tests focused solely on airflow, the implications extend to drying efficiency and acoustic performance. The perforated drum design challenges the long-standing assumption that process air must enter the drum axially. By utilising the drum’s cylindrical geometry for radial inflow, the design simultaneously improves aerodynamic efficiency while increasing the effective drum volume. Future work will extend this analysis to drying tests and experimental modelling to optimise operational parameters, drying time, energy efficiency, and moisture extraction rate.

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Zasnova in analiza kriterijev za določitev agresivnosti vožnje avtobusa

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Agresivnost vožnje znatno vpliva na porabo energije za pogon vozil. Zato je cilj raziskave razvoj enostavnega in splošno uporabnega kriterija za določitev agresivnosti vožnje, ki se čim bolj ujema z močjo, ki je potrebna za premikanje vozila, a kot vstopne podatke upošteva zgolj parametre dinamike vozila, kot so pospešek, hitrost in sprememba višine. Na osnovi realnih meritev vožnje avtobusov na zelo različnih linijah je bil identificiran najbolj primeren kriterij, ki zraven zmnožka hitrosti in pospeška vozila upošteva tudi zmnožek gravitacijskega pospeška in vertikalne hitrosti. Podani so tudi razponi vrednosti tega kriterija in vrednosti, ki nakazujejo na agresivnejšo vožnjo.

Uvod

Promet je velik porabnik energije in znatno doprinaša k izpustom toplogrednih plinov ter človeku škodljivih snovi. Na porabo energije pri vožnji in torej izpuste onesnažil ima znaten vpliv agresivnost vožnje, ki je za določen tip vozila v največji meri odvisna od voznika. Pri istem tipu vozila na isti liniji je možno doseči občutno nižjo porabo, če voznik vozi bolj umirjeno. Viri navajajo, da je možno prihraniti kar do 23 odstotkov [1].

Način vožnje ima še posebej velik vpliv na okolje za vozila, ki so v redni rabi, in za vozila, ki imajo večjo porabo goriva. V raziskavi smo se osredotočili na avtobuse LPP, ki se uporabljajo dnevno in predstavljajo velike porabnike goriva. Agresivnost vožnje najnatančneje določamo z močjo, ki je potrebna za premikanje vozila, in upošteva vse relevantne parametre dinamike vožnje in parametre vozila. Izračun moči torej zahteva poznavanje mnogo parametrov vozila, kar je ovira za splošno, hitro in enostavno rabo takšnega kriterija.

Zato je cilj raziskave razvoj kriterija, ki se čim bolj ujema z močjo, ki je potrebna za premikanje vozila, a kot vstopne podatke upošteva zgolj parametre dinamike vozila, kot so pospešek, hitrost in sprememba višine. Vsi ti parametri so enostavno merljivi z GPS merilci. S tem namenom smo zasnovali tri kriterije za popis agresivnosti vožnje, katerih ustreznost smo preverili z ujemanjem z močjo, ki je potrebna za premikanje vozila. Podali smo tudi razpone vrednosti najustrežnejšega kriterija za vožnjo avtobusa po zelo različnih voznih cikli in jih primerjali z vrednostmi za osebne automobile.

Materiali in metode

Pogonsko silo (F_{pog}) določimo iz dinamike vozila, zračnega upora, sile kotalnega trenja pnevmatik in dinamične komponente sile teže.

$$F_{pog} = a \cdot m_{avtobus} + F_{zr.upor} + F_{kot.upor} + F_d \quad (1)$$

Moč, ki je potrebna za premikanje vozila, izračunamo z zmnožkom F_{pog} in hitrosti

$$P = F_{pog} \cdot v \quad (2)$$

Za izračun vseh prej naštetih sil in posledično moči potrebujemo podatke kot so masa vozila, čelna površina, koeficient zračnega upora in koeficient trenja pnevmatik ter podatke o gostoti okoliškega zraka, kar otežuje enostavno uporabo takšnega izračuna za določitev agresivnosti vožnje za veliko število različnih avtobusov.

Zaradi kompleksnosti izračuna agresivnosti na prej opisani način je cilj naloge določiti najustrežnejši kriterij, ki bi kar najbolje koreliral s potekom odvisnosti moči od časa, hkrati pa bi kot vstopne podatke uporabljal zgolj parametre, ki jih je enostavno meriti z GPS merilnikom ali celo mobilnim telefonom.

V skladu s temi cilji smo v okviru raziskave raziskali ustreznost naslednjih treh kriterijev za določitev agresivnosti vožnje. Kriterij, ki določa agresivnost zgolj na osnovi pospeška:

$$K_1 = a \quad (3)$$

kriterij, ki določa agresivnost na osnovi zmnožka hitrosti in pospeška v smeri vožnje vozila.

$$K_2 = v \cdot a \quad (4)$$

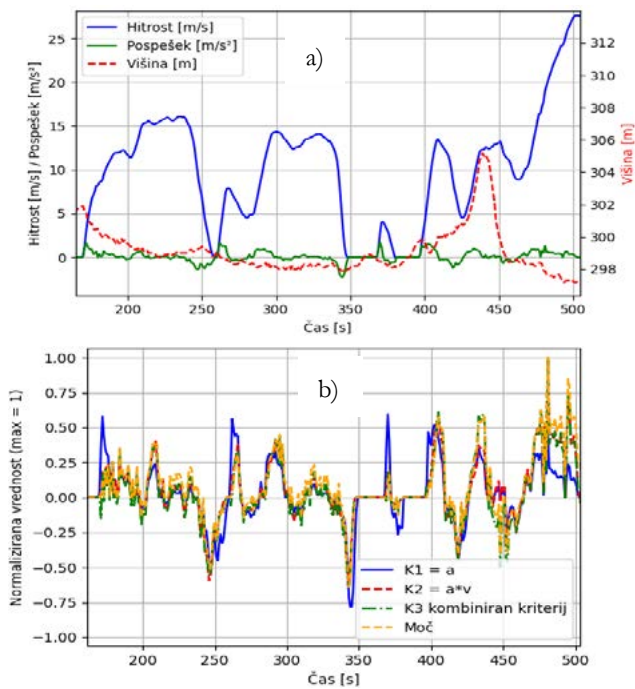
in kriterij K_3 , ki zraven vodoravne komponente K_2 upošteva tudi zmnožek gravitacijskega pospeška in vertikalne hitrosti.

$$K_3 = v \cdot a + v \cdot g \cdot \sin \alpha \quad (5)$$

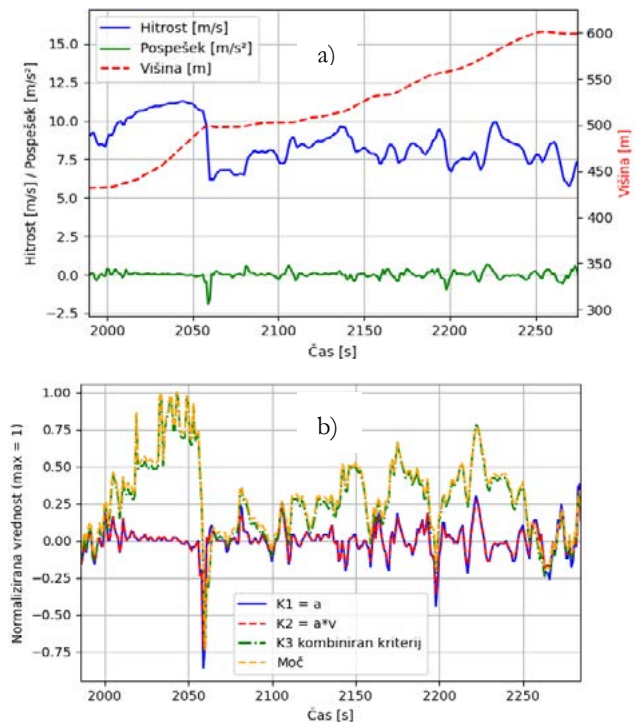
Meritve so bile izvedene z merilnikom Sensors Semtech DS na medkrajevem avtobusu, ki ga poganja EURO 6 dizelski motor, na treh tipičnih in zelo različnih linijah: ravninska linija (Ljubljana - Grosuplje), hribovita linija (Ljubljana - Šentjošt) in avtocestna linija (Ljubljana - Vrhnika). Različne topologije linij so namreč ključne za analizo ustreznosti posameznih kriterijev. Testne vožnje so bile opravljene v času običajnega prometa, vozilo pa je bilo obteženo s povprečnim številom potnikov.

Rezultati in diskusija

Slika 1 prikazuje parametre vozila in primerjavo kriterijev K_1 - K_3 in moči za del ravninske linije Ljubljana - Grosuplje. Kot je razvidno iz enačb (1) in (2) je moč, ki je potrebna za premikanje vozila, odvisna od produkta $v \cdot a$, kar pomeni, da $K_1 = a$ ni ustrezen kriterij, saj slabo korelira z močjo. Pričakovano so normalizirane vrednosti pospeška višje od normaliziranih vrednosti moči (Slika 1 b), ko je hitrost vozila nizka, in nižje, ko je hitrost vozila visoka (Slika 1 a) okoli časa 210 s in med 470 s in 500 s). Ker je na tej liniji sprememba višine majhna, imata kriterija K_2 in K_3 v večini analiziranega intervala podobne vrednosti in v splošnem dobro korelirata s potekom moči. Večje odstopanje se pojavi v delih linije, kjer se višina bolj intenzivno spremeni (na primer okoli časa 430 s). V teh primerih kriterij K_3 pričakovano bolje sovпада z močjo, saj upošteva spremembo višine cestišča.



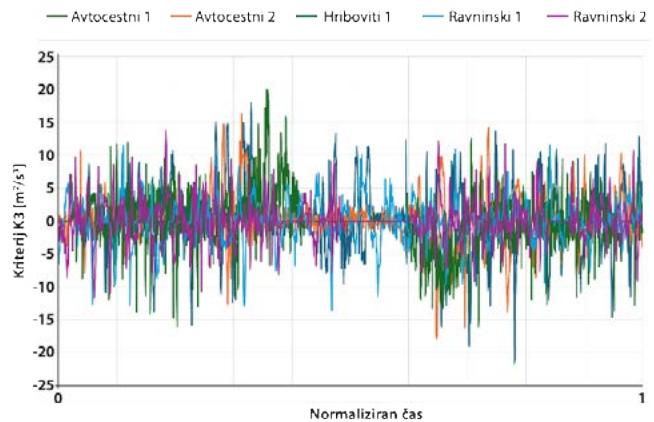
Slika 1: a) Hitrost, pospešek in višina ter b) normalizirane vrednosti kriterijev $K_1 - K_3$ in moči za del ravninske linije Ljubljana - Grosuplje. Razlika med kriterijema K_2 in K_3 pa je še mnogo bolj očitna na hribovitem delu linije (Slika 2), kjer je zelo očitna razlika med korelacijo kriterija K_2 in K_3 z močjo v vseh analiziranih delih cikla razen redkih izjem, kjer se višina bistveno ne spremeni. Slika 2 a) in b) jasno nakazuje, da v primerih, ko se znatno spreminja višina, zmnožek gravitacijskega pospeška in vertikalne hitrosti najbolj odločilno vpliva na moč. Iz analiziranih podatkov lahko jasno zaključimo, da je za določanje agresivnosti vožnje v primeru poljubnih voznih ciklov najbolj primeren kriterij K_3 , kriterij K_2 pa je primeren za ravninske linije.



Slika 2: a) Hitrost, pospešek in višina ter b) normalizirane vrednosti kriterijev $K_1 - K_3$ in moči za del hribovite linije Ljubljana - Šentjošt.

Slika 3 prikaže absolutne vrednosti kriterija K_3 za vse tri linije, za ravninsko in avtocestno linijo pa sta dodatno prikazani dve vožnji po tej liniji. Iz slike je razvidno, da je za večino delov voženj značilna vrednost K_3 v času pozitivnih moči za pogon vozila manjša od $10 \text{ m}^2/\text{s}^3$, redkeje pa se te vrednosti povzpnejo do $20 \text{ m}^2/\text{s}^3$. V slednjih primerih se moč motorja približa največji vrednosti 250 kW, ker pomeni, da ta vrednost predstavlja agresivno vožnjo.

Za osebne avtomobile so za vožnje v prostem prometnem toku skladno z RDE protokolom določene največje vrednosti zmnožka $v \cdot a$, ki se od vrednosti približno $15 \text{ m}^2/\text{s}^3$ pri hitrosti 0 poveča do približno $25 \text{ m}^2/\text{s}^3$ pri hitrosti 75 km/h in do približno $30 \text{ m}^2/\text{s}^3$ pri hitrosti 150 km/h [2]. Za avtobuse te vrednosti niso tako enolično določene, a lahko na podlagi izvedene analize povzamemo, da vrednosti nad $10 \text{ m}^2/\text{s}^3$ nakazujejo na agresivnejšo vožnjo.



Slika 3: Kriterij K_3 za pet ciklov v odvisnosti od normaliziranega časa.

Zaključek

Na osnovi realnih meritev vožnje avtobusa na zelo različnih linijah je bil identificiran najbolj primeren, enostaven in splošno uporaben kriterij, ki upošteva zgolj parametre dinamike vozila, kot so pospešek, hitrost in sprememba višine. Kriterij zraven zmnožka hitrosti in pospeška vozila upošteva tudi zmnožek gravitacijskega pospeška in vertikalne hitrosti, ki je ključen člen za določitev agresivnosti vožnje na hribovitih linijah. Na osnovi analiziranih podatkov lahko povzamemo, da vrednosti kriterija nad $10 \text{ m}^2/\text{s}^3$ nakazujejo na agresivnejšo vožnjo.

Zahvala Avtorja se zahvalujeta prof. dr. Tomažu Ktrašniku za pomoč pri koncipiranju objave in potrjujeta, da je bila študija izvedena ob podpori projekta CRP V2-2134.

- [1] A. Mohammadnazar et al. Transp. Res. Part D: Transp. Environ. 126 (2024) 104025.
- [2] Komisija EU. Uredba (EU) 2016/427, UL EU L 82/1 (2016).

Trdnostna analiza ogrodja gorskega kolesa pri testu zaviranja

Valentin Šmon, Andrej Škrlec, Marko Nagode, Jernej Klemenc, Domen Šeruga*

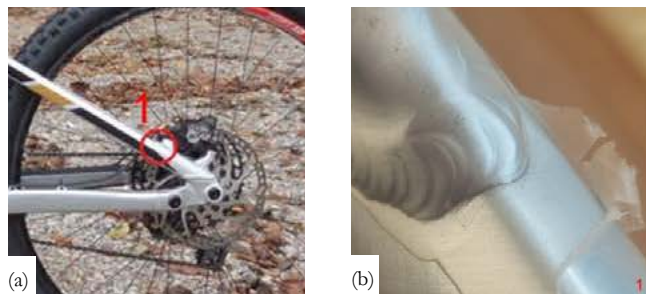
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V raziskavi smo obravnavali del ogrodja gorskega kolesa, ki smo ga obremenili z enako obremenitvijo kot pri standardnem testu zaviranja. Zanimalo nas je, ali je pojav razpoke na okvirju poleg nosilca zadnje zavorne čeljusti posledica preobremenitev ali pa se lahko pojavi kot posledica utrujanja gradiva.

Uvod

Obremenitve pri vožnji povzročajo kompleksno napetostno stanje v okvirju gorskega kolesa, kar lahko vodi v nastanek razpok na izdelku in nenazadnje porušitev konstrukcije [1,2]. Problem predstavljajo predvsem geometrijski prehodi, saj je tam večja koncentracija napetosti. Vsaka razpoka predstavlja problem, ki lahko pomembno vpliva na vzdržljivost konstrukcije, v primeru porušitve med uporabo pa lahko pride celo do poškodb uporabnika.

Pri uporabi obstoječega okvirja se je pojavila razpoka poleg nosilca zadnje zavorne čeljusti (Slika 1a). Standard ISO 4210:6 opisuje obremenitve in kriterije pritrditve okvirja za izvedbo testa zaviranja, ki ga mora okvir prestati, da bi zagotovil nemoteno obratovanje v velikocikličnem območju [3,4]. Zanimalo nas je, kakšno deformacijsko stanje se pojavi v okolici kritičnega detajla (na Sliki 1b) pri standardnem testu zaviranja in ali bi lahko takšno stanje bilo razlog za pojav utrujenostne poškodbe izdelka.



Slika 1: (a) Mesto poškodbe okvirja gorskega kolesa in (b) poškodba poleg nosilca zavorne čeljusti.

Uporabili smo simulacijo z metodo končnih elementov, s pomočjo katere smo lahko analizirali obnašanje dela okvirja gorskega kolesa pri zaviranju, kot verifikacijo za namen potrditve predpostavk pa smo pri enakih pogojih izvedli laboratorijski preizkus.

Metoda

Geometrijski model zadnjega dela gorskega kolesa (slika 2a) smo uvozili v programsko okolje Abaqus, v katerem smo dodatno modelirali poenostavljeno zadnje platišče vključno z zavorno čeljustjo (slika 2b). Na tak način smo lahko prenesli vzvojni moment velikosti 258 Nm, ki nastane kot posledica

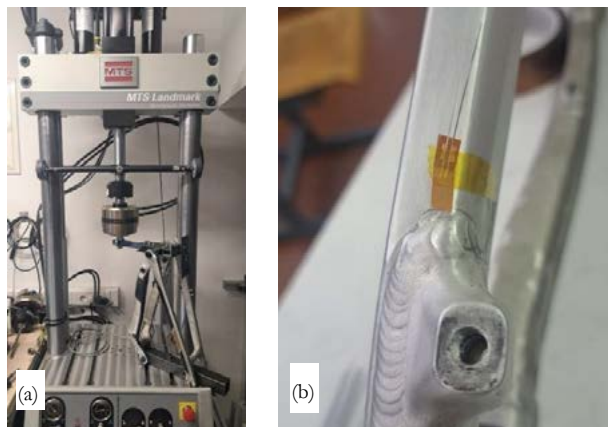
zaviralne sile, ki jo predpisuje standard, na mesto, kjer bi bila v realnosti pritrjena zavorna čeljust. Pri izdelavi poenostavljenega platišča smo upoštevali standard, ki določa dolžino ročice 368 mm v primeru obravnavanega 29 colskega kolesa. Poenostavljeno platišče smo nato povezali s sestavo zadnjega dela okvirja gorskega kolesa, njegovo pozicijo in orientacijo prikazuje slika 2b. Na mestu, kjer je pritrjena zavorna čeljust, smo uporabili večtočkovno omejitve in izbrali togo povezavo. Enako smo naredili na obeh mestih, kjer se čeljust pritrdi na okvir. Zadnje platišče smo pritrčili na okvir preko simuliranega pesta platišča, pri tem pa smo morali sprostiti rotacijsko prostostno stopnjo. S tem smo omogočili realen prenos obremenitev neposredno na nosilec zavorne čeljusti pri simulaciji zaviranja. Pri izdelavi modela končnih elementov smo izdelali mrežo, pri kateri nismo upoštevali opažene razpoke (mreža 1) in mrežo z opaženo velikostjo razpoke (mreža 2).



Slika 2: (a) Geometrijski model zadnjega dela okvirja gorskega kolesa in (b) modeliranje platišča, pritrditve zavorne čeljusti in vnos robnih pogojev.

Za izvedbo laboratorijskega preizkusa smo morali testirane dele okvirja ustrezno pritrčiti, da med obremenjevanjem ne bi prihajalo do premikov. Najprej smo izmerili preizkuševališče, nato pa izdelali poenostavljen geometrijski model, s katerim smo preverili možnost pozicioniranja in pritrditve testnega kosa. Poleg pritrditve smo zasnovali tudi ročico, ki smo jo pritrčili na hidravlični valj preizkuševališča, s čimer smo ustvarili aksialno silo in posledično zaviralni moment (slika 3a). Ročico smo pritrčili na nosilno strukturo z uporabo osi, ki je omogočala rotacijo, medtem ko so bile translacijske prostostne stopnje onemogočene – enako kot pri simulaciji oz. pri zaviranju s testiranim okvirjem gorskega kolesa. Ob obremenitvi se je sila neposredno prenesla na okvir preko nosilca zavorne čeljusti. Za izdelavo vpenjalnega sistema in ročice smo uporabili jeklene profile različnih oblik, s čimer smo zagotovili čim večjo togost vpenjalnega sistema za prenos obremenitev. V nadaljevanju smo namestili merilni listič v neposredno bližino razpoke, usmerjen v smeri delovanja prve glavne napetosti v okolici tega geometrijskega detajla. Na podlagi simulacij smo analizirali smer silnic napetostnega polja in izbrali območje čim bližje razpoki z ravno površino, primerno za namestitev merilnega lističa. Analiza je pokazala, da so bile silnice prve glavne napetosti na merilnem mestu

usmerjene vzporedno z osjo cevi okvirja, zato smo merilni listič namestili vzdolž cevi kot prikazuje slika 3b. Uporabili smo merilni listič tipa 1-LY11-3/120. Po namestitvi smo ga vključili v polmostično vezavo, skupaj z dodatnim lističem za temperaturno kompenzacijo.

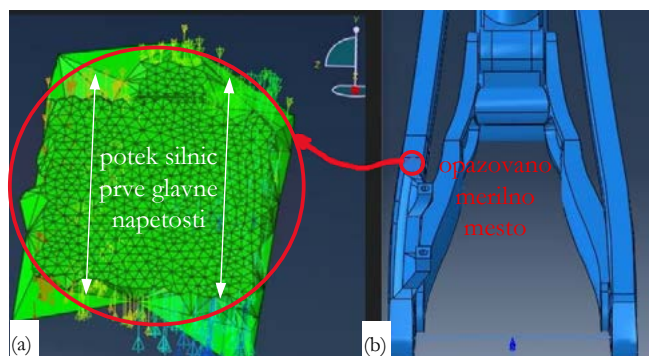


Slika 3: (a) Postavitev zadnjega dela okvirja gorskega kolesa pred začetkom laboratorijskega preizkusa in (b) namestitev merilnega lističa.

V čeljust servo-hidravličnega preizkuševališča smo vpeli očesni vijak, skozi katerega smo pozicionirali ročico za prenos obremenitve (slika 3a). Merilni listič (slika 3b) smo povezali z ojačevalnikom HPSC 3102, ki je ojačal izhodni signal. Ta se je zajemal z računalnikom in sproti zapisoval v tekstovno datoteko.

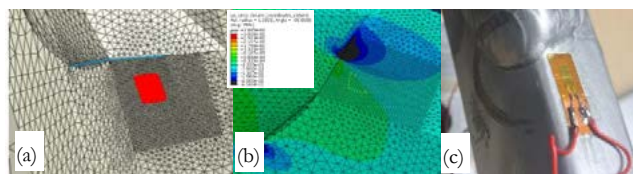
Rezultati in diskusija

Rezultat simulacije na merilnem mestu pri zaviranju z analiziranim zadnjim delom okvirja gorskega kolesa in mrežo 1 je prikazan na sliki 4. Silnice prve glavne napetosti potekajo vzdolž cevi okvirja, v smeri katere smo tudi nalepili merilni listič. Simulirana vrednost prve glavne specifične deformacije z mrežo 1 je znašala $-0,00935 \text{ mm/mm}$.



Slika 4: (a) Potek silnic prve glavne napetosti pri simulaciji obremenitve z mrežo 1 na (b) lokaciji merilnega mesta.

Rezultat trdnostne analize z MKE in mrežo 2 je na lokaciji merilnega lističa (slika 5a) pokazal vrednost prve glavne specifične deformacije $-0,00360 \text{ mm/mm}$ (slika 5b), rezultat laboratorijskega preizkusa specifične deformacije na merilnem lističu (slika 5c) pa je znašal $-0,00316 \text{ mm/mm}$.



Slika 5: (a) Mreža 2 s prikazano lokacijo merilnega lističa, (b) rezultat trdnostne analize z MKE pri mreži 2 in (c) merilni listič v okolici razpoke.

Če v simulaciji ne upoštevamo razpoke (mreža 1), je opazno, da rezultati precej odstopajo od rezultatov laboratorijskega preizkusa. Ob upoštevanju razpoke v simulaciji (mreža 2) se z rezultati približamo deformacijskemu stanju pri laboratorijskem preizkusu. Odstopanje specifične deformacije pri nazivni obremenitvi (vzvojni moment velikosti 258 Nm) v tem primeru znaša $12,4 \%$. Sklepamo, da je odstopanje simuliranih in pomerjenih rezultatov predvsem posledica geometrijskega odstopanja geometrijskega modela okvirja in razpoke v simulacijah, predpostavljenega modula elastičnosti v simulacijah, predpostavljenih izotropnih mehanskih lastnosti gradiva okvirja in v simulacijah zanemarnjenih sprememb mehanskih lastnosti materiala zaradi toplotno vplivanega področja pri varjenju nosilca zavorne čeljusti na okvir gorskega kolesa. Dodatno negotovost pripisujemo pozicioniranju merilnega lističa, nekaj merilne negotovosti pa sta tudi doprinesli napaka merilne opreme in napaka meritve vnosa sile. Čeprav so dobljene specifične deformacije pri zaviranju v tlačnem območju, standard predvideva tudi prenos dela maksimalnega vzvojnega momenta v nasprotni smeri zaviranja, kar pa na merilnem mestu povzroči natezne specifične deformacije. Čeprav so bile vrednosti specifičnih deformacij na območju merilnega mesta okvirja gorskega kolesa znatne, sklepamo, da je pojav razpoke na testiranem okvirju posledica preobremenitev pri vožnji in ne tipičnih obremenitev, za katere je okvir izdelan.

Zaključki

Okvir gorskega kolesa je med uporabo potrjen kompleksnim obremenitvam. Velike obremenitve se pojavijo predvsem pri zaviranju. S primerjavo simulacij z metodo končnih elementov in laboratorijskega testa smo pokazali, da je pri standardnem testu zaviranju okolica nosilca zavorne čeljusti močno obremenjena, opažena razpoka na testiranem okvirju pa je bolj verjetno posledica preobremenitve pri uporabi.

ZAHVALA. Zahvala gre Javni agenciji za raziskovalno dejavnost Republike Slovenije za finančno podporo raziskovalnega programa št. P2-0182 Razvojna vrednotenja.

- [1] J. Klemenc et al. *Metals* **9** (2019) 973.
- [2] D. Šeruga et al. *Procedia Structural Integrity* **35** (2022) 150-158.
- [3] Standard ISO 4210:2023. Cycles — Safety requirements for bicycles. *International Standard Organisation* (2023)
- [4] J. Vanwalleghe et al. *Sports Engineering* **21** (2018): 75-84

Analiza obratovanja upogibnega ležaja pri podanem zasuku in radialni obremenitvi

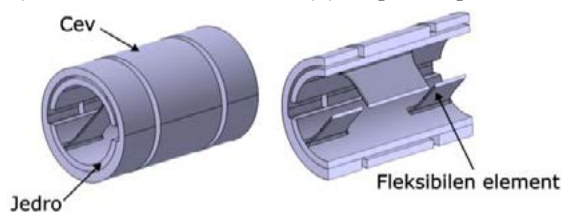
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V tej raziskavi obravnavamo ovrednotenje ustreznosti izbire upogibnega ležaja, da bi zagotovili obratovanje in dobo trajanja pri podanem zasuku in radialni obremenitvi. S pomočjo metode končnih elementov smo analizirali dvostranski ležaj v pogojih, ki ustrezajo predvideni uporabi. Rezultati kažejo, da izbrani ležaj nudi zadosten faktor varnosti, kar nakazuje njegovo primernost za dano aplikacijo.

Uvod

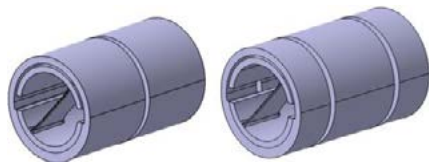
Upogibni ležaj (angl. *flexure bearing*), prikazan na sliki 1, predstavlja specializiran tip ležaja, ki omogoča gibanje ali rotacijo preko elastičnega upogibanja materiala namesto klasičnega drsenja ali kotaljenja. Njegovo delovanje temelji na elastičnih lastnostih uporabljenega materiala, kar omogoča visoko natančnost in ponovljivost gibanja. Ležaj je sestavljen iz dveh osnovnih komponent: jedra in cevi. Jedro vsebuje enega ali več fleksibilnih elementov, pogosto v obliki tankih nosilcev ali trakov. Ti elementi se elastično deformirajo in omogočajo rotacijo okoli osi, medtem ko ostajajo togi v drugih smereh [1].



Slika 1: Upogibni ležaj.

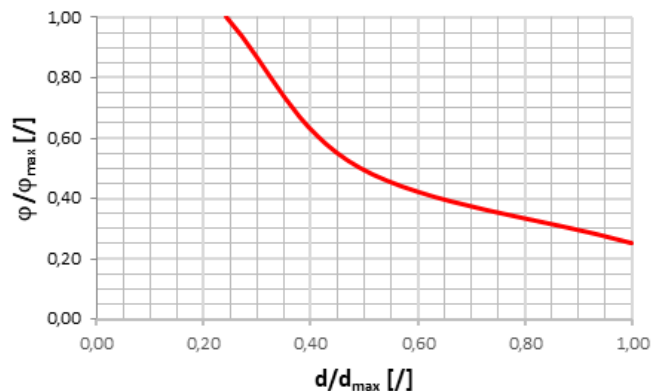
Prednosti upogibnih ležajev so visoka natančnost, delovanje brez trenja in brez zračnosti, kompaktna zasnova, minimalna histereza ter tiho in stabilno delovanje brez vibracij. Slabosti upogibnih ležajev pa so omejen razpon gibanja, nosilnost, utrujanje materiala pri obratovanju in občutljivost na temperaturo [2]. Upogibni ležaji so nepogrešljivi predvsem v preciznem inženiringu, kjer sta zanesljivost in natančnost ključnega pomena. Zaradi svojih edinstvenih lastnosti so idealni za uporabo v visoko tehnoloških in zahtevnih aplikacijah, od letalske industrije do nanotehnologij [3].

Na trgu obstajajo standardni upogibni ležaji v dveh osnovnih oblikah: konzolni enostranski in dvostranski ležaji (Slika 2). Konzolni ležaji nudijo enostransko podporo in imajo zato manjšo radialno togost ter nosilnost, medtem ko dvostranski ležaji z obojestransko podporo dosegajo večjo togost in nosilnost.



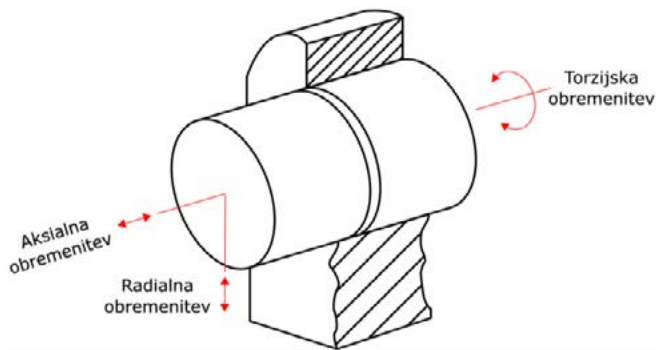
Slika 2: Konzolni enostranski upogibni ležaj (levo), dvostranski upogibni ležaj (desno) [4].

Za vsak tip ležajev so na voljo različne dimenzije. Poleg tega je mogoče izbrati med različnimi debelinami listnatih vzmeti, kar nato določa kot vrtenja ležaja. Z naraščajočo togostjo vzmeti se nazivni kot vrtenja zmanjšuje, hkrati pa se povečuje debelina vzmeti, kar je prikazano na sliki 3.



Slika 3: Odvisnost zasuka od debeline vzmeti povzeta po [4].

Nosilnost upogibnega ležaja zaradi statičnih sil je odvisna od smeri vektorske sile glede na listnate vzmeti. Na (Slika 4) so prikazane vrste obremenitev, ki lahko delujejo na ležaj.



Slika 4: Obremenitve na upogibni ležaj povzeta po [4].

Običajno se navaja nosilnost le v aksialni in radialni smeri, saj je mogoče vse druge vektorske sile preračunati na ti smeri. Radialna obremenitev glede na orientacijo ležaja, lahko povzroči natezno ali tlačno radialno obremenitev. Pri tlačni obremenitvi lahko pride do uklona listnatih vzmeti ležaja, zlasti pri ležajih manjše togosti. Zato je priporočljiva orientacija vgradnje ležaja tako, da je obremenjen predvsem natezno, če je to mogoče. Proizvajalci upogibnih ležajev ponujajo priročnike [4], s katerimi lahko izberemo pravi ležaj za določeno aplikacijo. Na podlagi diagramov, tabel in podatkov lahko tudi hitro ugotovimo, kateri ležaj bo ustrezal zahtevam in zagotovil zanesljivo delovanje.

V raziskavi smo se osredotočili na ovrednotenje ustreznosti določitve upogibnega ležaja na podlagi priročnika proizvajalca. Z metodo končnih elementov (MKE) smo analizirali izbran ležaj in preverili, ali ustreza zahtevam aplikacije glede maksimalnega kota zasuka in radialne obremenitve.

Metoda

Najprej smo določili dva ključna robna pogoja, ki izhajata iz zahtev aplikacije: maksimalni kot zasuka $\pm 4^\circ$ in maksimalno radialno obremenitev 500 N. Ti mejni pogoji zagotavljajo, da bo ležaj sposoben prenesti pričakovane obremenitve in omogočiti potrebno rotacijo brez preseganja dopustnih deformacij. Poleg tega smo upoštevali še dva pomembna kriterija: maksimalno togost ležaja, ki je ključna za natančnost obratovanja, ter neomejeno življenjsko dobo ležaja, ki je povezana z utrujanjem materiala. Izbor upogibnega ležaja sledi napotkom v proizvajalčevem priročniku: 1) izbor oblike ležaja - odločitev med konzolnim enostranskim in dvostranskim ležajem glede na konstrukcijske zahteve; 2) izbor velikosti in togosti ležaja - za vsako velikost je na voljo več torzijskih togosti, ki definirajo dopusten kot zasuka. Pri izboru upoštevamo, da večja togost pomeni manjši nazivni kot rotacije; 3) izbor življenjske dobe - na podlagi diagramov preverimo, ali izbrani ležaj pri predvidenih obremenitvah in kotih zasuka zagotavlja neomejeno življenjsko dobo ter 4) izračun potrebnega momenta zasuka - določimo moment, ki ga je potrebno zagotoviti za doseg zahtevanega kota rotacije. Na podlagi opisanega postopka smo izbrali upogibni ležaj z dimenzijami in obratovalnimi karakteristikami v preglednici 2, ki smo ga nato analizirali z metodo končnih elementov (MKE). Numerična analiza je bila izvedena v programu Ansys z uporabo linearnega materialnega modela, saj so bile obremenitve in deformacije omejene na območje elastičnega obnašanja materiala. Posebna pozornost je bila namenjena zgostitvi mreže elementov na območjih največjih napetosti, kjer so bila preverjena lokalna napetostna stanja. Na koncu smo določili faktor varnosti glede na mejo tečenja materiala, kar je omogočilo ovrednotenje primernosti izbranega ležaja za predvideno aplikacijo.

Rezultati in diskusija

Na podlagi robnih pogojev smo izbrali dvostranski upogibni ležaj. Lastnosti ležaja so prikazane v preglednici 1. Proizvajalci za ležaje uporabljajo poboljšano jeklo AISI 420. V simulacijah smo uporabili naslednje materialne lastnosti: Youngov modul $E = 199948$ MPa, Poissonovo število $\nu = 0,28$ in mejo tečenja $\sigma = 1358$ MPa in natezno trdnost 2027 MPa.

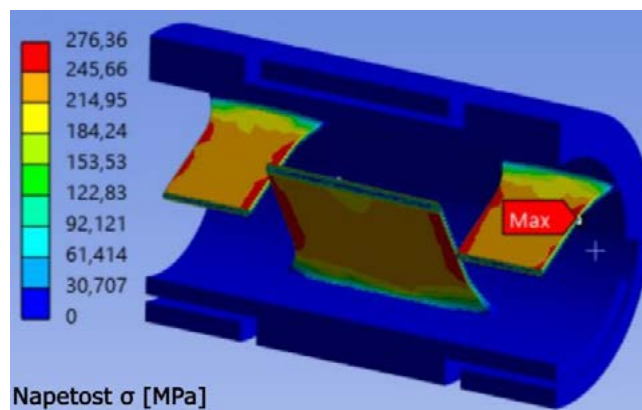
Preglednica 1: Dimenzije in obratovalne lastnosti upogibnega ležaja za zagotavljanje maksimalnega zasuka $\pm 4^\circ$ in maksimalno radialno obremenitev 500 N [4].

Lastnosti	Vrednosti
Tlačna obreme. V_c	4893 N
Natezna obreme. V_t	6672 N
Aksialna obreme.	3599 N
Vzmetna konstanta C	614,1 Ncm/rad
Nazivni kot vrtenja	$\pm 7,5^\circ$
Max. kot vrtenja	$\pm 15^\circ$
Radialna togost [$\mu\text{m}/\text{N}$]	Nateg 0,057; Tlak 0,029
Aksialna togost	0,057 $\mu\text{m}/\text{N}$
Zunanji premer	25,4 mm
Dolžina	40,64 mm

Pri analizi smo obravnavali upogibni ležaj kot samostojno mehansko komponento. Rezultati simulacije (slika 5) kažejo, da se največja primerjalna napetost po von Misesovem kriteriju pojavi pri maksimalnem zasuku in maksimalni radialni obremenitvi v listnati vzmeti in znaša približno 277 MPa.

Ta vrednost je približno petkrat manjša od meje tečenja materiala, kar pomeni, da je faktor varnosti glede na mejo tečenja približno 5. To nakazuje, da je izbira ležaja ustrezna in zagotavlja zanesljivo delovanje pri statični obremenitvi.

Potrebni navor za zasuk 4° smo izračunali s pomočjo vzmetne konstante in znaša 0,44 Nm, kar kaže na minimalne izgube pri obratovanju upogibnega ležaja in s tem visoko učinkovitost sistema.



Slika 5: Porazdelitev primerjalne napetosti po vom Misesovem kriteriju v upogibnem ležaju pri maksimalnem zasuku in maksimalni radialni obremenitvi.

Rezultati analize potrjujejo, da je izbran upogibni ležaj primeren za predvidene obratovalne pogoje, saj združuje dovolj visoko trdnost z nizkimi mehanskimi izgubami.

Zaključki

Z metodo končnih elementov smo ovrednotili ustreznost izbire upogibnega ležaja. Analiza je pokazala, da izbrani ležaj zagotavlja zadosten faktor varnosti pri obratovanju. Nadaljnje raziskave bi se lahko osredotočile na simulacije, ki bi upoštevale tudi tolerance montaže in variabilnost materialnih lastnosti, ter eksperimentalno validacijo rezultatov pri enakih pogojih obratovanja.

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Morphological diagnostics and replication of heritage artefacts using 3D technologies (3D scanning, 3D modelling, 3D printing)

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This study investigates the use of 3D technologies for morphological diagnostics and replication of a damaged cast iron candlestick from the Ironworks at Dvor, Slovenia. The artefact was digitised through 3D scanning, and the missing leaf was digitally reconstructed using 3D modelling and printed using 3D printing technology.

Introduction

The integration of digital technologies into cultural heritage preservation plays a crucial role in enabling non-invasive diagnostics and high-fidelity replication of artefacts. Specifically, 3D scanning and 3D printing enable an accurate reconstruction and reproduction of such artefacts. This study explores the potential of these technologies through a case study of a decorative 19th-century cast-iron candlestick from Dvor, Slovenia (archived at the Dolenjski Museum in Novo mesto) [1].

An original 19th-century cast iron candlestick is designed as a grapevine leaf and has two major defects: one decorative leaf-like element is missing, and the base is unstable. Due to its fragility and historical value, the original is unsuitable for frequent handling. A traditional cast-iron replica was produced in the 1990s for display in the Dolenjski Museum in Novo mesto. Still, it differs significantly—it is thicker, slightly larger, less refined, and includes an added decorative leaf does not present in the original. These differences highlight the need for a more faithful reproduction using modern technologies. The aim of this study was to produce a 3D printed replica and compare it to the casting replica (1990s).

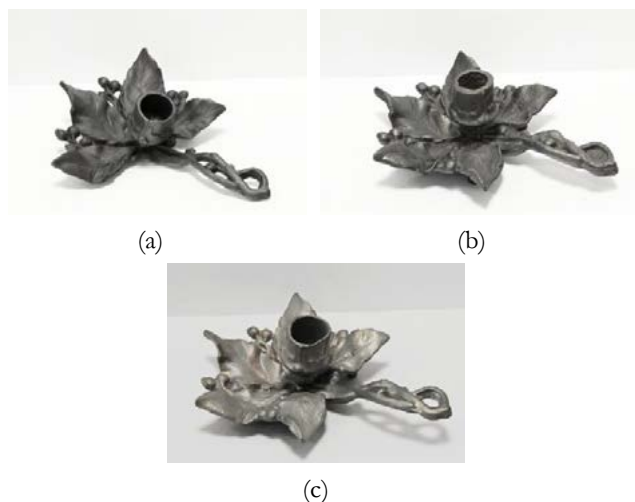


Figure 1: (a) Original iron candlestick with missing leaf and foot, (b) casting candlestick and (c) 3D printed candlestick.

Methods

The methodology for this study follows a comprehensive three-step process (Figure 2), designed to effectively document, replicate, and restore cultural heritage artefacts. The steps outlined below illustrate how each phase of the process contributes to the overall goal of restoring incomplete objects.

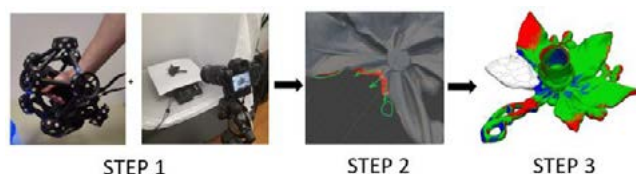


Figure 2: The methodology with a comprehensive three-step process.

STEP 1: 3D Digitisation: In the first step, the original candlestick was digitised using 3D laser scanning and photogrammetry. The 3D scanner, with an accuracy of 25 μm and a resolution of 0.2 mm (CREAFORM MetraSCAN), provided precise measurements and captured intricate surface details of the artefact. For photogrammetry, the camera (Nikon Z6 II) was employed to capture high-quality images of the artefact from multiple angles. The number of photos taken was extensive, ensuring a minimum overlap of 80% between images. These images were then processed using photogrammetry software to generate the 3D model of the candlestick.

STEP 2: 3D Modelling for stability: Once the original object was digitised, the next step involved 3D modelling to restore the missing part of the artefact. In this case, a decorative leaf and foot was digitally reconstructed. The missing part was modelled in software Blender based on the object's morphological symmetry and stylistic features.

STEP 3: 3D Printing and Surface Deviation Comparison: The final step involved fabricating the complete digital model using metal 3D printing (the binder jetting technique). This technique enabled the creation of a highly accurate and durable replica of candlesticks. After 3D printing, the replica was compared with the original artefact as well as with a previous casting replica (Geomagic Control X) to assess the surface deviations and compare the dimensional fidelity. This comparison was made by a “best-fit” algorithm for matching points and evaluated the precision of the replication process, highlighting how closely the 3D-printed replica mirrored the original artefact.

Results and discussion

The comparison between the casting and the original candlestick (see Figure 3, Table 1) revealed a maximum deviation of +4.79 mm, with the minimum deviation being -4.79 mm. The average deviation was -0.17 mm, and the standard deviation was 1.44 mm. Out of the measured areas, 36.48% were within the acceptable tolerance range. In contrast, 63.51% of the measurements fell outside the tolerance range. Specifically, 23.00% of the measurements exceeded the upper tolerance limit, while 40.51% exceeded the lower tolerance limit.

Table 1: Surface deviations (in mm) between the original artefact and the casting replica.

Min.	-4.79
Max.	4.79
Avg.	-0.17
Standard Deviation	1.44
In Tol. (%)	36.48
Out Tol. (%)	63.51
Over Tol. (%)	23.00
Under Tol.(%)	40.51

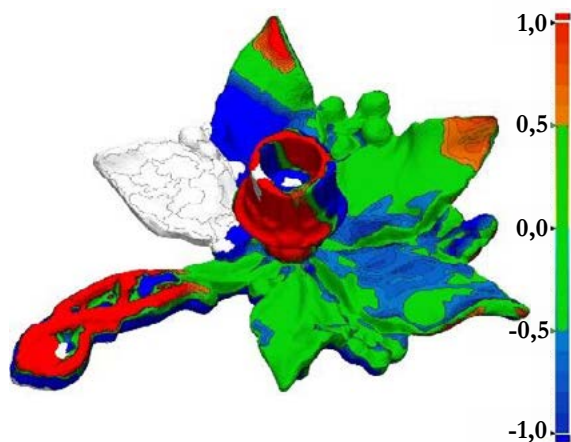


Figure 3: Surface deviations (in mm) between the original artefact and the casting replica (green – max up to 0.5 mm, orange - between 0.5-0.7 mm, red - more than 0.7 mm).

The comparison between the 3D-printed and the original candlestick (see Figure 4, Table 2) showed a maximum deviation of +3.28 mm, with a minimum deviation of -4.78 mm. The average deviation was +0.11 mm, and the standard deviation was 0.73 mm. Of the measured areas, 61.76% were within the acceptable tolerance range. On the other hand, 38.24% of the measurements were outside the tolerance range. Of those, 14.53% exceeded the upper tolerance limit, while 23.70% exceeded the lower tolerance limit.

Table 2: Surface deviations (in mm) between the original artefact and the 3D-printed replica.

Min.	-4.78
Max.	3.28
Avg.	0.11
Standard Deviation	0.73
In Tol. (%)	61.76
Out Tol. (%)	38.23
Over Tol. (%)	23.70
Under Tol.(%)	14.52

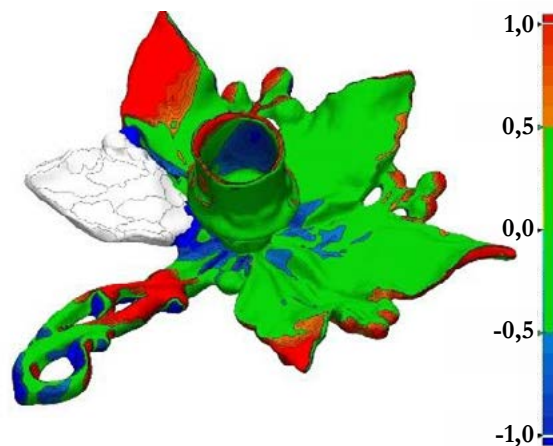


Figure 4: Surface deviations (in mm) between the original artefact and the 3D-printed replica (green – max up to 0.5 mm, orange - between 0.5 - 0.7 mm, red - more than 0.7 mm).

The comparison between the 3D-printed and casting replicas shows that the 3D-printed candlestick offers greater accuracy and consistency. The maximum deviation of the 3D-printed replica (+3.28 mm) is lower than the casting's (+4.79 mm), and the average deviation (+0.11 mm) is smaller compared to the casting's (-0.17 mm), indicating better overall precision. The 3D-printed candlestick also has a lower standard deviation (0.73 mm) than the casting (1.44 mm), demonstrating less variation in measurements. Additionally, 61.76% of the 3D-printed measurements were within the acceptable tolerance range, a significant improvement over the casting's 36.48%.

Conclusions

The results show that the 3D-printed replica achieves higher accuracy in shape and form than the casting replica. By integrating 3D scanning, modelling, and printing, this three-step approach provides an efficient and scalable solution for digital restoration and reproduction. However, exploring different 3D printing materials and printers in the future may enhance accuracy.

ACKNOWLEDGEMENTS. The research of the authors was funded by the Slovenian Research and Innovation Agency (ARIS) through the annual work program of Rudolfovo.

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Heat transfer analysis during droplet impact onto a hot or a cold surface using a fluorescent temperature sensitive paint

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Impact of an ambient temperature droplet at ~25 °C onto a cold or a hot surface was studied using a fluorescent temperature sensitive paint to quantify transient temperature fields with a high spatial (10 μm) and temporal (0.5 ms) resolution. The paint was applied onto a 50 μm aluminium foil, onto which droplets at $We = \{10, 30, 90\}$ were deposited. The results show that this approach captures transient temperature fields during droplet impact onto a surface at -35 °C or at 100 °C well and the response time of the TSP on the bottom side of the foil is < 1 ms in regard to the moment of the initial droplet-surface contact.

Introduction

Droplet impact onto solid surfaces is a fundamental phenomenon relevant to a wide range of natural and industrial processes, including spray cooling, inkjet printing, surface coating fabrication, combustion, and anti-icing technologies. When droplets strike a hot or cold surface, heat transfer occurs and can also include phase change, such as solidification (freezing of the droplet) or vaporization (boiling of the droplet). To analyse these phenomena, sufficient temporal and spatial resolution is needed. Temperature-sensitive paints (TSPs) have emerged as powerful tools for non-intrusive surface temperature measurements, particularly in transient heat transfer studies [1,2]. These paints contain fluorescent dyes whose emission intensity varies predictably with temperature, enabling quantitative surface thermography with high spatial (< 1 ms) and temporal resolution (< 10 μm). Fluorescence thermography has significant advantages over conventional contact sensors as it eliminates thermal interference and allows measurements with microscale resolution. Furthermore, fluorescence thermography is vastly superior to IR thermography at low temperatures (e.g., below 0 °C) due to typically increasing signal with decreasing temperature.

In this study, a fluorescent temperature-sensitive paint was applied to quantify transient temperature fields during droplet impact on heated and cooled thin metallic foils. We show the temperature response of the coating and an analysis of transient temperature fields with a high spatiotemporal resolution.

Materials and methods

Aluminium foil (>99.9% Al) with a thickness of 50 μm was used as the substrate. Its underside was first coated with a matte white acrylic paint, forming a ~10 μm layer, onto which a ~3 μm TSP layer was applied via spin coating. The TSP was formulated as a mixture of a binder (poly(acrylic acid)), a fluorescent dye in the form of a ruthenium complex

(dichlorotris(1,10-phenanthroline)ruthenium(II) hydrate), and a solvent (absolute ethanol) [1-3].

To evaluate the transient heat transfer, the experimental setup shown in Figure 1 was used. The optical part of the system consists of an excitation source for the TSP (450 nm LED), a low-pass filter, a dichroic mirror, a dielectric mirror, a high-pass filter and a high-speed camera with a macro lens. The spatial resolution was 10 μm/px while the temporal resolution was 0.5 ms. Another synchronized high-speed camera was used to record the droplet impact on the upper side of the surface.

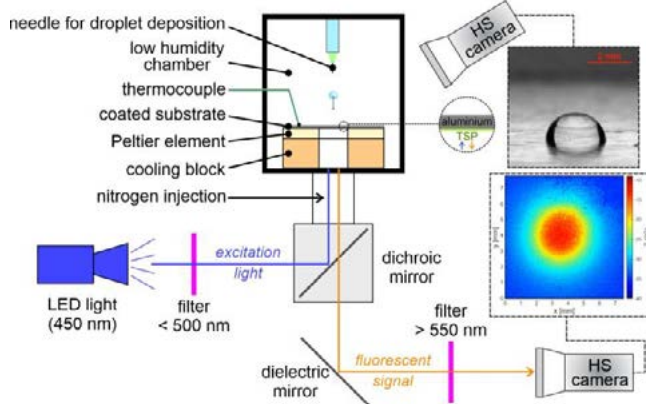


Figure 1: Experimental setup for evaluation of droplet impacts onto hot or cold surfaces using fluorescence thermography.

The thermal part of the setup included a cooling block connected to a circulating chiller, on top of which an annular Peltier element was positioned. The foil was attached to the top of the Peltier cooler with thermal paste with the TSP layer facing downward. Temperature control within ± 0.1 °C was realized using PID regulation of the Peltier element. To avoid condensation and frosting, dry nitrogen was injected below the sample and into the chamber. For each series of measurements, temperature calibration of the TSP was performed by capturing sets of 10 images at temperatures between -38 °C and 20 °C. Droplet impact experiments were performed using room-temperature water droplets with a diameter of ~2.0 mm at a pre-impact Weber number of 10, 30 or 90.

Figure 2 shows an example of the TSP calibration, which was performed in accordance with the following equation [1]:

$$\ln\left(\frac{I_{\text{ref}}}{I}\right) = A\left(\frac{1}{T_{\text{ref}}} - \frac{1}{T}\right)^2 + B\left(\frac{1}{T_{\text{ref}}} - \frac{1}{T}\right) + C \quad (1)$$

where I is the intensity and T is the temperature. The “ref” subscript denotes the reference measurement at 20 °C. Figure 2 shows an example of the calibration curve used to determine the temperatures from the intensity of the recorded images.

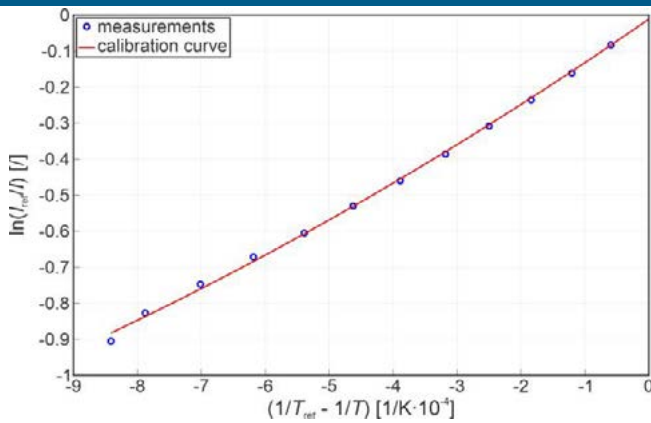


Figure 2: Example calibration curve from -38 °C to 20 °C.

Image analysis was performed in MATLAB R2025a. Each image was cropped and local defects such as dust particles or dye aggregates were masked and the values interpolated.

Results and discussion

Figure 3 shows the transient temperature fields $T(x,y,t)$ and corresponding droplet dynamics on the surface during an impact of a droplet at $We = 10$ onto a surface cooled to -35 °C.

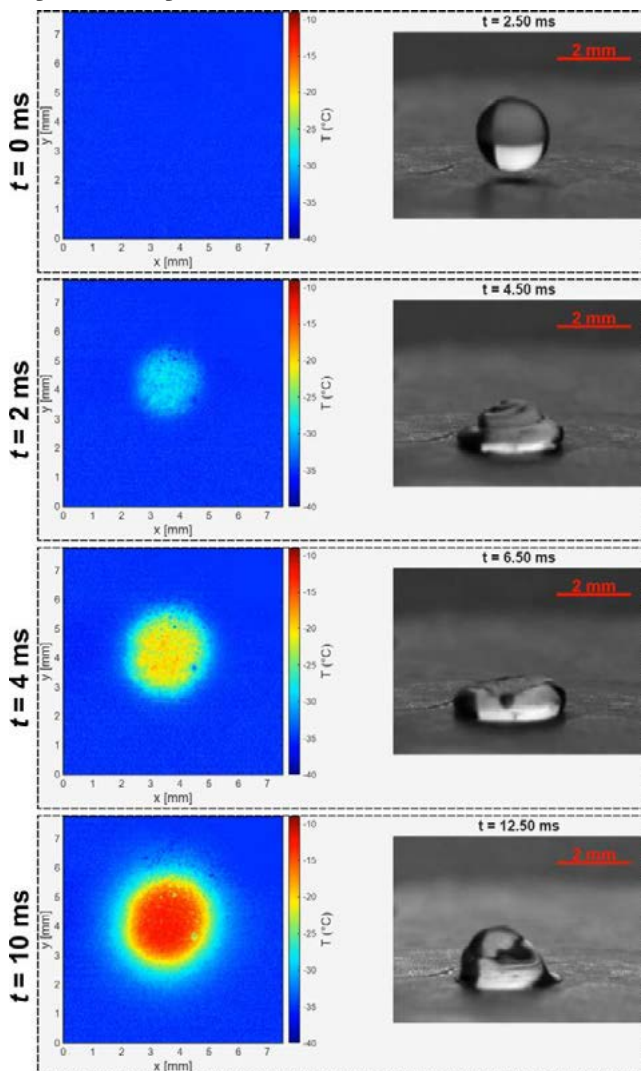


Figure 3: Transient temperature fields (left) and corresponding high-speed-video snapshots (right) for droplet impact at $We = 10$ onto a surface at -35 °C.

Figure 4 shows the transient temperature fields $T(x,y,t)$ and corresponding droplet dynamics on the surface during an impact of a droplet at $We = 10$ onto a surface heated to 100 °C.

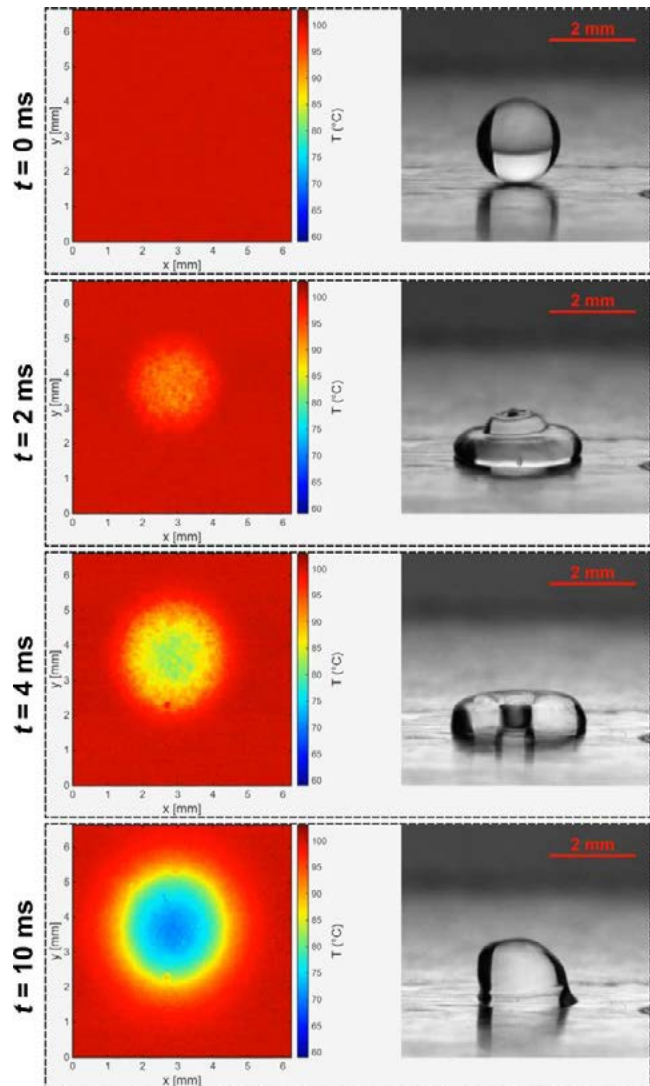


Figure 4: Transient temperature fields (left) and corresponding high-speed-video snapshots (right) for droplet impact at $We = 10$ onto a surface at 100 °C.

In both cases, excellent temperature response was recorded with the temperature disturbance observable within the TSP signal only 1 ms after the initial droplet impact.

Conclusions

The study showcases the applicability of fluorescent TSPs for observation of fast heat transfer phenomena within a wide temperature range with a high spatial and excellent temporal resolution. Transient heating of the cooled substrate and cooling of the heated substrate during a droplet impact event is easily quantified. Future work will focus on improving the spatial resolution and calculating transient heat flux fields.

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Temperature response calibration and photobleaching evaluation of Ruthenium-based fluorescence thermography coatings

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Fluorescence thermography is a non-contact temperature measurement technique offering higher spatial resolution than infrared thermography and improved sensitivity at low temperatures. This study presents the fabrication and evaluation of ruthenium-complex-based coatings for fluorescence thermometry, focusing on temperature response and long-term photostability. Coatings were applied via spin coating and tested between $-40\text{ }^{\circ}\text{C}$ and $60\text{ }^{\circ}\text{C}$ on substrates with different surface pretreatments. Results show that a matte white substrate enhances emission intensity, while an optimal dye concentration of $\sim 0.8\text{ g/g}$ binder yields a temperature sensitivity of $1.8\text{ \% }^{\circ}\text{C}^{-1}$ and only $21\text{ \%}$ fluorescence loss after 60 minutes of illumination.

Introduction

In many engineering and scientific applications, non-contact temperature measurement is required, either because of extreme temperature conditions or to avoid interference with the observed process. A major advantage of optical methods lies in their ability to record full temperature fields rather than single-point data. The most common such technique is infrared (IR) thermography, which estimates temperature based on the emitted thermal radiation. However, the spatial resolution of IR thermography is limited to the micrometre range, and the radiative intensity increases with the fourth power of temperature, resulting in weak signals and poor signal-to-noise ratios at low temperatures.

Fluorescence thermography provides an alternative approach, relying on temperature-dependent emission intensity from fluorescent dyes [1]. Upon illumination, the fluorescent dye emits light at a longer wavelength due to the Stokes shift, and the emission intensity variation is used to infer temperature. Most dyes exhibit decreasing fluorescence with increasing temperature [2], making this method particularly suitable for low-temperature measurements. Furthermore, because emission occurs in the visible range, spatial resolution is significantly enhanced compared to IR thermography. Typically, a polymer coating containing the fluorescent dye is applied to the surface [3,4] and excited with light matching the dye's absorption spectrum. The emitted signal is recorded by a visible-light camera equipped with an optical filter. Previous studies have demonstrated the method's applicability between $0\text{ }^{\circ}\text{C}$ and $150\text{ }^{\circ}\text{C}$. This study extends the temperature range down to $-40\text{ }^{\circ}\text{C}$, enabling temperature field measurements relevant to solidification heat transfer. The paper presents calibration of a Ruthenium-based fluorescence thermography coating for various substrate treatments, dye concentrations, and investigates photostability under prolonged illumination.

Materials and methods

Aluminium alloy 1050A plates ($30 \times 30 \times 0.6\text{ mm}$) were used as substrates. Since previous studies indicate that a white underlayer enhances fluorescence emission, three substrate conditions were tested: (i) untreated aluminium, (ii) aluminium coated with a glossy white acrylic paint, and (iii) aluminium coated with a matte white acrylic paint.

The temperature-sensitive coating consisted of a ruthenium complex dye dichlorotris(1,10-phenanthroline)ruthenium(II) hydrate (RC) dispersed in a poly(acrylic acid) (PAA) matrix. The base formulation contained 5 g of ethanol, 25.3 mg of PAA, and 10 mg of RC. The mixture was heated to $60\text{ }^{\circ}\text{C}$ until complete dissolution of both components. To assess the effect of dye concentration, the RC mass was increased to 20 mg while keeping PAA and ethanol constant. Before coating, substrates were cleaned with isopropanol and treated in a UV/ozone cleaner for 10 min to remove organic contaminants and enhance adhesion. Coatings were deposited by spin-coating at 1000 rpm for 60 s, during which 200 μL of the prepared solution was pipetted onto the rotating substrate, producing a $\sim 3\text{ }\mu\text{m}$ thick uniform layer. Coatings were cured at an elevated temperature to ensure insolubility of the PAA.

The experimental setup (Figure 1) included a 450 nm blue LED excitation source directed via a dichroic mirror toward the coated substrate. Emitted light ($520\text{--}700\text{ nm}$) was collected by a Basler a2A2448-75umPRO monochrome camera equipped with a macro lens and appropriate emission filter. Images (12-bit TIFF, 40 fps, 20 ms exposure) were acquired while temperature was controlled using a Peltier module regulated by a PID controller within $\pm 0.1\text{ }^{\circ}\text{C}$. To avoid condensation, dry nitrogen was flowed beneath the sample. Each calibration cycle covered the range between $-40\text{ }^{\circ}\text{C}$ and $60\text{ }^{\circ}\text{C}$ in $5\text{ }^{\circ}\text{C}$ steps, with 20 frames recorded per temperature. To assess photostability, coatings were continuously illuminated for 60 min at $20\text{ }^{\circ}\text{C}$ while capturing one image per minute. Calibration before and after illumination quantified fluorescence decay.

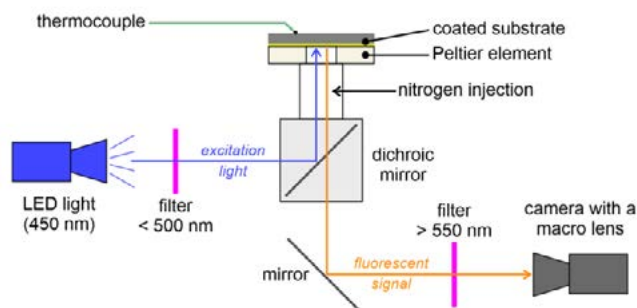


Figure 1. Experimental setup for coating evaluation.

Image analysis was performed in MATLAB R2025a. Each image was cropped automatically, with only the central 80 % retained to exclude edge shadows. Local defects such as dust particles or dye aggregates were removed, and the mean intensity was computed for each temperature. The results were expressed as both absolute intensity (I) and normalized intensity relative to 20 °C (I/I_{20}).

Results and discussion

Figure 2 compares the normalized fluorescence intensity, relative to its value at 20 °C, for coatings applied on three substrates with different pretreatments. All calibration curves exhibit similar trends, with a steeper slope observed when temperature increases from −40 °C to 60 °C, particularly for uncoated and matte-white substrates. Across the tested temperature range, the signal varies by approximately 500 %, corresponding to an average sensitivity of about 1.8 % °C^{−1}.

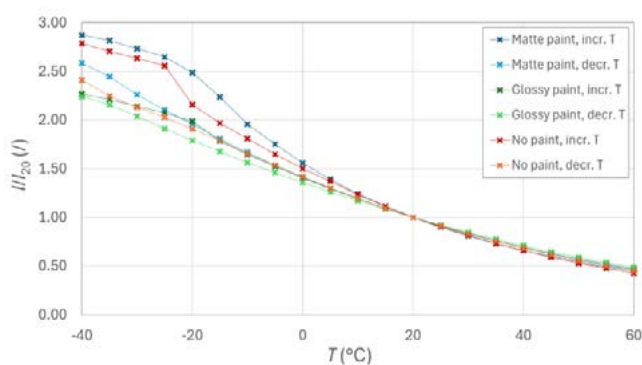


Figure 2: Normalized fluorescence emission for different substrate pretreatments.

As shown in Figure 3, both white coatings significantly enhance fluorescence emission under identical excitation conditions compared with the uncoated substrate. Moreover, the matte white surface yields stronger emission than the glossy one, and was therefore selected for subsequent measurements.

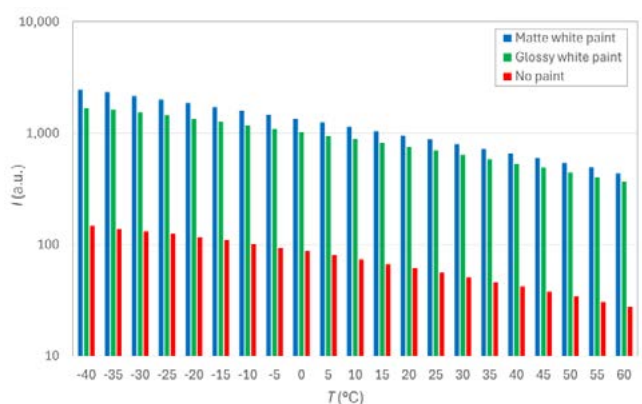


Figure 3: Comparison of absolute fluorescence intensity for different substrate pretreatments.

The impact of doubling the ruthenium complex dye concentration on the calibration curve is presented in Figure 4. While the relative fluorescence–temperature relationship remains similar to that of the baseline formulation, the higher dye concentration improves the reproducibility and overlap between heating and cooling calibration cycles, suggesting enhanced photostability and reduced hysteresis.

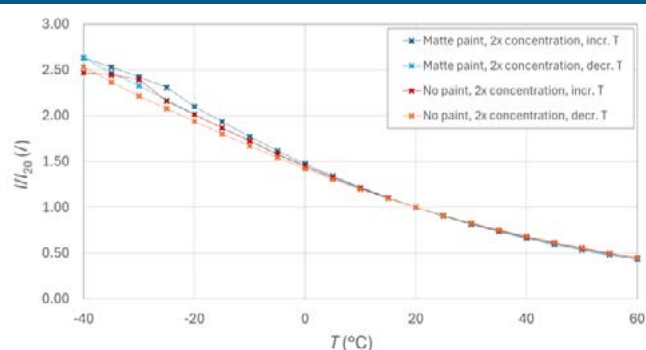


Figure 4: The effect of doubled fluorescent dye concentration on normalized fluorescence emission.

Degradation tests were performed for coatings with the doubled dye concentration on both matte-white and uncoated substrates. Measurements were conducted either in ambient air or in pure nitrogen to account for oxygen sensitivity of the dye. Figure 5 shows normalized fluorescence intensity versus illumination time. Under nitrogen, fluorescence decayed monotonically, with a smaller intensity loss for the matte-white substrate (21 % after 60 min) than for the uncoated one (42 % after 60 min). The difference arises from the higher excitation power required for uncoated aluminium, where the excitation intensity must be about eight times greater to produce a comparable signal. In air, fluorescence initially increases due to oxygen permeation before rapidly decaying after approximately 20 min, eventually reaching the same level as in nitrogen.

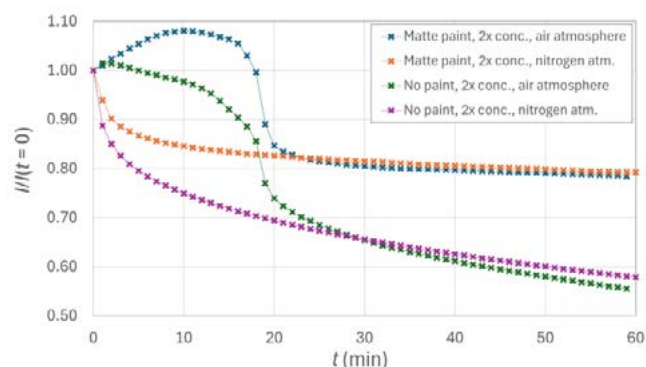


Figure 5: Reduction of fluorescence intensity during constant illumination for two pretreatments and two atmospheres.

Conclusions

The optimal configuration of ruthenium-complex-based fluorescent coatings was achieved with a matte-white substrate and a doubled dye concentration. The coatings demonstrated a consistent temperature sensitivity of ~1.8 % °C^{−1} and only a 21 % reduction in fluorescence intensity after 60 min of illumination. Such performance indicates excellent suitability for transient temperature measurements on the time scale of seconds to minutes, with minimal signal degradation. Future work should investigate the influence of the white underlayer on the thermal response time due to its heat transfer resistance.

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DED-LB Ti-6Al-4V as a Template for TiO₂ Nanotube Growth: Comparison with Wrought Alloy

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This study investigates the formation of self-organized TiO₂ nanotube layers on Ti-6Al-4V alloys produced by Laser beam directed-energy deposition (DED-LB) and compares them with those formed on the conventionally wrought material. Both alloys were anodized in ethylene glycol solution containing NH₄F and H₂O at 30 V for 2 h at room temperature. SEM and potentiodynamic polarization tests were used to evaluate morphology and corrosion behavior. The DED-LB alloy exhibited irregular and partially deformed nanotubes due to its α' martensitic microstructure and surface heterogeneity, whereas the wrought alloy formed uniform and well-aligned nanotubes. Electrochemical results confirmed improved passivation of both materials, with the wrought alloy showing superior stability. The findings highlight the influence of additive manufacturing induced microstructures on anodization behavior and support microstructural optimization of DED-LB Ti-6Al-4V for biomedical applications.

Introduction

Additive manufacturing (AM) enables the production of complex, high-performance metallic components that are difficult to fabricate using conventional processes. Among AM techniques, laser beam directed-energy deposition (DED-LB) has attracted considerable attention for processing titanium alloys.[1]

Ti-6Al-4V remains the benchmark titanium alloy for implants due to its strength, corrosion resistance, and biocompatibility. The wrought alloy exhibits an α -phase matrix with intergranular β -phase [2], whereas DED-LB Ti-6Al-4V develops a lamellar Widmanstätten structure with α' martensite in columnar grains aligned along the build direction.[3] These microstructural differences affect mechanical and electrochemical behaviour, including the alloy's response to surface modification.[4]

Anodization in fluoride-containing electrolytes produces self-organized TiO₂ nanotube arrays (tens to hundreds of nanometres in diameter)[5] that improve bioactivity, cell adhesion, and osseointegration. The nanotube morphology strongly depends on the substrate microstructure, as variations in phase distribution and conductivity influence oxidation and dissolution kinetics, as well as anodization parameters such as applied voltage, electrolyte and process time.[5-6]

While anodization of wrought Ti-6Al-4V has been widely studied, data for DED-LB Ti-6Al-4V remain limited. This study, therefore, compares the anodization behaviour of DED-

LB and wrought Ti-6Al-4V under identical conditions to clarify how their distinct microstructures influence the formation and morphology of TiO₂ nanotube layers.

Materials and methods

Conventional wrought Ti-6Al-4V (Grade 5) and DED-LB-fabricated Ti-6Al-4V samples were prepared as discs (15 mm diameter, 2 mm thickness) for comparative analysis. Prior to anodization, both were chemo-mechanically polished following the procedure described previously.[3] Anodization was performed in a two-electrode configuration, using the Ti-6Al-4V sample as the working electrode and a graphite rod as the counter electrode. The electrolyte consisted of ethylene glycol containing 0.5 wt% NH₄F and 2.5 wt% H₂O, and the process was carried out at 30 V for 2 h at room temperature (~23 °C). After anodization, the samples were rinsed with deionized water and ethanol and air-dried. Electrochemical testing was conducted in Hanks' balanced salt solution (HBSS), which simulates the ionic composition of human extracellular fluid. All chemicals were of analytical grade. After 60 min stabilization at open-circuit potential, potentiodynamic polarization was performed at a scan rate of 1 mV s⁻¹. The corrosion potential (E_{corr}) and corrosion current density (j_{corr}) were determined by Tafel extrapolation. The surface morphology was examined by scanning electron microscopy (SEM) to assess nanotube formation and uniformity, with representative images acquired at magnifications ranging from $\times 1200$ to $\times 50\,000$.

Results and discussion

After anodization process, both wrought and DED-LB Ti-6Al-4V samples developed porous oxide layers with distinct morphologies determined by their manufacturing processes (Figure 1). Localized dissolution was evident in both samples on the β phase, likely due to vanadium enrichment and a higher electrochemical potential, whereas the α phase displayed uniform nanotube coverage at higher magnification, reflecting its more stable anodic behavior.

The wrought Ti-6Al-4V surface (Figure 1a) exhibited a uniform, continuous oxide layer composed of well-defined, vertically aligned nanotubes with diameters of 70 to 90 nm, indicating stable anodization conditions across the surface.

In contrast, the DED-LB sample (Figure 1b) displayed a rougher, more heterogeneous surface. The oxide film contained irregular and partially deformed nanotubes with diameters ranging from 30 to 90 nm, as well as local tube collapse and oxide agglomerates, particularly along melt-track boundaries. The observed irregularities are a consequence of

surface roughness and compositional variations produced by the layer-by-layer solidification process, which cause local distortions in the electric field during anodization and result in uneven nanotube formation.[5,6]

Although less uniform, the increased roughness and heterogeneity of the DED-LB surface may enhance surface area and active sites, potentially improving bioactivity or enabling controlled drug release.[4] Further optimization of DED-LB parameters could mitigate microstructural heterogeneity and promote more uniform anodization, while maintaining the mechanical and design advantages of the additively manufactured alloy.

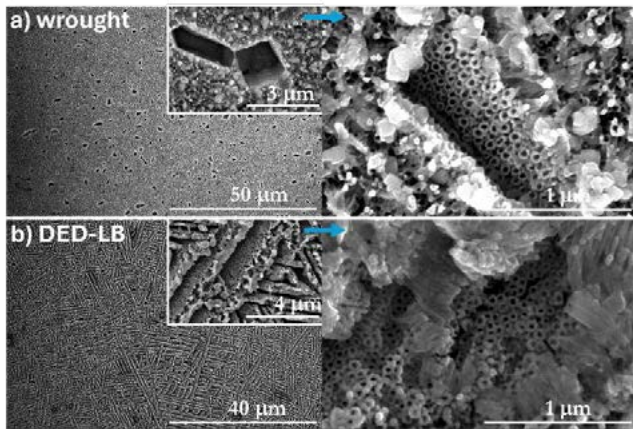


Figure 1: SEM images of anodized Ti-6Al-4V samples (30 V, 2 h): (a) wrought and (b) DED-LB. Insets show low-magnification views; high magnifications reveal uniform nanotubes on the wrought and irregular, partially collapsed structures on the DED-LB sample.

Potentiodynamic polarization tests (Figure 2) revealed clear differences in corrosion behaviour between the two anodized samples. Both showed notable passivation improvements compared to non-anodized samples, confirming the protective effect of the TiO₂ layer.

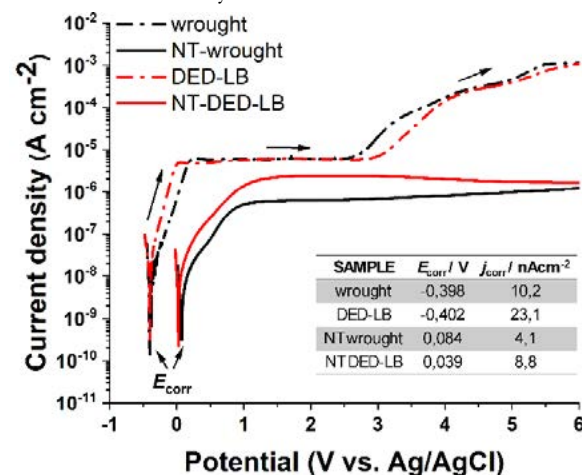


Figure 2: Potentiodynamic polarization curves of wrought and DED-LB Ti-6Al-4V samples, both freshly polished and anodized (NT), measured in Hanks' solution.

The improvement is evident from the decrease in corrosion current density (j_{corr}) by approximately one order of magnitude after anodization. For the wrought sample, j_{corr} decreased from 10.2 to 4.1 nA cm⁻², while for the DED-LB sample, it

decreased from 23.1 to 8.8 nA cm⁻² (inset table in Figure 2). The anodized samples also exhibited a positive shift in corrosion potential (E_{corr}), indicating enhanced surface passivation.

However, the anodized DED-LB samples exhibited slightly higher j_{corr} values than the anodized wrought alloy, consistent with their less uniform oxide structure and with localized defects acting as preferential dissolution sites. The wrought alloy displayed a more noble E_{corr} and lower j_{corr} values, indicating greater passivation stability. This superior performance is attributed to its homogeneous microstructure and uniform phase distribution, which promote consistent oxide composition and thickness.

In contrast, microstructural heterogeneity and residual stress gradients in the DED-LB sample likely generate microgalvanic regions that accelerate localized corrosion, as reported previously.² These electrochemical trends align with morphological observations, suggesting that the microstructural anisotropy and α' -martensitic content of DED-LB Ti-6Al-4V influence both oxide growth and corrosion response.

Conclusions

- Both wrought and DED-LB Ti-6Al-4V alloys successfully formed self-organized TiO₂ nanotube layers by anodization in an ethylene glycol-based electrolyte at 30 V for 2 h.
- The wrought alloy developed uniform, well-ordered nanotubes and exhibited superior passivation stability, whereas the DED-LB alloy formed irregular, locally deformed nanotubes and showed slightly higher corrosion currents, reflecting the influence of its α' martensitic microstructure on inferior corrosion resistance and microstructural heterogeneity.
- The heterogeneous solidification features of DED-LB processing strongly affect oxide growth and electrochemical behavior, but post-processing or heat treatment could improve oxide uniformity and enable reliable biofunctionalization for implant applications.
- Overall, the results demonstrate that the fabrication process governs anodic oxide morphology and corrosion performance, emphasizing the need to control both bulk microstructure and anodization parameters to achieve reproducible TiO₂ nanotubular coatings on additively manufactured titanium alloys.

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Using High-Performance Computing for Engineering Innovation: The HPCFS Infrastructure 2025 Upgrade

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High Performance Computing (HPC) has become a key enabler of innovation in modern engineering. At the Faculty of Mechanical Engineering, University of Ljubljana, the HPCFS infrastructure enables researchers and students with the computational power necessary for advanced simulations, modelling, and data analysis. This paper presents the motivation for using HPC in engineering, an overview of the HPCFS system, and the planned 2025 Infrastructure upgrade. The selected projects demonstrate how HPC supports complex analyses ranging from plasma simulations to AI-driven modelling.

Introduction

High Performance Computing (HPC) enables engineers and scientists to solve complex problems that exceed the capabilities of conventional computers. In mechanical engineering, HPC allows advanced modelling, simulation, and optimization of systems with high computational demands. At the Faculty of Mechanical Engineering, University of Ljubljana, the HPCFS infrastructure provides access to large-scale parallel computing resources that support both research and education.

HPC cluster

HPC clusters are specialized computing systems designed to solve complex scientific and engineering problems that exceed the capabilities of standard desktop computers. As presented in Figure 1, by linking multiple compute nodes through a high-speed interconnect, HPC clusters operate as a single unified system, allowing researchers to perform parallel computations on large datasets or highly detailed numerical models. Each node typically contains several multicore processors and large memory banks, while the network fabric ensures efficient communication between processes running across nodes.

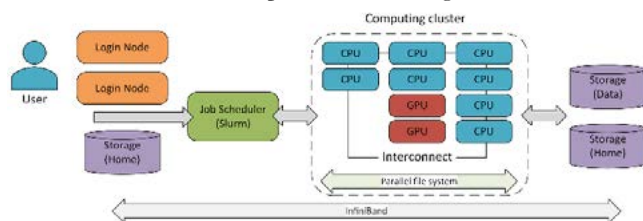


Figure 1: Generalised HPC Cluster Architecture.

HPC clusters serve as a cornerstone of innovation. They enable a wide range of applications, from thermomechanical modelling, computational fluid dynamics (CFD), finite element analysis (FEA), to modern data analytics, and artificial intelligence (AI). The ability to simulate physical systems at high resolution reduces the need for experiments and accelerates the development of new technologies. HPC thus enables scientific insight and industrial competitiveness.

Presentation of HPCFS with 2025 upgrade

The continuous growth of computational requirements makes regular upgrades of HPC infrastructure essential. The 2025 upgrade, presented in Figure 2, ensures that the platform continues supporting advanced simulations, data-driven research and modern AI workloads.

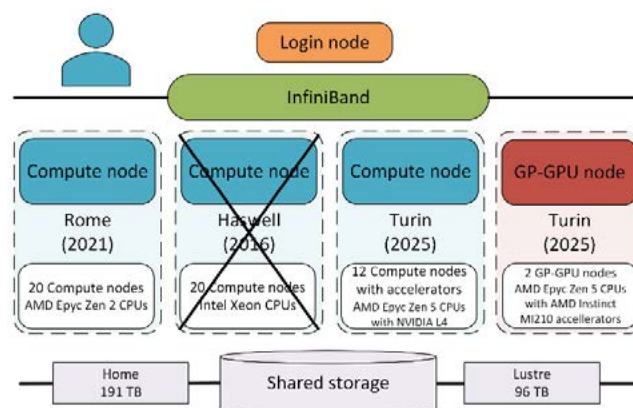


Figure 2: Upgraded HPCFS cluster setup.

The HPCFS system consists of two main compute partitions (Haswell and Rome) and will be upgraded in 2025 to include new CPU and GPU nodes, fast storage, and enhanced InfiniBand interconnect. The upgrade will improve computational performance and support for heterogeneous workloads. Software updates will include containerization, Spack-based package management, and improved user tools.

Hardware

The upgraded HPCFS features next-generation compute nodes with high-core-count CPUs boosted with GPU accelerators, connected through an upgraded high-speed, low-latency interconnect (EDR). A tiered storage system with an expanded parallel file system, will offer both speed and capacity.

Software environment

The system runs a current Linux distribution with the SLURM scheduler for resource management and GPU job execution. Software deployment is handled with Module systems, complemented by container support using Apptainer/Singularity. This setup simplifies application management and improves portability and reproducibility of workflows.

Expected performance and user experience

The upgrade will result in better computational and storage performance. Workloads, particularly in CFD, FEA, and materials modelling will benefit from reduced runtimes and improved scalability. For users, this will mean faster job execution, more efficient data handling, and access to GPU acceleration for modern AI and machine learning tasks.

Methodology of using HPC

The effective use of HPC resources, highlighted in Figure 3, requires a structured approach that combines technical understanding, efficient workflow and resource management. HPCFS system provides an environment that supports these principles, enabling users to run complex simulations and analyses in an optimized and reproducible way.

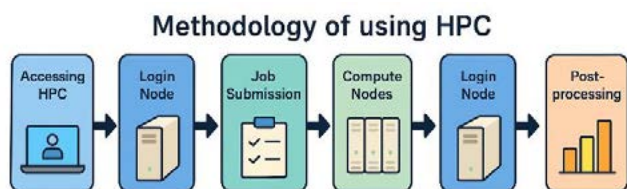


Figure 3: Generalised workflow of using an HPC.

Access and user environment

Access to HPCFS is granted to registered users, including researchers, students, and project partners. Each user receives a secure account for login to a Linux-based environment with preinstalled compilers, libraries, and applications. Software modules enable easy loading of required versions and dependencies.

Job submission and scheduling

Jobs are submitted through the Slurm workload manager, which allocates resources based on job requirements and system load. Users define submission scripts specifying the number of nodes, cores, memory, and runtime. Parallel applications typically use MPI for distributed and OpenMP for shared-memory computing, while GPU workloads run on dedicated GPU partitions.

Data management and workflow optimization

Input and output data are stored on a high-performance Lustre file system, while long-term user data are kept on network-attached home directories. This separation ensures both high throughput and data security.

To support reproducibility and portability, HPCFS enables containerized environments. Containers allow to bundle software dependencies into self-contained images, ensuring consistent execution across different systems and projects.

Training and support

Recognizing that efficient HPC usage depends on user knowledge, HPC training sessions, workshops, and tutorials are regularly organized covering topics such as job submission, parallel programming, and performance optimization.

Examples of projects on HPCFS

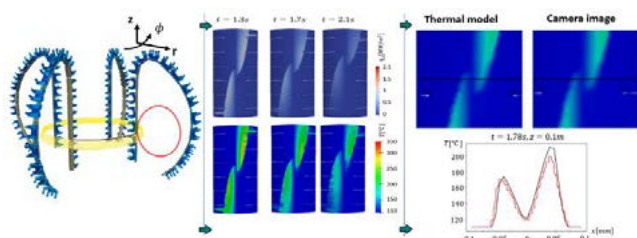


Figure 4: Excellerat P2 – Thermal simulations for Tokamak reactor using HPC [1].

The HPCFS infrastructure supports a diverse range of national and European research projects, providing the computational foundation for advanced simulations, modelling, and training in high performance computing.

Selected projects that illustrate the variety of its applications and collaborations are:

- **CoE Excellerat P2:** Thermal simulations for the first wall of a tokamak fusion reactor, example in Figure 4. [1]
- **CoE Plasma PEPSC:** Plasma modeling using the BIT particle simulation code. [2]
- **EuroCC 2:** Supporting the Slovenian National Competence Centre for HPC. [3]
- **EuMaster4HPC:** Providing HPC training and education for students across Europe. [4]
- **DESY, Hamburg:** Innovative methods for imaging with the use of X-ray free-electron laser (XFEL) and synchrotron sources: simulation of sample delivery systems [5].
- **CABUM ERC project,** An investigation of the mechanisms at the interaction between cavitation bubbles and contaminants [6].

Conclusion

HPC has become an indispensable tool in modern engineering research. The HPCFS infrastructure provides computational support for demanding simulations, design optimization, and education. The planned 2025 upgrade will significantly enhance performance and user experience, ensuring continued support for scientific and industrial challenges.

Acknowledgements

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Alternativni materiali za razvoj vodno-hidravličnih drsniških ventilov

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Mineralna olja so trenutno najpogostejše uporabljena hidravlična kapljevina, saj zagotavljajo dobro mazanje in dolgo življenjsko dobo komponent. V zadnjem času se kljub temu povečuje zanimanje za vodno hidravliko, saj uporaba vode prinaša številne prednosti, kot so okoljska neškodljivost, negorljivost ter cenovna dostopnost. Glavni izzivi pri razvoju vodno-hidravličnih sistemov so povezani z nizko viskoznostjo vode, ki povzroča povečano notranje puščanje in slabše mazalne lastnosti, ter z njeno kemijsko reaktivnostjo, ki lahko vodi do korozije konvencionalno uporabljenih kovinskih komponent.

V članku je predstavljen razvoj vodno-hidravličnega drsniškega potnega ventila, ki temelji na predelavi ventila, prvotno namenjenega delovanju v olju. Raziskava se osredotoča na delovanje, odzivnost in notranje puščanje ventila pri uporabi krmilnih batov iz aluminija in eloksiranega aluminija. Izvedeni so bili tudi trajnostni testi na namenskem preizkuševališču, ki potrjujejo uspešno delovanje ventila v vodnem okolju.

Uvod

Voda je že tisočletja eden ključnih elementov človeškega razvoja – ne le kot osnovni vir življenja, temveč tudi kot sredstvo za pridobivanje in prenos energije. Tako kot Ktezibijev izum prve hidravlične črpalke okoli leta 270 pr. n. št. je tudi Joseph Bramah-ov izum prve industrijske hidravlične stiskalnice leta 1795 temeljil na uporabi vode kot hidravlične kapljevine [1]. Voda je ostala ključni pogonsko-hidravlični medij vse do začetka 20. stoletja, ko so jo zaradi tehničnih omejitev postopoma nadomestila hidravlična olja [2]. Z uvedbo mineralnih olj so hidravlični sistemi dosegli večjo zanesljivost, manjšo obrabo in daljšo življenjsko dobo komponent, predvsem zaradi boljšega mazanja in višje viskoznosti olja. Z rastjo industrijske proizvodnje pa je kmalu postalo očitno, da ima uporaba olja tudi številne okoljske in ekonomske slabosti. Izlitje olja v okolje lahko povzroči trajno onesnaženje tal in vodnih virov, proizvodnja olj pa je energetsko zahtevna in povezana z emisijami toplogrednih plinov. Po ocenah Nemške zvezne agencije za okolje v Nemčiji vsako leto kar 25 % uporabljenih hidravličnih olj konča v okolju ali pa je nepravilno zavrženih, kar predstavlja približno 26 250 ton olja, ki vsako leto onesnaži okolje. [3]. V zadnjem desetletju se zato znova krepi interes za uporabo okolju prijaznih kapljev. Napredek v materialih in površinskih obdelavah je omogočil ponovno obravnavo vode kot realne alternative olju zlasti v aplikacijah, kjer sta trajnost in varnost pomembna dejavnika. Čeprav ima voda izrazite pomanjkljivosti – predvsem nizko viskoznost (tudi 100-krat nižjo od olja), omejene mazalne sposobnosti in kemijsko reaktivnost, ki lahko povzroča korozijo, sodobni

razvoj materialov in aditivov ponuja možnosti za njihovo učinkovito obvladovanje.

Ventili so osrednji element vsakega hidravličnega sistema, saj omogočajo nadzor nad pretokom in smerjo kapljevine. Posebej zanimivi so digitalni 2/2 potni ventili z drsniškim krmilnim batom, ki z visoko frekvenco preklopov omogočajo natančno regulacijo sistema. Eden izmed pristopov za povečanje hitrosti delovanja je uporaba krmilnega bata, izdelanega iz lažjega materiala, kar neposredno vpliva na hitrost preklopa ventila. Aluminij in eloksiran aluminij se v ta namen izkazujeta kot obetavni izbiri, saj združujeta nizko maso, zadostno mehansko trdnost in odpornost proti koroziji. V tem okviru raziskava obravnava eksperimentalni preizkus drsniškega potnega ventila, prilagojenega za delovanje v vodni hidravliki, s poudarkom na primerjavi aluminijastih in eloksiranih aluminijastih krmilnih batov glede na njihov vpliv na tesnjenje in obrabo.

Materiali in metode

Ventil EVH2C je normalno zaprt, drsniški 2/2 potni ventil, krmiljen s pomočjo elektromagneta. Namenjen je za delovanje v oljnem hidravličnem sistemu do delovnega tlaka 250 bar ter pretoka 20 l/min [4]. Izbran drsniški 2/2 potni ventil (slika 1 a) je v osnovi izdelan tako, da je ohišje narejeno iz enega dela in ga posledično ni mogoče razstaviti in dostopati do krmilnega bata. S tem razlogom smo originalen ventil razžagali in po njegovem vzoru izdelali eksperimentalen ventil (slika 1 b), sestavljen iz dveh delov ohišja, kar nam je omogočalo enostavno razstavljanje ventila in menjavo originalnega krmilnega bata s krmilnim batom iz aluminija in eloksiranega aluminija.



Slika 1: (a) Razžagan ventil EVH2C; (b) Predelan ventil.

V drsniskih ventilih je notranje puščanje vedno prisotno, saj je tesnjenje zagotovljeno zgolj z natančnim ujemom med krmilnim batom in pušo oziroma ohišjem ventila. Med njima mora obstajati radialna zračnost oziroma ohlapen ujem, ki omogoča nemoteno gibanje krmilnega bata znotraj ventila [5]. Pri izvedbi meritev imata zato ključno vlogo krmilni bat in puša, saj je velikost reže med njima odločilnega pomena za delovanje ventila.

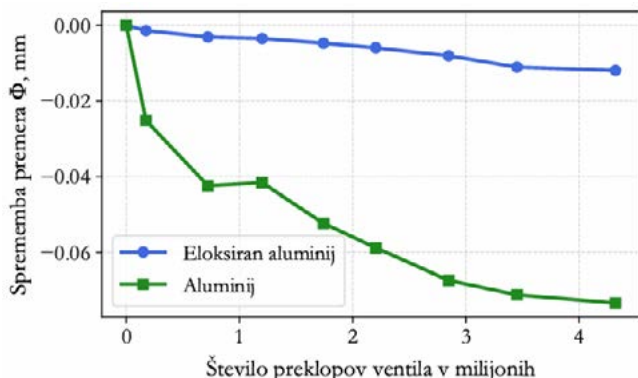
Izdelali smo 2 puši iz nerjavnega jekla AISI 440B ter 20 krmilnih batov iz aluminijeve zlitine EN AW-6082. Obe puši sta bili po obdelavi kaljeni, medtem ko je bilo 10 od skupno 20 krmilnih batov dodatno površinsko obdelanih z eloksacijo.

Za potrebe raziskave smo zasnovali vodno-hidravlično preizkuševališče, namenjeno merjenju notranjega puščanja in trajnostnemu testiranju ventilov. Vsaka izmed obeh puš je bila uporabljena za preizkus desetih krmilnih batov – prva z aluminijastimi, druga z eloksiranimi aluminijastimi bati. Za vsako materialno kombinacijo smo tako izmerili notranje puščanje pri desetih različnih parih bat–puša ter nato izbrali krmilni bat z najmanjšim začetnim puščanjem za nadaljnji trajnostni preizkus in obravnavo. Vsi testi so bili izvedeni v vodi pri tlaku 100 bar.

Pred začetkom testov smo z dvotočkovnim mikrometrom izmerili notranji premer obeh puš ter zunanji premer vseh krmilnih batov. Trajnostni preskusi so skupaj zajeli več kot 4 300 000 prekopov ventila. Skozi celoten potek trajnostnega testa smo izvajali periodične meritve notranjega puščanja in zunanjega premera posameznega krmilnega bata predelane ventila. Notranjega premera puše med testom nismo ponovno merili, saj bi bilo za to potrebno vsakič odviti ventil iz hidravličnega bloka, kar bi lahko negativno vplivalo na ponovljivost rezultatov.

Rezultati in diskusija

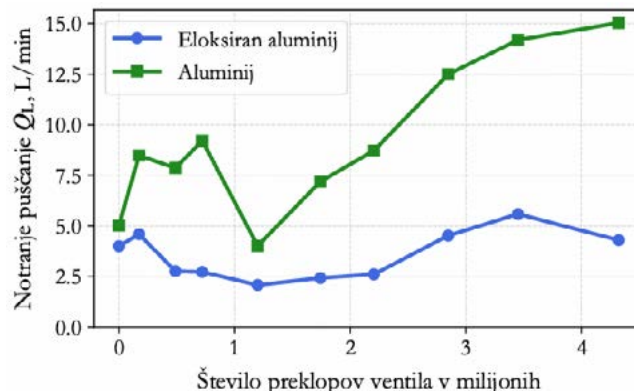
Na sliki 2 opazimo, kako se je z večanjem števila prekopov ventila zaradi obrabe zmanjševal premer krmilnega ventila. Originalnega ventila na grafu ni prikazanega, saj zaradi njegovega nerazstavljivega ohišja merjenje krmilnega bata brez porušitve ni bilo mogoče.



Slika 2: Spreminjanje premera krmilnega bata s številom prekopov ventila.

Rezultati kažejo, da se je premer aluminijastega bata zmanjšal za več kot 6-krat bolj kot premer bata iz eloksiranega aluminija. Ugotovitve tako potrjujejo rezultate, objavljene v članku [6], da eloksacija aluminija bistveno zmanjša obrabo komponent pri delovanju v vodnem okolju.

Na sliki 3 je prikazano spreminjanje notranjega puščanja skozi čas trajnostnega testa. Tudi v tem primeru originalnega ventila ni bilo mogoče vključiti, saj je kljub nizkemu začetnemu notranjemu puščanju (0,135 L/min) odpovedal že pred prvo meritvijo pri približno 170 000 ciklih. Razlog za odpoved je verjetno korozija, ki je onemogočila gibanje krmilnega bata znotraj puše, kjer je bila začetna reža zgolj 3 μm.



Slika 3: Notranje puščanje posameznega ventila v odvisnosti od števila prekopov.

Pri obeh izvedbah ventila (z aluminijastim in eloksiranim aluminijastim batom) je bila začetna reža med batom in pušo 8 μm. Razlika v začetnih vrednostih notranjega puščanja je najverjetneje posledica ekscentričnosti bata v izvrtini, saj ta pomembno vpliva na velikost puščanja – popolnoma ekscentričen bat lahko povzroči do 2,5-krat večje puščanje v primerjavi s centričnim. V obeh primerih notranje puščanje doseže najnižjo vrednost pri približno $1,2 \times 10^6$ ciklih, kar pripisujemo postopni obrabi, ki je omogočila bolj centrično poravnavo krmilnega bata znotraj puše.

Zaključki

V raziskavi je bil originalni ventil predelan z uporabo krmilnih batov iz alternativnih materialov. Dokazano je bilo, da je z uporabo aluminija mogoče zagotoviti zanesljivo delovanje ventila v vodi pri tlaku do 100 bar. Nadalje je bilo ugotovljeno, da eloksacija aluminija občutno izboljša obrabno odpornost in stabilnost delovanja ventila v vodnem okolju.

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Design of a scratch testing apparatus for investigating the repassivation capability of corrosion-resistant alloys

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A custom scratch testing apparatus was developed to investigate the repassivation behavior of corrosion-resistant alloys under open-circuit conditions. The system, fabricated via rapid prototyping and 3D printing, enables controlled mechanical damage through rotational scratching while continuously monitoring potential evolution. Using Ti6Al4V alloy as a model material, the effects of applied normal force and rotation speed on open-circuit potential (OCP) were systematically studied in 0.9 wt% NaCl solution. Results show that rotational speed exerts a stronger influence on OCP than applied force, with both higher force and faster rotation leading to lower potentials, consistent with enhanced film breakdown. Optimal reproducibility was achieved with a spring length of 20–22.5 mm and a rotation speed of 11.2 rpm. This apparatus offers a versatile platform for studying passive film rupture and spontaneous repassivation mechanisms, providing a foundation for further in situ electrochemical investigations.

Introduction

The durability of titanium alloys and stainless steels is primarily attributed to the formation of passive oxide films and their ability to rapidly repassivate following film damage. Under freely corroding conditions—i.e., in the absence of an applied potential—in situ electrochemical techniques are employed to investigate this intrinsic self-healing behavior. Traditionally, repassivation studies have relied on potentiostatic control during film disruption via micro-indentation, scratching, or guillotine cutting [1]. However, externally imposed potentials can influence the measured currents and potentials, potentially masking the alloy's natural response. Consequently, recent research has increasingly focused on open-circuit methods that better simulate real-world conditions. For instance, scratch testing at open-circuit potential (OCP) involves mechanically rupturing the passive film, followed by monitoring spontaneous recovery via OCP transients or galvanic current measurements between coupled identical electrodes [2]. To enhance spatial resolution, complementary localised techniques, such as scanning electrochemical microscopy (SECM), have been employed to map anodic activity and detect pH variations during spontaneous repassivation events [3].

Therefore, to gain a deeper understanding of the significance of open-circuit potential (OCP), we designed a custom apparatus with stable rotational scratching capability using rapid prototyping and 3D-printed components. This system enables the observation of OCP fluctuations during and post scratching process. It serves as a preparatory tool for

optimizing experimental parameters in related studies and, once the scratching procedure is further stabilised, will support future in situ investigations such as electrochemical impedance spectroscopy (EIS) and other electrochemical techniques.

Materials and methods

The apparatus was rapidly designed using the ThinkerCAD online platform, with plastic components fabricated via 3D printing. A motor with a maximum rotational speed of 11.2 rpm was employed. Preliminary scratch experiments under OCP conditions were conducted on three 3D-printed Ti6Al4V alloy. The samples were machined into discs with a diameter of 15 mm and a thickness of 2 mm. Prior to testing, the specimen surfaces were metallographically polished using a LaboPol-20 grinding system (Struers, Denmark) to a P4000 finish.

Electrochemical measurements for the parameter tests were performed in a 0.9 wt% NaCl solution, and the preliminary scratch test was performed in 0.9 wt% NaCl solution with addition of 33 mM H₂O₂. Solutions were prepared using deionized water (Milli-Q Direct, resistivity ≥ 18.2 M Ω -cm at 25 °C). Scratching commenced during OCP measurements once a stable potential was achieved, typically around 1750 s, and was followed by continued OCP monitoring until a new steady-state potential was reached.

Scratch tests were performed under varying parameters, with the applied normal force ranging from 0.75 to 4.4 N (77–405g). The force was calibrated using a balance, and the corresponding spring constants were recorded. OCP during scratching were monitored on additively-manufactured Ti6Al4V samples [4] to explore the relationship between test parameters and OCP evolution, thereby providing insight into the repassivation behavior.

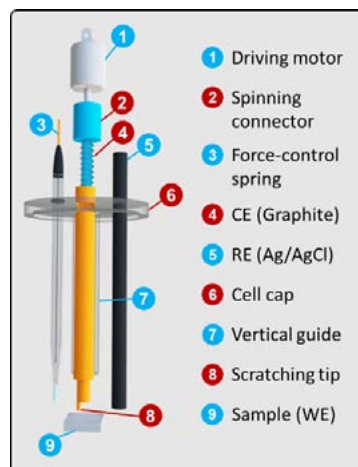


Figure 1: Schematic plot of the scratch apparatus

Results and discussion

Design of the scratch apparatus

The scratching apparatus for repassivation research is designed to enable in situ investigation of localized film breakdown and subsequent repassivation behavior under controlled electrochemical conditions. The system comprises nine key components that work synergistically. A **driving motor (1)** provides precise rotational motion, transmitted through the **spinning connector (2)** to ensure stable and consistent movement of the **scratching tip (8)**. The **force-control spring (3)** regulates the contact pressure between the tip and the **sample surface (9)**, preventing excessive deformation while maintaining reproducible mechanical damage. The electrochemical environment is maintained by a **three-electrode configuration**, which includes a **graphite counter electrode (4)** and an **Ag/AgCl reference electrode (5)**, both integrated within the **cell cap (6)** to minimise solution resistance and maintain stable potential control. The **vertical guide (7)** ensures linear alignment of the scratching path, providing accurate positioning of the tip. During operation, the **scratching tip (8)** periodically removes the passive film formed on the **working electrode (9)** surface, while the potential and current responses are continuously monitored, allowing for real-time characterisation of repassivation kinetics. This compact and modular design provides reliable mechanical and electrochemical coupling, making it ideal for systematic studies of film rupture and repair mechanisms on various metal substrates.

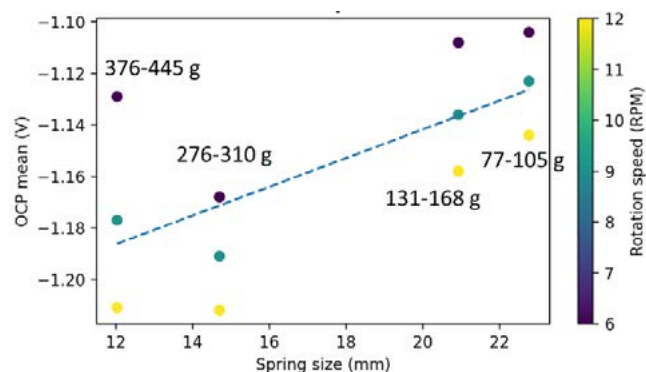


Figure 2: Relationship between OCP and applied force, rotation speed, and spring size.

Parameters for scratch tests

By maintaining a constant applied force, the effect of varying rotational speeds on the OCP was investigated in a 0.9 wt% NaCl solution. Conversely, the applied force was varied—via adjustment of spring compression—while keeping the rotational speed constant, to examine its influence on the OCP. Given that the applied force originates from a calibrated spring mechanism, a quantitative relationship can be established between spring length, applied force, and the corresponding OCP response.

Experimental observations revealed that rotational speeds and variations in spring size (i.e., applied force) at a fixed rotation speed produced limited OCP differences—generally less than 100 mV. These findings suggest that using a low applied force in combination with a high rotation speed is advantageous for repassivation measurements.

Based on the results, a spring length of 20–22.5 mm, combined with a rotational speed of 11.2 rpm, appears to be an appropriate parameter set for reliable scratch testing.

Simple scratch experiment

As shown in **Figure 3**, after applying a scratch for approximately 25 s, subfigure A indicates that the OCP drops sharply and then gradually recovers to its initial value after about 1500 s once scratching is stopped. Subfigure B presents an enlarged view of the OCP response between 1700 s and 1800 s in subfigure A, highlighting the potential evolution during the scratching period. The OCP rapidly decreases upon scratch initiation and stabilises around $-0.4 \text{ V}_{\text{Ag/AgCl}}$. After the scratch is removed, the OCP first increases quickly, followed by a slower but continuous rise until it reaches—or even exceeds—the pre-scratch OCP, indicating ongoing repassivation of the surface.

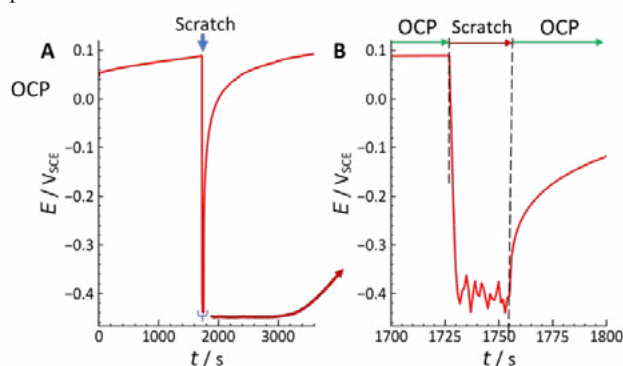


Figure 3: Scratch experiment on Ti6Al4V alloy in 0.9 wt% NaCl + 33 mM H_2O_2 during one hour at OCP.

Conclusions

- Through rational design and the use of 3D printing technology, a scratch testing apparatus was developed to investigate the evolution of OCP during the repassivation process of Ti6Al4V alloy.
- Experimental results indicate that the applied force during scratching has a relatively minor effect on OCP, whereas the scratching speed exhibits a more pronounced influence. Nevertheless, the difference in OCP between rotation speeds of 6 rpm and 11.2 rpm remains below 100 mV.
- A greater applied force and higher rotational speeds result in a more negative OCP. These trends are consistent with the theoretical understanding of passive film breakdown and repassivation.
- A rotation speed of 11.2 rpm, combined with a spring length in the range of 20–22.5 mm, was found to yield a relatively stable and repeatable scratching process.

ACKNOWLEDGEMENTS. The authors acknowledge the Slovenian Research and Innovation Agency (ARIS) for the funding of the project »Antibacterial alloys: Development by additive 3D manufacturing, characterisation and clinical applications«, acronym BIOAD, <https://bioad.ijs.si/> (grant No. J7-4639) and core funding (grant No. P2-0393).

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High-Intensity Focused Pressure Wave Generation via Q-Switched Er:YAG Laser

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We present coating-free optodynamic generation of focused ultrasound using a mechanically Q-switched Er:YAG laser ($\lambda = 2.94 \mu\text{m}$, $\approx 100 \text{ ns}$, $\leq 20 \text{ mJ}$) combined with a concave water interface that simultaneously acts as an acoustic lens and conversion layer. The focused pressure field was characterized using a hydrophone scan while varying beam diameter ($2w = 5\text{--}15 \text{ mm}$) and pulse energy. The maximum positive pressure reached 7 MPa at an intermediate diameter ($\sim 10 \text{ mm}$), while the strongest confinement and spectral enhancement occurred for 14–15 mm beams (central frequency $f_c \approx 5 \text{ MHz}$). For equal fluence, larger diameters yielded higher focal pressures due to greater focusing gain. The method enables generation of localized, MHz-range pressure waves without absorptive coatings, suitable for contamination-sensitive biomedical applications such as contact-mediated acoustic therapy or ultrasound-triggered drug release.

Introduction

Laser-generated focused ultrasound (LGFU) offers sub-millimetre spatial precision and high acoustic amplitudes exceeding those achievable with conventional piezoelectric transducers [1]. It is based on rapid optodynamic (OD) conversion, where a short laser pulse induces thermal expansion in an absorbing medium, producing broadband acoustic waves. However, most LGFU emitters rely on composite coatings [1, 2]—typically polymers embedded with carbon nanotubes or graphene—which complicate fabrication, limit biocompatibility, and hinder sterilization for medical use.

To overcome these limitations, we explore a coating-free focusing concept employing a mechanically Q-switched Er:YAG (MQS-Er:YAG) laser operating at $2.94 \mu\text{m}$, a wavelength strongly absorbed in water [3]. By shaping a thin water layer into a spherical interface, this layer acts simultaneously as OA converter and acoustic lens. This simple configuration allows pressure wave generation and focusing directly within water, eliminating the need for additional absorber layers while maintaining high energy localization and thermal confinement on the 100 ns timescale.

Materials and methods

A dedicated MQS-Er:YAG system was developed from a modified clinical laser (Fotona Fidelis). Mechanical Q-switching was implemented using a motor-driven high-reflective mirror whose position was synchronized with the flashlamp trigger via a photodiode feedback circuit. The system produced stable single pulses of 90–110 ns with energies between 10 and 20 mJ and near-Gaussian temporal profiles.

The experimental setup (Fig. 1) consisted of a plano-convex lens to adjust the beam diameter ($2w = 5\text{--}15 \text{ mm}$); a plano-concave fused-silica lens partially immersed in water, forming a spherical water interface that served as both OD generation site and focusing element; a needle hydrophone (Precision Acoustics NH0200) mounted on a robotic arm (UR5) for 3D spatial scanning; and a photodiode used for triggering digital oscilloscope for synchronous acquisition.

Hydrophone signals were recorded at each position and averaged over 50 laser shots. Maximal compressional (P_{max}) and rarefactional (P_{min}) pressures were extracted, and Fast Fourier Transform (FFT) was applied to obtain central frequency f_c .

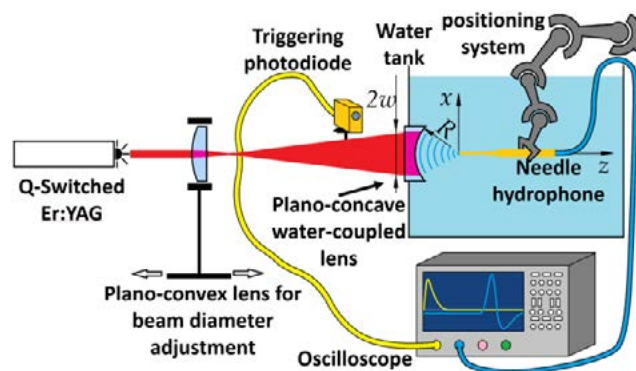


Figure 1: Experimental setup for coating-free optoacoustic focusing using a Q-switched Er:YAG laser. The concave water interface simultaneously serves as an optoacoustic converter and acoustic lens enabling pressure-wave focusing.

Results and discussion

A typical time-domain waveform (Fig. 2a) shows a sharp compressional peak followed by rarefaction, with peak-to-peak amplitude of about 10 MPa. The corresponding frequency spectrum (Fig. 2b) reveals a central frequency of 4.1 MHz, confirming that the generated pulse is broadband and confined in the MHz range.

Figure 3 reveals that increasing the beam diameter strengthens the focusing effect and enhances spectral components up to $\sim 5 \text{ MHz}$, while smaller beams yield broader waveforms and lower bandwidths due to early shock-like emission from localized vaporization at higher fluence.

Figure 4 shows the variation of peak positive pressure P_{max} as a function of laser fluence F for different beam diameters. Pressure increases nearly monotonically with fluence. For equal fluence, larger diameters produce higher pressures due to increased focusing gain. Saturation was noticed at the fluence $> 80 \text{ mJ/cm}^2$.

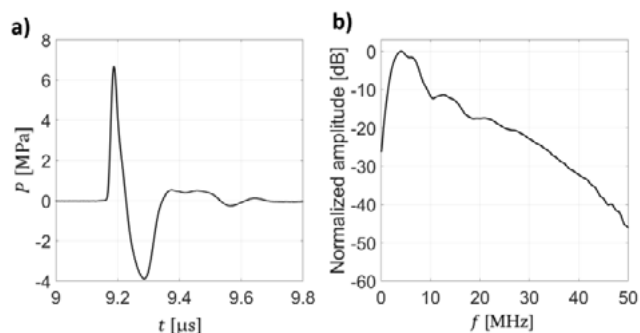


Figure 2: Typical time-domain pressure waveform (a) showing compressional (positive) and rarefactional (negative) phases. (b) Normalized frequency spectrum with $f_c \approx 4$ MHz (right).

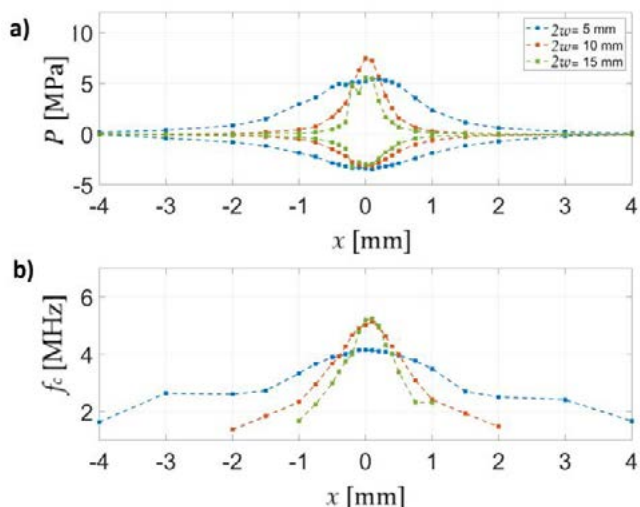


Figure 3: Lateral profiles of (a) peak pressure and (b) central frequency f_c measured at the focal plane for different beam diameters ($2w = 5, 10, 15$ mm). Larger diameters result in stronger confinement and higher spectral components near the axis.

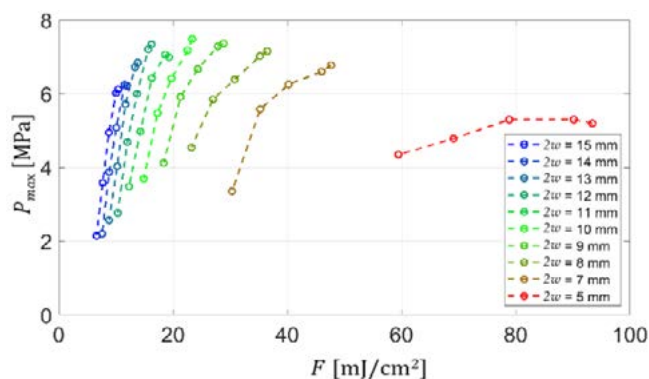


Figure 4: Dependence of peak positive pressure P_{max} on average fluence F for various beam diameters. Larger beam diameters ($2w$) yield higher focal pressures for equal fluence due to greater focusing gain.

At small diameters ($2w \leq 8$ mm), focusing is weak and waveform broadens. Intermediate diameters (~ 10 mm) yield the highest $P_{max} \approx 7$ MPa, while larger diameters (≥ 14 mm) enhance spectral confinement but slightly reduce amplitude because of lower fluence at the periphery and increased optical losses through the thicker lens edge.

The observed trends arise from the trade-off between acoustic gain (improving with aperture size) and optical fluence (decreasing with beam expansion). For a constant pulse energy, increasing the beam diameter enlarges the effective acoustic aperture, improving lateral and axial confinement (lateral FWHM ≈ 0.35 – 0.5 mm; axial ≈ 3 – 4 mm), but at the expense of slightly reduced pressure amplitude.

Spectral analyses show that f_c and bandwidth both increase near the focal plane, consistent with higher local gradients in the acoustic field. The central frequency of ~ 5 MHz corresponds closely to the inverse of the laser pulse duration (~ 100 ns), implying nearly full temporal utilization of the pulse envelope for acoustic generation.

Compared with composite LGFU emitters using carbon-based absorbers, the present coating-free approach provides similar focal pressure levels while eliminating the need for curved absorptive coatings, reducing fabrication steps, contamination risk, and cost. The optical wavelength of $2.94 \mu\text{m}$ ensures strong absorption in water and confined thermal diffusion.

Conclusions

A mechanically Q-switched Er:YAG laser (~ 100 ns, ≤ 20 mJ) combined with a concave water interface enables efficient coating-free optoacoustic focusing. Key findings of this study are: (i) Peak positive pressure up to 7 MPa at beam diameter of 10 mm; (ii) Optimal spectral confinement at $2w \approx 14$ – 15 mm is $f_c \approx 5$ MHz; (iv) Larger beam diameters yield higher focal pressures for equal fluence; and (v) saturation fluence is > 80 mJ/cm².

The approach provides a simple, biocompatible, and reproducible method for generating focused, MHz-band ultrasound without absorbing coatings, offering a promising basis for contamination-sensitive biomedical applications and future miniaturized optoacoustic devices. Potential biomedical uses include *Acoustic subcision*—localized shearing of fibrous septa in subdermal tissue; *Ultrasound-triggered drug release* from thermosensitive liposomes; and *Laser-assisted cleaning or cavitation control* in fluidic environments.

ACKNOWLEDGEMENTS. Supported by the Slovenian Research and Innovation Agency (ARIS, J7-50094, P2-0392) and within the GREENTECH project co-financed by the European Union – NextGenerationEU.

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Corrosion Behavior and Protection of AZ91 Magnesium Alloy in Eagle's Medium: Toward Biomedical Applications

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This study presents the corrosion behavior of the AZ91 magnesium alloy in Minimum Essential Eagle's Medium (α -MEM) and shows its protection approach for biomedical use, employing a PMMA-siloxane-silica coating to enhance corrosion resistance. The surface was mechanically pretreated and then coated. Surface morphology was characterized using scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy (SEM/EDS). The corrosion performance during one week of immersion was evaluated with electrochemical impedance spectroscopy (EIS). The results indicate the formation of a native surface layer that slightly increases the alloy's resistance, and a significant improvement in corrosion protection with the coating.

Introduction

Bone implant materials represent a crucial category of biomedical materials, with approximately 70–80% of implants made from metallic alloys such as stainless steel, cobalt-chromium alloys, and titanium and its alloys. These materials provide excellent mechanical strength and good biocompatibility.[1,2] However, these permanent implants often require a secondary removal surgery after bone healing, causing additional pain for patients.[1] Wrought magnesium (Mg) alloys, particularly AZ91, have attracted attention as potential biodegradable implant materials due to their biodegradability, mechanical properties close to those of natural bone (density of 1.74 g/cm³ and elastic modulus of 41–45 GPa), and the biological role of Mg as an essential nutrient.[3] Nevertheless, their high corrosion rate can lead to premature degradation and inflammation before bone healing is complete.[4] Therefore, developing effective corrosion protection during the initial healing phase is essential. In this study, the corrosion behavior of the AZ91 alloy was investigated in α -MEM medium, which simulates the ionic composition of human blood, and its performance was evaluated with a PMMA-siloxane-silica coating.

Materials and methods

AZ91 alloy (Goodfellow Cambridge Ltd, Wales, England) with a thickness of 2 mm was cut into plates sized 20 mm × 20 mm. First, samples were ground using 1200, 2400, and 4000 grit SiC, and then polished with the 3 μ m diamond paste,

with ethanol used as a lubricant to achieve a smooth, uniform surface. Then, ultrasonic cleaning in ethanol was used to remove residues, followed by ethanol rinsing and drying with compressed nitrogen.

PMMA-siloxane-silica coating was synthesized by combining two separately prepared solutions: Sol 1 (copolymerized MMA/MAPTMS sol) and Sol 2 (hydrolyzed TEOS sol), as shown in Figure 1.[5] The synthesis used a molar ratio of MMA:MAPTMS:TEOS:BPO:THF:EtOH = 8:1:2:0.08:9:20:4, with acidified water (pH = 1). Sol 1 was prepared by copolymerization at 70°C for 4 hours, while Sol 2 was prepared by hydrolysis of TEOS with acidified water for 15 min. Finally, Sol 2 was added dropwise to Sol 1, and the mixture was vigorously stirred for 1 hour at ambient temperature to produce the sol-gel solution (Figure 1).

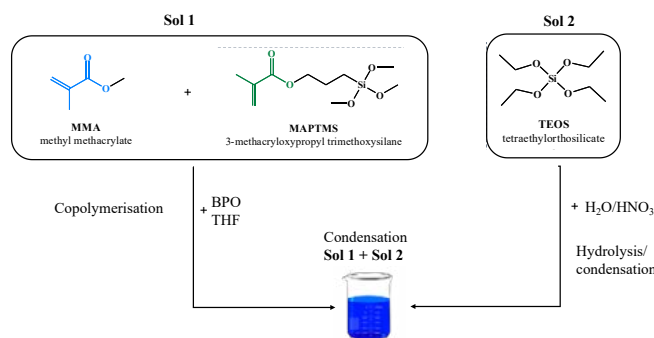


Figure 1: Flow chart of the PMMA-siloxane-silica, combining Sol 1 and Sol 2 to obtain the final solution.

The sol-gel solution was applied via single-layer dip-coating at a dip-in and pull-out rate of 14 mm/min. After deposition, the sample was thermally cured at 180°C for 1 hour.

SEM/EDS analyses were performed to study the morphology and elemental composition of the bare alloy and coated surfaces. Prior to imaging, the samples were coated with a thin carbon film. The imaging was performed using secondary electron (SE) with an Everhart-Thornley detector (ETD) and a composition backscattered detector (CBS).

Corrosion performance was evaluated by electrochemical impedance spectroscopy (EIS) using a custom-made polymethylmethacrylate three-electrode cell (250 mL volume) in α -MEM solution after 1 week of immersion at 37.5 °C. The solution was freshly prepared with the following composition: 6.8 g/L NaCl (Merck), 2.2 g/L NaHCO₃ (Sigma Aldrich), 0.4 g/L KCl (Sigma Aldrich), 0.12 g/L Na₂HPO₄·2H₂O (Merck), 0.09 g/L MgSO₄, 0.2 g/L CaCl₂·2H₂O (Sigma Aldrich), and 1

g/L D-glucose (Sigma Aldrich). All inorganic salts were dissolved in 1 L of deionized water (Milli-Q Direct water, resistivity $> 18.2 \text{ M}\Omega \cdot \text{cm}^2$ at 25°C (Millipore, Billerica, MA, USA). The pH was adjusted to 7.4. A three-electrode system was employed, consisting of a silver/silver chloride (Ag/AgCl) reference electrode, a carbon counter electrode, and the uncoated/coated AZ91 alloy as a working electrode. The impedance data were collected over a frequency range of 100 kHz to 10 mHz.

Results and discussion

Figure 2 presents the SEM image of the bare AZ91 alloy captured using a CBS detector. The brighter regions correspond to heavier intermetallic phases composed of aluminium (Al) and manganese (Mn), while the darker regions correspond to the Mg-rich matrix. The intermetallic phases in the alloy are typically the initial area of corrosion due to microgalvanic coupling with the surrounding α -Mg matrix. EDS analysis given as weight percentage (wt.%), confirms that the alloy contains more than 80.1 wt.% Mg, 12.8 wt.% Al, 1 wt.% Zn, 4.9 wt.% Mn, and 1.2 wt.% of O.

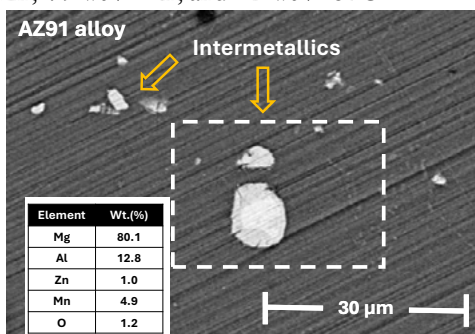


Figure 2: SEM image of the uncoated (polished) AZ91 sample recorded using a CBS detector. The EDS values obtained from the selected area are provided in the table.

Figure 3 presents the SEM/EDS analysis of the coated sample recorded in SE mode, confirming a dense, homogeneous, and crack-free coating. EDS analysis confirmed a composition of silicon (37 wt.%) and oxygen (63 wt.%) as the main elements (carbon was excluded from the study).

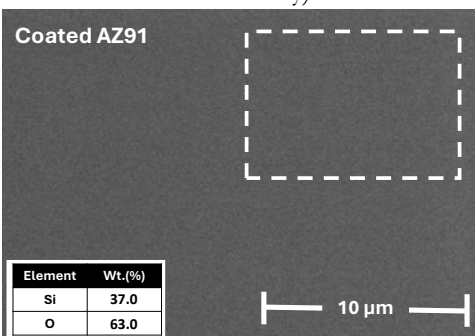


Figure 3: SEM image of the PMMA-siloxane-silica coated sample recorded in SE mode. The EDS values obtained from the selected area are provided in the table.

Figure 4 presents the Bode plot of uncoated and coated AZ91 alloy after 1 hour and after 1 week of immersion in α -MEM medium. The impedance magnitude of the uncoated sample increased with immersion time ($|Z_{10 \text{ mHz}}| = 1.3 \text{ k}\Omega \cdot \text{cm}^2$ after 1 h and $|Z_{10 \text{ mHz}}| = 85 \text{ k}\Omega \cdot \text{cm}^2$ after 1 week). This can be

attributed to the formation of an apatite layer due to the presence of calcium and phosphate ions in the α -MEM media.[6] Furthermore, comparing the uncoated and coated alloy, the coated sample exhibited significantly greater impedance across the entire frequency range after 1 h of immersion ($|Z_{10 \text{ mHz}}| = 0.9 \text{ G}\Omega \cdot \text{cm}^2$ for the coated sample vs. $|Z_{10 \text{ mHz}}| = 1.3 \text{ k}\Omega \cdot \text{cm}^2$ for the uncoated sample). This indicates enhanced corrosion protection provided by the PMMA-siloxane silica coating. Additionally, barrier protection remained stable for more than 1 week, suggesting that this coating can provide reliable protection.

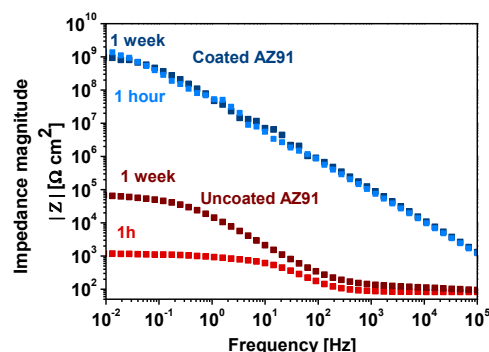


Figure 4: Bode plot for uncoated and PMMA-siloxane silica coated AZ91 alloy recorded after 1 hour and 1 week of immersion in α -MEM solution.

Conclusions

This study showed that exposure of the AZ91 alloy in α -MEM led to a continuous increase in corrosion resistance, and the improved corrosion protection obtained by depositing a PMMA-siloxane-silica coating.

Key observations of this study are:

- SEM/EDS analysis confirmed a uniform, homogeneous, and crack-free coating.
- EIS showed an increase in impedance for the uncoated AZ91 alloy due to native-layer formation in α -MEM. The PMMA-siloxane-silica coated alloy exhibited four orders of magnitude greater impedance values (improved corrosion protective properties).
- The coating remained stable for 1 week of immersion, indicating potential to enhance the durability and corrosion resistance of Mg-based implants.

Future studies should focus on monitoring coating degradation and the growth of the native surface layer in α -MEM.

ACKNOWLEDGEMENTS

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Improving energy efficiency and environmental footprint of hydrogen supply chain by upgrading to 500 bar technology

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Energy efficient hydrogen distribution is a key challenge in scaling up hydrogen mobility. This study compares energy intensity and GHG emissions of a conventional 200 bar and an innovative 500 bar hydrogen supply chain. The 500 bar concept integrates metal hydride compressors (MHCs) utilizing waste heat, Type IV composite trailers with higher payload, and optimized cascading at refuelling stations. Results show a 45 % reduction in energy use and 46 % lower GHG emissions for a 100 km transport distance. Benefits increase with transport distance and are most significant in countries with fossil-intensive electricity. The results confirm that upgrading to 500 bar can substantially improve the energy efficiency and environmental performance of hydrogen logistics.

Introduction

Hydrogen technologies offer strong potential to decarbonize hard-to-electrify sectors such as long-distance and heavy-duty transport, where battery systems face limitations. When produced from surplus renewable electricity, hydrogen can achieve very low global warming impacts [1]. However, hydrogen logistics remain a major barrier to large-scale deployment. Current 200 bar supply chains consume significant energy and show low efficiency due to compression and transport losses [2]. Hydrogen is first compressed to over 200 bar for transport, then depressurized to about 30 bar before being recompressed to 900 bar for vehicle refuelling.

This study explores a high-pressure 500 bar supply chain integrating advanced technologies: metal hydride compressors (MHC) using waste heat from on-site hydrogen production, Type IV composite trailers carrying up to three times more hydrogen than steel vessels [3], and optimized cascading storage at refuelling stations. These innovations enhance overall efficiency by utilizing waste heat during compression, cutting transport energy per kilogram of hydrogen, and reducing refuelling losses through direct hydrogen transfer from trailers to vehicles when pressure levels allow it.

The objective is to quantify the energy and environmental benefits of the proposed 500 bar system compared with the current 200 bar supply chain using integrated technical and life-cycle assessments.

Methods

Two supply chain scenarios were defined for comparison: (1) state-of-the-art 200 bar supply chain with mechanical compressors and steel cylinders for transportation, and (2) innovative 500 bar supply chain with metal hydride

compressors, Type IV composite cylinders, and cascading storage and refuelling optimization.

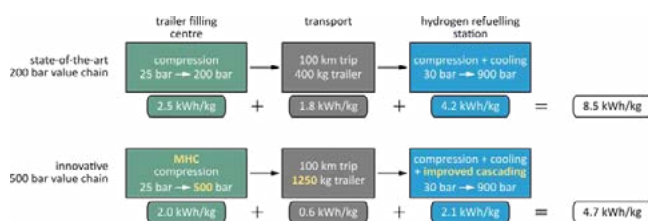


Figure 1: Description of the two supply chains.

Energy demand estimation

The total energy demand for hydrogen distribution consists of three main components:

- Compression energy at the production site, required to load hydrogen onto transport trailers.
- Transportation energy, corresponding to the fuel consumed by delivery vehicles.
- Compression and cooling energy at the hydrogen refuelling station, needed to achieve storage and dispensing pressures.

Compression energy depends on the pressure ratio, hydrogen flow rate, and compression technology. Conventional systems use multi-stage mechanical compressors with intercooling. While theoretical energy demand can be calculated, data from commercial systems show that actual consumption, including compressor inefficiencies and balance-of-plant (BoP) losses, is about twice the theoretical value.

The innovative supply chain presented here includes a metal-hydride compressor powered mainly by heat rather than electricity, resulting in significantly lower power demand compared to conventional systems. Higher transport pressure and advanced Type IV trailer designs enable larger hydrogen capacity per trip, reducing the number of deliveries required. Transportation energy is estimated based on typical fuel consumption of semi-trailer trucks.

Additionally, the higher delivery pressure reduces electricity demand at refuelling stations when improved cascading refuelling strategies are used. Overall, energy savings of up to 50 % compared with current state-of-the-art systems are estimated. Both scenarios and consumption values are shown in Figure 1.

Greenhouse gas (GHG) emissions assessment

GHG emissions were calculated following the European Commission methodology for renewable fuels of non-biological origin (RFNBO) [4]. The functional unit is 1 kg of hydrogen delivered to the vehicle. Emission factors for electricity and diesel are summarized in Table 1. The diesel emission factor accounts for both upstream and combustion-related emissions.

Table 1: Emission factors for different energy sources [4]

Type	Country	GHG emissions [kg CO ₂ eq./kWh]
Diesel	/	0.342
Electricity	France	0.071
	Spain	0.195
	Slovenia	0.252
	Germany	0.357
	Poland	0.707

The analysis covers only the operational supply chain emissions (compression, transport, and refuelling), excluding hydrogen production.

The **reference scenario** assumes a 100 km transport distance within Slovenia. Other countries and transport distances are included in sensitivity analysis to analyse the impact on GHG emissions.

Results and discussion

Total energy consumption

The total energy consumption of the innovative 500 bar supply chain is 4.7 kWh/kg H₂ for a 100 km transport distance, compared to 8.5 kWh/kg H₂ for the conventional 200 bar system. This represents an energy reduction of 3.8 kWh/kg H₂, or approximately 45 % improvement. Initial compression with MHC and improvements in cascading account for the 68 % of the total energy savings, while the increased payload of the trailer accounts for the remaining 32 %. The effect of increased trailer payload becomes more pronounced with increasing transport distance. For a 50 km supply chain, the total energy savings reach 3.2 kWh/kg H₂, whereas for a 400 km route, they increase to 7.4 kWh/kg H₂.

Environmental Impact

The total GHG emissions of the hydrogen supply chain decrease from 2.31 to 1.24 kg CO₂eq./kg H₂ when upgrading from 200 to innovative 500 bar supply chain, representing a 46 % reduction (Figure 2). Emissions from the first compression are reduced by 20 %, from truck transport by 67 %, and from final compression at the hydrogen refuelling station by 50 %.

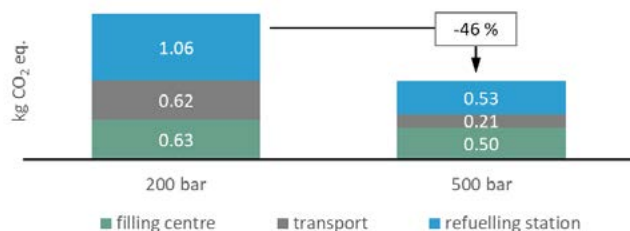


Figure 2: GHG emissions of 200 bar and 500 bar hydrogen supply chains, showing a 46 % total reduction with the 500 bar system.

Sensitivity analysis

With increasing transport distance, total GHG emissions rise for both supply chains due to higher fuel consumption, but the relative advantage of the 500 bar configuration becomes more pronounced. Emission reductions range from 43 % at 50 km to 55 % at 400 km transport distance, confirming that the type IV vessels are especially beneficial when longer distance road transport is needed (Figure 3).



Figure 3: Total GHG emissions of the hydrogen supply chain for different transport distances in Slovenia.

When comparing electricity mixes, the largest absolute reductions are achieved in countries with higher fossil fuel shares, such as Poland and Germany, where compression related electricity use dominates the supply chain emissions. However, relative improvements are even higher in countries with high shares of renewable and nuclear power production, demonstrating that the 500 bar system delivers significant emission savings across all regions (Figure 4).

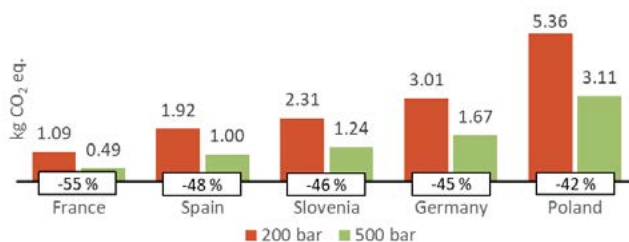


Figure 4: Total GHG emissions of the hydrogen supply chain in different countries for a 100 km transport distance.

Conclusions

- The hydrogen supply chain remains a key challenge for large-scale hydrogen mobility due to its high energy demand.
- The innovative 500 bar supply chain reduces total energy use by 45 % and GHG emissions by 46 % compared to the conventional 200 bar system.
- Benefits are greatest for long transport distances and in regions with fossil-based electricity.

ACKNOWLEDGEMENTS. This work was supported by the European Union's Horizon Europe programme under grant agreement No. 101137867 (HYGHER project).

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Vpliv premera mikroelektrode in koncentracije elektrolita na dinamiko rasti vodikovih mehurčkov pri elektrolizi

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Dinamika rasti vodikovih in kisikovih mehurčkov, ki nastajajo pri elektrolizi vode, pomembno vpliva na učinkovitost procesa elektrolize vode. V prispevku je prikazan vpliv premera mikroelektrode ter koncentracije žveplove kisline na dinamiko rasti mehurčkov pri različnih napetostih. Z naraščajočo napetostjo v splošnem narašča premer mehurčkov ob odcepitvi z elektrode. Prehod med režimi posameznih koalesciranih mehurčkov je odvisen od koncentracije elektrolita in premera elektrode. Rezultati kažejo, da pri zelo nizkih koncentracijah elektrolita že pri nizki napetosti nastopi koalescenca in doseganje velikih premerov mehurčkov ob odtrganju z elektrode. Razumevanje dinamike rasti mehurčkov omogoča optimizacijo zasnove elektrod za učinkovitejšo proizvodnjo vodika.

Uvod

Elektroliza vode je eden ključnih procesov za trajnostno proizvodnjo vodika, ki se uveljavlja kot nosilec čiste energije prihodnosti. Pri elektrolizi se voda razcepi na vodik in kisik pod vplivom električne napetosti pri čemer imajo nukleacija, rast, koalescenca (združevanje) in odcepljanje mehurčkov ključno vlogo pri učinkovitosti procesa. [1]. Mehurčki vplivajo na porazdelitev električnega toka, lokalno koncentracijo ionov in potek elektrokemijskih reakcij, saj njihovo kopičenje povečuje efektivni upor elektrolita in zmanjšuje prevodno pot med površino elektrode ter raztopino, kar vodi v povečanje prenapetosti [1, 2]. Razumevanje teh pojavov je bistveno za optimizacijo elektroliznih sistemov, kot so PEM elektrolizerji in mikrofluidične naprave, ter izboljšanje njihove učinkovitosti.

Raziskave so pokazale, da lahko pri visokih gostotah električnega toka združevanje mehurčkov izboljša učinkovitost elektrolize [3]. Večji mehurčki, ki nastanejo zaradi koalescence, povzročajo intenzivnejše mešanje v bližini površine, s tem vplivajo na koalescenca majhnih mehurčkov na površini in zmanjšajo difuzijske omejitve, poveča se delež aktivne površine [1,4]. Vrsta in koncentracija elektrolita pomembno vplivata na koalescenca. V kislilih elektrolitih, kot je H_2SO_4 , se mehurčki hitro združujejo, zato se učinkovitost lahko izboljša z večjo verjetnostjo koalescence [4]. Povezava med koncentracijo elektrolita, lokalnimi spremembami pH in površinsko napetostjo bistveno vpliva na to, ali bo prišlo do hitrejšega odcepljanja ali do združevanja mehurčkov. Pri nizkih koncentracijah se mehurčki tvorijo redkeje in rastejo dlje časa.

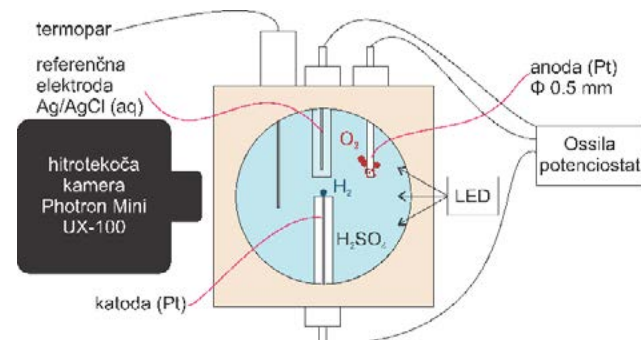
Geometrija in velikost elektrode dodatno vplivata na dinamiko mehurčkov. Na mikroelektrodah majhnega premera je število nukleacijskih mest omejeno, kar omogoča opazovanje posameznih mehurčkov, medtem ko večje elektrode

omogočajo večje število nukleacijskih mest in večjo verjetnost koalescence. Čeprav so številne študije obravnavale vpliv napetosti, vrste elektrolita in materiala elektrode na učinkovitost elektrolize, ostaja vpliv kombinacije velikosti mikroelektrode in koncentracije elektrolita na rast posameznih mehurčkov slabo raziskan. Kljub številnim raziskavam elektrolize ostaja sistematična primerjava rasti in odcepljanja mehurčkov na mikroelektrodah različnih premerov v odvisnosti od koncentracije elektrolita večinoma neraziskana.

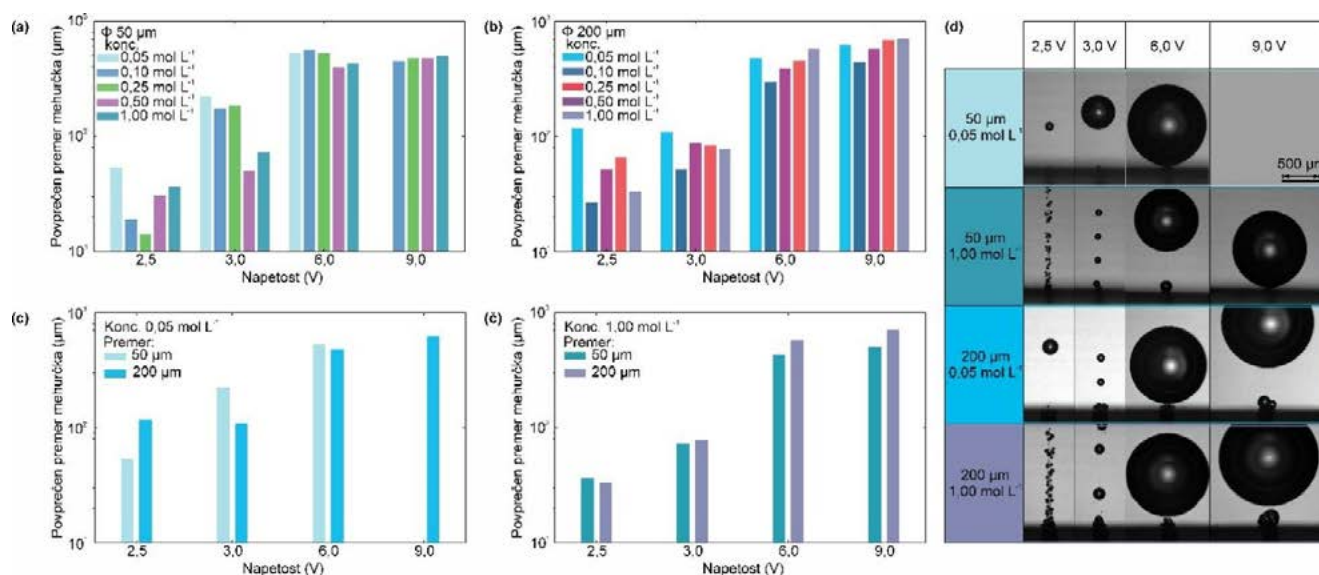
V tej raziskavi je obravnavan vpliv premera mikroelektrode in koncentracije elektrolita na rast in odcepljanje posameznih vodikovih mehurčkov pri elektrolizi z namenom boljšega razumevanja mehanizmov, ki določajo učinkovitost procesa elektrolize. Obravnavani sta dve mikroelektrodi različnih premerov (50 in 200 μm) in pet koncentracij elektrolita (0,05-1,00 mol L^{-1} H_2SO_4). Z uporabo hitrotekoče kamere smo omogočili neposredno opazovanje in analizo dinamike posameznih mehurčkov, kar omogoča pojasnitev povezave med geometrijo elektrode, koncentracijo elektrolita in obnašanjem plinskih mehurčkov ter prispeva k razvoju smernic za načrtovanje učinkovitih elektrod in optimizacijo proizvodnje vodika v elektroliznih sistemih.

Metodologija dela

Eksperimentalna proga. Eksperimenti so bili izvedeni v PEEK celici, opremljeni z opazovalnima stekelcema na stranskih straneh, kar je omogočilo vizualno spremljanje procesa elektrolize. Katoda, platinasta žica, je bila vstavljena v stekleno kapilaro, tako da je bila elektrolitu izpostavljena le njena zgornja površina. Nad katodo sta bili nameščeni referenčna elektroda in anoda (platinasta žica premera 500 μm), ki sta bili skupaj s katodo priključeni na potenciostat. V celico je bil dodatno vstavljen termopar za merjenje temperature elektrolita. Postavitev eksperimentalne proge je prikazana na sliki 1. Proces rasti vodikovih mehurčkov na katodi spremljamo s strani celice, skozi stekleno okence, z uporabo hitrotekoče kamere Photron Mini UX-100. Z druge strani je skozi opazovalno okence izvedena osvetlitev celice z difuznim virom LED svetlobe.



Slika 1: Zasnova merilne proge.



Slika 2: Izmerjeni povprečni premeri mehurčkov pri različnih kombinacijah premera elektrode in koncentracije elektrolita (a–c) in slike mehurčkov (d).

Z modro barvo je shematsko prikazan vodikov mehurček, z rdečo barvo so shematsko prikazano kisikovi mehurčki. Kot elektrolit je uporabljena žveplove kisline (H_2SO_4) koncentracij 0,05, 0,1, 0,25, 0,5 in 1 mol L⁻¹. Pred izvedbo meritev elektrolit razplinimo v ultrasoničnem čistilniku ter v celici pri napetosti 3,0 V izvajamo elektrolizo 900 s. Sledi izvedba meritev pri napetostih med 2,5 V in 9 V, vsaka meritev traja 300 s. S hitro kamero zajamemo rast mehurčkov znotraj zadnjih 50 s meritve, kjer se trend spreminjanja gostote električnega toka asimptotično približuje končni vrednosti.

Rezultati in diskusija

Z zviševanjem napetosti se povečuje premer vodikovih mehurčkov ob odcepitvi s površine elektrode, kar je razvidno z vseh diagramov na sliki 2. Kombinacija premera elektrode in koncentracije elektrolita vpliva na napetost, pri kateri nastopi prehod med posameznimi režimi rasti mehurčkov: (i) majhni nekoalescirani mehurčki, (ii) delna koalescenca, še vedno se odtrga tudi nekaj nekoalesciranih mehurčkov, (iii) režim velikih koalesciranih mehurčkov ter (iv) »pinned single bubble growth« režim, kjer mehurčki dolgo sedijo na površini elektrode in počasi rastejo (slika 2d).

Pri nizki koncentraciji elektrolita ni jasnega trenda vpliva premera elektrode na premer mehurčka ob odcepitvi. Na manjši elektrodi (50 µm) se pri nižjih napetostih tvorijo manjši mehurčki, medtem ko pri višjih napetostih ($\geq 3,0$ V) njihova rast postane izrazitejša in odcepitev počasnejša. Pri najvišji napetosti 9,0 V odcepitve v času meritve ni bilo mogoče opaziti, kar kaže na pojav počasnega naraščanja mehurčkov, ki ostanejo pritrjeni na površini elektrode.

Najbolj izrazit je vpliv koncentracije elektrolita na premer mehurčkov, zlasti na večji elektrodi, kjer je delovanje najbolj stabilno. Pri uporabi 0,1 mol L⁻¹ H_2SO_4 so mehurčki ob odtrganju pri vseh napetostih najmanjši. Od trenda odstopata meritvi pri 200 µm elektrodi in koncentraciji 1,0 mol L⁻¹ pri 2,5 in 3,0 V, kjer so mehurčki nekoliko manjši. Pri 0,05 mol L⁻¹ H_2SO_4 so mehurčki pri vseh napetostih izrazito večji, kot bi

pričakovali glede na trend višjih koncentracij. Koncentracija elektrolita vpliva na število aktivnih nukleacijskih mest in napetost prehoda v režim koalesciranih mehurčkov. Pri nizkih napetostih so razlike med premeri mehurčkov večje zaradi različnih režimov in intenzivnosti koalescence. Pri visoki koncentraciji prevladuje odtrganje posameznih mehurčkov, med tem ko pri 0,05 mol L⁻¹ že pri najnižji napetosti opazimo en sam, koalescirani mehurček-zgodnejši prehod v režim koalesciranih mehurčkov.

Premer mehurčkov je na večji elektrodi ob enakih pogojih večji. Naraščanje premera mehurčkov je najizrazitejše pri napetostih 3–6 V, ko sistem pride v režim rasti koalesciranih mehurčkov. Premer elektrode vpliva na število nukleacijskih mest ter verjetnost medsebojne interakcije mehurčkov. Večja elektroda pri isti napetosti pomeni tudi večji električni tok, zato je pri interpretaciji rezultatov ključno upoštevati gostoto električnega toka, preračunano na enoto površine.

Zaključki

Preučili smo vpliv premera mikroelektrode in koncentracije elektrolita na rast in odcepljanje vodikovih mehurčkov pri elektrolizi vode. Mehurčki so z naraščajočo napetostjo povečevali svoj premer, pri čemer so nizke koncentracije H_2SO_4 (0,05 mol L⁻¹) povzročile zgodnejši prehod v režim koalesciranih mehurčkov, medtem ko je bila najbolj stabilna rast opažena pri 0,1 mol L⁻¹. Večji premer elektrode (200 µm) je povečal število nukleacijskih mest in pogostost koalescence. Ugotovitve prispevajo k optimizaciji zasnove elektrod in povečanju učinkovitosti proizvodnje vodika.

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Parameter Optimization of Laser-Based Directed Energy Deposition (DED-LB) for Cladding In718, Fe64Ni36, and 18Ni300 on Cast Iron

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Surface degradation in cast iron components from wear and corrosion limits their service life in industrial environments. Laser Beam Direct Energy Deposition (DED-LB) cladding offers an effective method to restore and improve surfaces by depositing metallurgically bonded coatings with precise control. This study examines the influence of laser power (1400–1700 W) and powder feed rate (4–10 g/min) on the cladding of In718, Fe64Ni36, and 18Ni300 alloys on GJS400 cast iron using an annular laser beam. Microstructural and hardness analyses showed that moderate feed rates (4–6 g/min) with high laser power (~1700 W) produced uniform, defect-free coatings with low dilution, while excessive feed caused porosity and irregular beads. In718 demonstrated superior metallurgical bonding and surface compatibility, making it the most effective reinforcement material. The findings define optimal parameters for achieving high-quality, wear- and corrosion-resistant In718 coatings via DED-LB.

Introduction

DED-LB based cladding is a prominent additive manufacturing and surface engineering process that enables the deposition of high-quality coatings with good metallurgical bonding and minimal heat input [1]. Due to precise control of the energy input, it surpasses conventional coating methods for producing clads with low dilution and refined microstructures [2,3], enhancing mechanical, wear, and corrosion resistance surface properties [4].

Among various alloys, Inconel 718, Fe64Ni36, and 18Ni300 are widely studied for surface enhancement due to their excellent mechanical and thermal properties [5]. When deposited on cast iron substrates, these alloys can significantly extend component life under severe operating conditions. Unlike plasma transferred arc processes, DED-LB cladding generates a smaller heat-affected zone and enables precise control of dilution between the melted powder and substrate, which is essential for achieving strong metallurgical bonding [6].

The quality of the clad layer depends strongly on process parameters such as laser power and powder feed rate, which directly affect the melt pool geometry, dilution level, and microstructure evolution [6,7]. Therefore, optimization of these parameters is critical to achieving coatings with uniform structure, minimal defects, and high hardness.

This study systematically investigates the influence of laser power P and powder mass flow rate ϕ_m on the cladding behaviour of In718, Fe64Ni36, and 18Ni300 alloys deposited on GJS400 cast iron. The objective is to analyse how these parameters affect clad integrity, including clad geometry, dilution, porosity, and hardness distribution, while identifying the alloy that provides the well-adhered and defect-free coating. The findings contribute to optimizing laser cladding conditions for producing durable, wear- and corrosion-resistant surfaces on cast iron components.

Materials and methods

The chemical composition of each material, GJS400 cast iron as the substrate material and three different metallic powders: In718, Fe64Ni36, and 18Ni300 as cladding materials, is presented in Table 1.

Table 1: Chemical composition (wt.%) of GJS400 cast iron substrate and cladding materials 18Ni300, In718, and Fe64Ni36.

	GJS400	18Ni300	In718	Fe64Ni36
<i>C</i>	3.2	0	0.01	0.1
<i>Si</i>	2.1	0.06	0.51	0.35
<i>Mo</i>	-	4.85	3.03	0.5
<i>Mn</i>	0.6	0.03	0.18	0.06
<i>P</i>	0.03	<0.001	0.002	0.025
<i>S</i>	0.1	0.002	0.002	0.025
<i>Fe</i>	Bal	Bal	Bal	Bal
<i>Ni</i>	-	18.6	54	36
<i>Co</i>	-	9	0.02	-
<i>Cr</i>	-	-	18.6	0.5
<i>Al</i>	-	-	0.39	-
<i>Ti</i>	-	0.65	0.73	-
<i>Nb</i>	-	-	5.33	-

Laser cladding was performed using a DED-LB system with an annular laser beam and axial powder feeding to ensure DED process stability a ring laser beam intensity distribution was used [8]. The laser beam spot diameter of 3 mm, and the deposition feed rate was maintained at 5 mm/s throughout all experiments.

The laser beam power P used were 1400, 1500, 1600, and 1700 W, and the powder mass flow ϕ_m feed rates were set to 4, 6, 8, and 10 g/min. As a DED process optimisation criteria the resulting clad geometry, dilution, and microstructure were considered. After cladding, cross-sectional specimens were prepared using standard metallographic procedures involving

grinding, polishing, and etching. Optical microscopy (OM) was employed to observe macrostructures and identify bead geometry and dilution zones. Microhardness testing was performed across the clad cross-section using a Vickers microhardness tester at a load of 200 g with 0.5 mm spacing between indents. The hardness profile from the substrate through the diffusion zone to the clad surface was analysed to evaluate the variation in mechanical properties across the interface.

Results and discussion

The combined influence of mass flow rate and laser power significantly affected the morphology and quality of the clad tracks. At a lower powder mass flow rate ϕ_m (4–6 g/min), the tracks exhibited smooth, uniform bead geometry with good dilution and minimal porosity, particularly at the highest laser power of 1700 W. Increasing the powder feed rate beyond 8 g/min led to clads with a noticeable reduction in dilution depth, as shown in Figure 1.

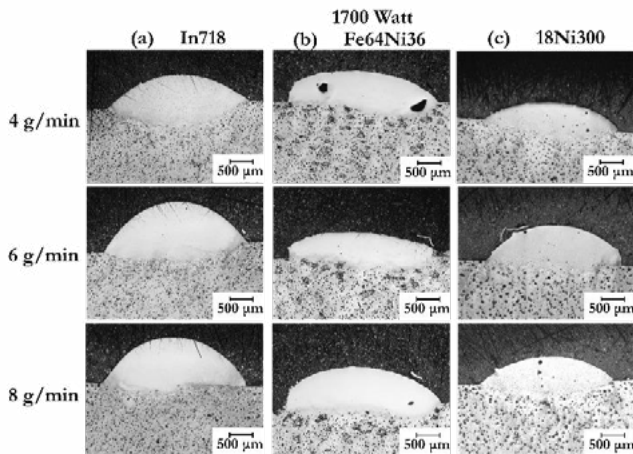


Figure 1: Cross-sectional macrographs of (a) In718, (b) Fe64Ni36, and (c) 18Ni300 clads deposited at 1700 W under powder feed rates of 4, 6, and 8 g/min. The images illustrate the influence of feed rate on melt pool geometry, dilution, and interfacial bonding characteristics.

Cross-sectional macrographs shown in Fig. 1 revealed a distinct clad geometry and a diffusion zone. The thickness and morphology of the diffusion and related dilution zones varied with both laser power and powder feed rate. Fe64Ni36 and 18Ni300 clads showed slightly rougher surfaces and visible irregularities in bead and dilution uniformity with the presence of pores, suggesting an unstable deposition process. In718 produced smooth, uniform surfaces with well-bonded and symmetrical dilution interfaces without the presence of pores, indicating a stable deposition process and effective material consolidation.

Considering the hardness properties shown in Fig.2, 18Ni300 exhibited a sharper but narrower hardness peak (~ 780 HV), within the diffusion zone, likely due to localized martensitic transformation during rapid cooling. In contrast, Fe64Ni36 presented moderate hardness (~ 600 HV) with fluctuations, reflecting uneven dilution and less stable solidification

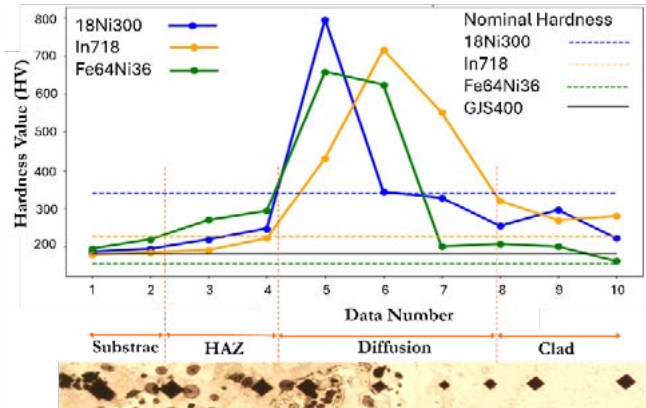


Figure 2: Hardness (HV) distribution across the substrate–clad interface at 1700 W laser power and 6 g/min powder feed rate, showing the corresponding clad regions.

behaviour. For the In718 clad, the hardness reaches approximately 700 HV within the diffusion zone and gradually decreases toward the top surface. However, unlike the other two materials, In718 maintains its hardness above the nominal hardness (shown by dashed lines) of the alloy itself throughout the clad region. This indicates enhanced mechanical performance and suggests a strong interfacial bond formed during the deposition process. The corresponding macrographs in Fig. 1 further support this observation, revealing good clad integrity and the absence of visible porosity, cracks, or delamination. These findings demonstrate that In718 provides the most reliable interfacial bonding and structural soundness among the materials investigated.

Conclusions

- Laser cladding of In718, Fe64Ni36, and 18Ni300 on GJS400 cast iron is most effective at moderate powder feed rates (4–6 g/min) and high laser power (~ 1700 W).
- Fe64Ni36 and 18Ni300 show poor clad geometry with not well-defined diffusion zones and some porosity.
- In718 forms smooth, uniform clad with well-defined diffusion zones, maintains hardness above its nominal value throughout the clad, and exhibits defect-free interfaces.

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Klasifikacija zvočnih signalov v proizvodnji z uporabo metode nenadzorovanega strojnega učenja k-means

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Raziskava obravnava uporabo nenadzorovanega strojnega učenja za klasifikacijo zvočnih signalov v industrijskem okolju. Cilj je bil razviti pristop, ki omogoča spremljanje stanja strojev in odkrivanje napak v realnem času. V sodelovanju s podjetjem TPV Automotive d.o.o. so bili zbrani podatki iz proizvodnega obrata, ki so bili analizirani z algoritmom k-means. Za obdelavo velikih količin podatkov so bile uporabljene metode za zmanjšanje dimenzionalnosti in optimizacijo razvrščanja, medtem ko so značilnosti zvoka zajemale frekvenčne in časovne lastnosti. Rezultati potrjujejo, da ima tak pristop velik potencial za izboljšanje nadzora, optimizacijo procesov in integracijo v proizvodne informacijske sisteme. Raziskava odpira možnosti za napovedno vzdrževanje in večjo učinkovitost proizvodnje.

Uvod

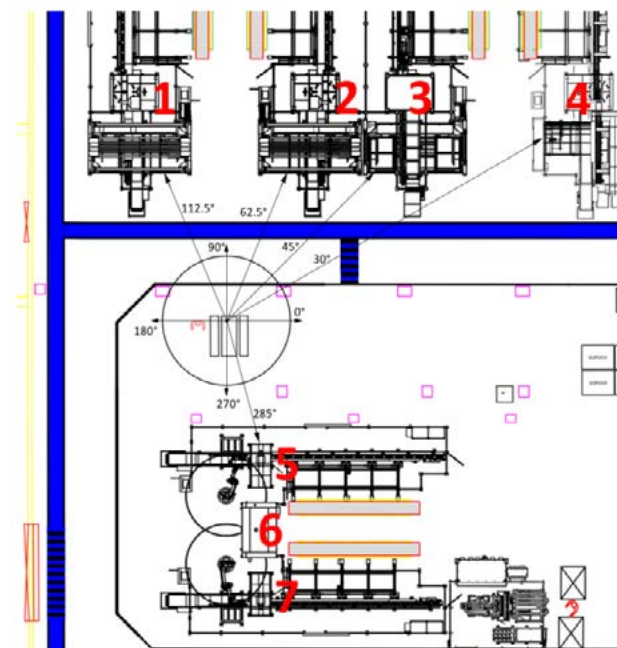
V sodobni proizvodnji je spremljanje stanja strojev ter pravočasno odkrivanje napak ključno za zagotavljanje visoke učinkovitosti in zmanjšanje stroškov. Tradicionalni pristopi, kot so vizualni pregledi ali osnovni senzorji, pogosto ne zaznajo subtilnih sprememb in ne omogočajo vpogleda v realnem času. V okviru raziskave, izvedene v sodelovanju s podjetjem TPV Automotive d.o.o., smo preučili možnost uporabe zvočnih signalov kot dodatnega vira informacij ter njihovo klasifikacijo z algoritmom nenadzorovanega strojnega učenja k-means. Cilj je bil razviti metodologijo, ki omogoča zanesljivo razvrščanje zvočnih podatkov, kar prispeva k identifikaciji delovnega stanja strojev in zgodnjemu zaznavanju odstopanj v proizvodnem procesu.

Metodologija

Raziskava se je začela z natančno izbiro snemalne lokacije v industrijskem obratu, kjer je bilo ključno zajeti reprezentativne zvočne vzorce. Izbrano je bilo območje z rezalnimi stroji za aluminijaste profile, saj ti procesi ustvarjajo značilne akustične podpise. Mikrofone smo namestili med sedem obdelovalnih strojev, kot je prikazano na sliki 1. Snemanje je potekalo z nizom štirih vsesernih mikrofonov, mehansko povezanih za natančno zaznavanje usmerjenosti zvoka.

Analiza zvočnih podatkov in pridobivanje značilk. Za analizo zvočnih podatkov je bila uporabljena kombinacija časovne in frekvenčne domene. Zvočni signal smo razdelili na krajše časovne segmente, ki so se nato združevali v daljše časovne konstante τ_k , kot prikazuje slika 2. V vsakem frekvenčnem pasu so bile izračunane vrednosti L_p -norme, njihovi odvodi in dolžina spektra. Te značilnosti, pridobljene

na nižji časovni konstanti, smo združili v statistične lastnosti na višji časovni konstanti, kot so srednja vrednost, razpon in koeficient variacije. Poleg tega smo vključili dodatne značilnosti, kot so RMS, ZCR, spektralni centroid in druge spektralne parametre. Izračunana je bila tudi usmerjenost dominantnega zvoka, ki je predstavljala eno ključnih značilk za učenje algoritma k-means.



Slika 1: Izbrana lokacija snemanja ter postavitve opazovanih strojev.

Dolžina nove časovne konstante					μ	max-min	...
Frekvenčni pasovi	$L_{p1,1}$	$L_{p2,1}$	... $L_{pi,1}$	→	z_1	z_{N+1}	...
	$L_{p1,2}$	$L_{p2,2}$	... $L_{pi,2}$	→	z_2	z_{N+2}	...
	$\vdots$	$\vdots$	$\ddots$ $\vdots$	→	$\vdots$	$\vdots$	$\vdots$
	$L_{p1,N}$	$L_{p2,N}$	... $L_{pi,N}$	→	z_N	z_{N+N}	...

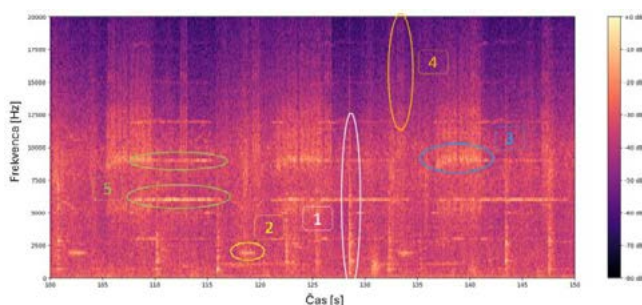
Slika 2: Združevanje i časovnih korakov v časovno konstanto τ_k za vsak frekvenčni pas.

Priprava podatkov in nastavitve parametrov za k-means klasifikacijo. Pred klasifikacijo so bili podatki skalirani, da se izenači vpliv različnih značilnosti. Nato je bila izvedena PCA analiza za zmanjšanje dimenzionalnosti, pri čemer je bilo izbranih 35 komponent, ki so ohranile 91,9 % variance. Za določitev optimalnega števila skupin k v algoritmu k-means sta

bili uporabljeni metoda komolca in metoda silhuete, ki sta nakazali, da je $k = 4$ ali $k = 6$ najbolj smiselna izbira. Pri večjem številu skupin k rezultati postanejo preveč fragmentirani, kar otežuje njihovo interpretacijo in povezovanje z dejanskimi dogodki v proizvodnji.

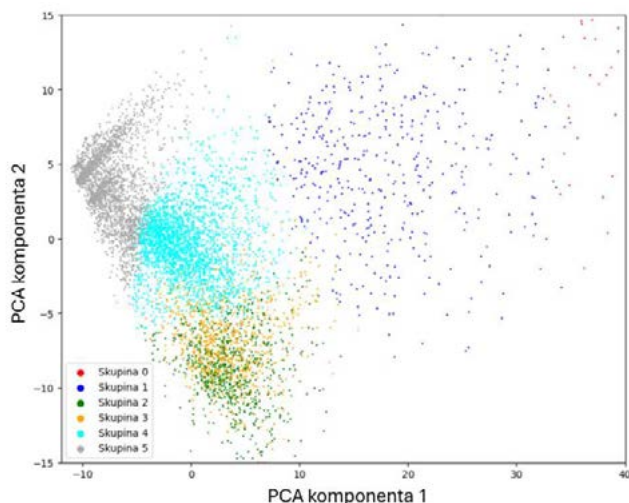
Rezultati in diskusija

Rezultati klasifikacije z algoritmom k-means so bili predstavljeni z več vizualnimi pristopi, ki omogočajo razumevanje strukture podatkov ter njihove časovne in prostorske dinamike. Na sliki 3 je prikazan spektrogram z označenimi petimi ponavljajočimi se vzorci industrijskega zvoka, ki so bili ročno identificirani pred uporabo algoritmov strojnega učenja. Vsak vzorec je povezan z značilnim akustičnim dogodkom, kar olajša interpretacijo rezultatov klasifikacije.



Slika 3: Ponavljajoči se akustični vzorci na spektrogramu.

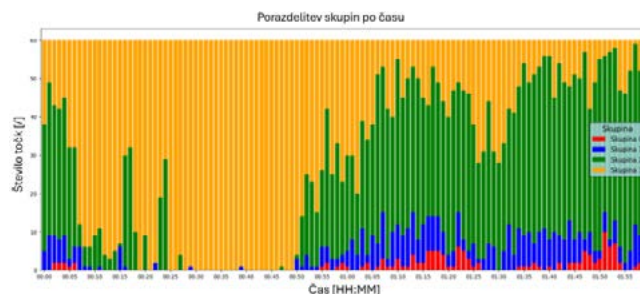
Eden ključnih prikazov rezultatov je vizualizacija v prostoru prvih dveh PCA komponent, kjer so podatkovne točke razporejene v skupine pri izbranem številu $k = 6$. Iz prikaza na Sliki 4 je razvidno, da je algoritem k-means oblikoval smiselne gruče, ki odražajo podobnosti med zvočnimi vzorci. Čeprav se nekatere skupine v projekciji delno prekrivajo, kar nakazuje sorodnost njihovih značilnosti, so v višje-dimenzionalnem prostoru jasno ločene.



Slika 4: PCA bi-plot z razporejenimi točkami v skupine pri $k = 6$.

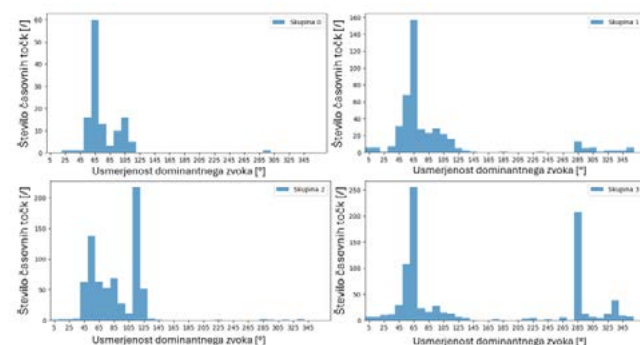
Slika 5 prikazuje časovno porazdelitev točk po skupinah pri $k = 4$, kar omogoča vpogled v dinamiko proizvodnje skozi obdobje snemanja. Iz prikaza je razvidno, kdaj prevladujejo

skupine, povezane z aktivnim obratovanjem določenega stroja oziroma sklopa strojev (skupine 0, 1 in 2), ter kdaj se pojavljajo skupine, ki označujejo tišino ali zmanjšano aktivnost, na primer med menjavo izmene (skupina 3).



Slika 5: Porazdelitev točk po skupinah po času.

Za boljšo interpretacijo virov hrupa so bili izdelani histogrami usmerjenosti dominantnega zvoka za posamezne skupine (glej sliko 6), ki prikazujejo povezavo med razvrščenimi skupinami in prostorsko postavitevjo strojev. Iz prikaza je razvidno, da so določene skupine močno korelirane z določenimi smermi glede na lokacijo snemanja, kar omogoča njihovo povezavo s specifičnimi delovnimi stroji.



Slika 6: Histogrami usmerjenosti dominantnega zvoka za skupine od 0 do 3 pri $k = 6$.

Zaključek

Rezultati raziskave potrjujejo, da ima klasifikacija zvočnih signalov z uporabo algoritma k-means velik potencial za vključitev v realne proizvodne procese. Pridobljeni modeli omogočajo sprotno spremljanje stanja strojev, prepoznavanje obdobja tišine, menjave izmen ter nenadnih akustičnih dogodkov, kot so udarci ali nepravilnosti v delovanju. Integracija teh podatkov v obstoječe informacijske sisteme (MES, MRP, ERP) odpira možnosti za napovedno vzdrževanje, optimizacijo materialnih tokov in učinkovitejšo načrtovanje proizvodnje. Tak pristop predstavlja nov način spremljanja proizvodnih procesov, ki lahko bistveno izboljša nadzor v realnem času ter zmanjša izpade z uvajanjem napovednih strategij vzdrževanja.

Optimizacija procesnih parametrov servo stiskalnice pri postopku preoblikovanja materiala

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V sklopu raziskave smo obravnavali optimizacijo procesnih parametrov servo stiskalnice Fagor TSED4-3000-7000-2500 pri postopku globokega vleka. Z uporabo programskega paketa Syncro je bil razvit in preizkušen optimiran hitrostni profil paha za štiri različna orodja. Z optimizacijo je bila produktivnost v povprečju povečana za 38 % ob nespremenjeni kakovosti izdelkov. Rezultati potrjujejo, da ustrezno oblikovan hitrostni profil in sinhronizacija transferja pomembno vplivata na učinkovitost in energijsko porabo stiskalnice.

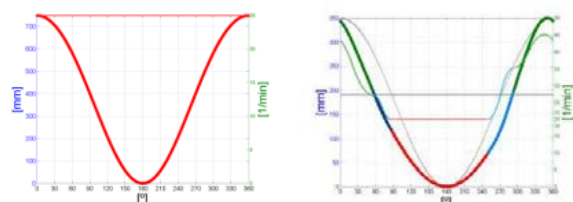
Uvod

V podjetju TPV Automotive d.o.o. se za model vozila U11 premijskega proizvajalca vozil serijsko proizvaja nosilec kolesa zadnje obese. Izdelek je sestavljen iz več preoblikovancev, ki se izdelujejo na servo stiskalnicah. Zaradi nenehnega povečevanja obsega industrijske proizvodnje se je izvedla raziskava za povečanje produktivnosti procesov preoblikovanja.

Cilj raziskave je bil določiti optimalne procesne parametre, s katerimi smo skrajšali cikel delovanja ob ohranjeni kakovosti izdelkov. Z uporabo programa Syncro je bil izveden virtualni model gibanja paha, sinhroniziran z delovanjem transferja. Na osnovi simulacij in preizkusov je bila dosežena pomembna optimizacija hitrosti in časa cikla.

Metode dela

Mehanske stiskalnice imajo stalno hitrost gibanja paha, ki jo določa vrtenje vztrajnika. Maksimalna preoblikovalna sila se doseže v bližini spodnje mrtve točke, zato je delovni cikel nefleksibilen. Servo stiskalnica uporablja električni pogon s servo motorji, kar omogoča poljubno nastavljanje hitrosti, položaja in hoda paha. Odpravlja potrebo po vztrajniku in sklopki, deluje le ob premiku in zato porablja manj energije. Primerjavo med mehansko in servo stiskalnico prikazuje slika 1.

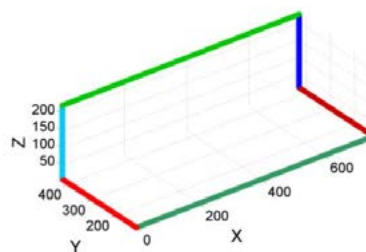


Slika 1: Mehanska krivulja (levo); Servo štiri-stopenjska krivulja (desno)

Hitrost preoblikovanja pomembno vpliva na kakovost izdelka. Pri višjih hitrostih se poveča možnost trganja materiala, pri nižjih pa se izboljša tečenje, vendar zmanjša produktivnost. Servo tehnologija omogoča kombinacijo – počasno gibanje v

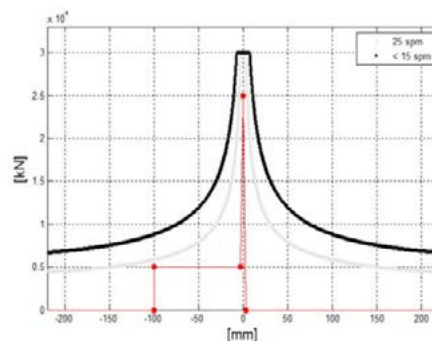
fazi preoblikovanja in hitro gibanje v približevanju in povratku, kar zagotavlja visoko kakovost in krajše čase cikla. Cikel gibanja paha je razdeljen v štiri dele: hitro približevanje, upočasnitev na hitrost preoblikovanja, možnost zadrževanja v spodnji mrtvi točki in hitro vračanje v izhodišče. Zaradi možnosti programiranja vsake faze posebej se lahko profil gibanja prilagodi posameznemu orodju in vrsti postopka. Transferni sistem s tremi osmi, prikazan na sliki 2 (X, Y, Z) je sinhroniziran s pahom – zapiranje, dvig, premik naprej, spust in odpiranje.

Syncro je programsko okolje proizvajalca Fagor za simulacijo in optimizacijo gibanja servo stiskalnic. Omogoča izgradnjo mehanske ali štiristopenjske servo krivulje ter vključitev realnih omejitev stroja – maksimalnega navora, hitrosti in sile. V program se vnesejo parametri orodja in transferja, nato pa se simulira gibanje ter izračuna čas cikla in energijska poraba.



Slika 2: Tri-osni ciklogram transferja.

Po določitvi krivulje gibanja samega paha in sinhronizacijo s transferjem je potrebno upoštevati še mehanske omejitve stiskalnice. Na sliki 3 graf profila sile prikazuje odvisnost razpoložljive sile od višine paha. Negativna os X predstavlja gibanje paha navzgor, pozitivna pa navzdol. S črno črto je prikazana maksimalna razpoložljiva sila. To pomeni, da lahko hipotetično stiskalnica zagotovi v obe smeri enako silo. Koordinatno izhodišče grafa prikazuje spodnjo mrtvo točko stiskalnice, kjer ima na voljo največjo nazivno silo. Z rdečim je pa označena sila potrebna za izdelavo kosa. S tem preverimo ali ima motor dovolj navora.

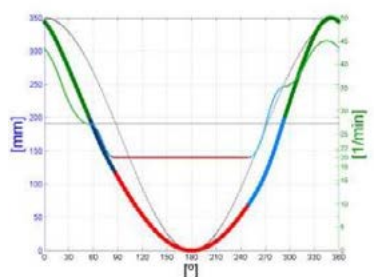


Slika 3: Graf profila sile.

Rezultati in diskusija

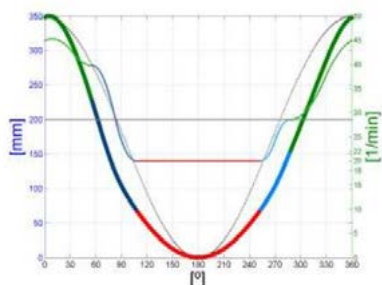
Optimizacija je bila izvedena na štirih orodjih: Rebro, Vezni element, Zunanja lupina in Notranja lupina. Vsako orodje je imelo začetni mehanski profil s konstantno hitrostjo. Postopno so bili določeni trije servo profili, pri katerih so se spreminjale faze pospeševanja, upočasnitve in zadrževanja v spodnji mrtvi točki.

Rebro: Za izdelavo rebra se uporablja progresivno orodje, katerega mehanski profil je imel pred optimizacijo konstantno hitrost 350 mm/s. Optimizirana servo krivulja ima štiri faze gibanja – hitro spuščanje, počasno preoblikovanje in hitro vračanje. Tanjša krivulja prikazuje hitrost paha med procesom. Z uporabo servo krivulje smo povečali produktivnost procesa za 36 %. Slika 4 prikazuje servo krivulja orodja za Rebro.



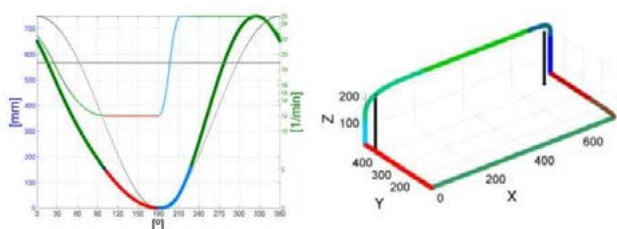
Slika 4: Servo krivulja – Rebro.

Vezni element: Za izdelavo veznega elementa se prav tako uporablja progresivno orodje, katerega začetni profil je bil mehanski s hitrostjo 20 udarcev na minuto. S pomočjo servo krivulje smo lahko to hitrost povečali za 8 udarcev. Pri progresivnih orodjih, kjer ni transferja, je pomembno določiti točko začetka podajanja in konca podajanja. Na sliki 5 je podajanje obarvano z zeleno krivuljo.



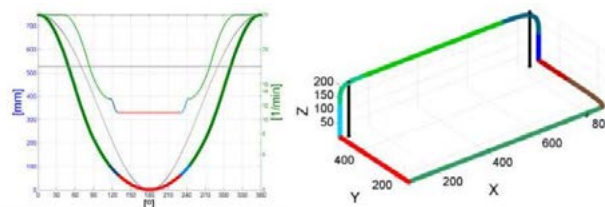
Slika 5: Servo krivulja - Vezni element.

Zunanja lupina: Orodje za zunanjo lupino je transferno. Pri optimizaciji je bil poudarek na sinhronizaciji transferja z velikimi pomiki. Servo profil (slika 6) ima daljšo fazo počasnega gibanja zaradi večjih sil preoblikovanja. Transfer krivulja prikazuje postopno zapiranje in odpiranje letev, kar je zmanjšalo takt s 6,0 s na 4,3 s.



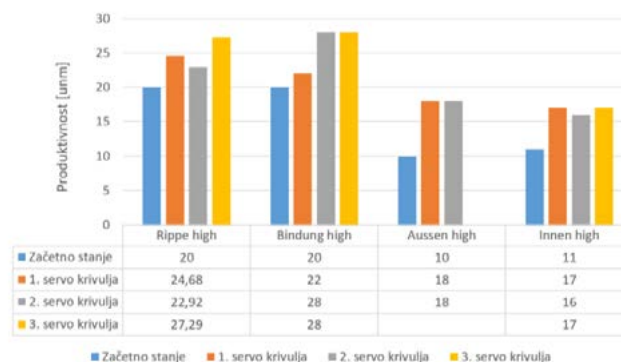
Slika 6: Servo krivulja (levo); Ciklogram transferja (desno).

Notranja lupina: Optimizacija (slika 7) je vključevala prilagoditev višine dviga transferja za boljši izogib orodju in kratki gib med preoblikovanjem. Rezultat je bil krajši cikel iz 5,5 s na 4 s.



Slika 7: Servo krivulja (levo); Ciklogram transferja (desno).

Na sliki 8 je prikazana primerjava produktivnosti pred in po optimizaciji. V vseh primerih je opazno povečanje števila udarcev na minuto (Rebro 20 → 28, Vezni element 20 → 27, Zunanja lupina 10 → 14, Notranja lupina 11 → 15).



Slika 8: Rezultati optimizacij.

Optimizacija hitrosti in sinhronizacije transferja je omogočila krajši cikel, boljši izkoristek servo tehnologije in nižjo energijsko porabo. Servo stiskalnice omogočajo natančno prilagoditev gibanja paha posameznemu orodju, program Syncro pa učinkovito podpira virtualno optimizacijo procesnih parametrov. Povprečno povečanje produktivnosti za 38 % potrjuje velik potencial servo tehnologije v avtomobilski industriji.

Zaključek

Zaključek raziskave potrjuje, da servo stiskalnice predstavljajo pomemben tehnološki napredek v procesih preoblikovanja pločevine. Z možnostjo popolnega nadzora gibanja paha in sinhronizacije transferja omogočajo bistveno višjo prilagodljivost procesa, krajše cikle in manjšo porabo energije. Optimizacija, izvedena s programom Syncro, je pokazala, da je mogoče brez mehanskih sprememb stroja doseči do 40-odstotno izboljšanje produktivnosti ob enaki kakovosti izdelkov. Analiza rezultatov je potrdila, da so s prilagajanjem hitrosti in zadrževanja paha med preoblikovanjem zmanjšane sile udarca in obremenitve orodij, kar podaljšuje njihovo življenjsko dobo. Servo tehnologija tako dokazuje svoj potencial za širšo uporabo v avtomobilski in drugih industrijah, kjer sta učinkovitost in kakovost ključnega pomena.

Viri

- [1] Pirc, M. (2023). Optimizacija procesnih parametrov servo stiskalnice pri postopku preoblikovanja materiala (Magistrsko delo). Fakulteta za strojništvo, Univerza v Mariboru.

Development of Ti-6Al-4V-4Cu alloy by DED-LB for biomedical applications

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A Ti-6Al-4V-4Cu alloy was developed using the DED-LB additive manufacturing process to enhance antibacterial properties for biomedical applications. The study investigates build strategies and heat treatment effects on microstructure, Cu-rich phase formation, and mechanical performance. Preliminary results show the presence of Ti₂Cu intermetallics and a mixed ductile-brittle fracture mode. The alloy demonstrates promising mechanical integrity and antibacterial potential, with further characterization and biocompatibility testing underway.

Introduction

Titanium Grade 23 (Ti-6Al-4V) is a well-known alloy, which has superior mechanical, anticorrosion and biocompatibility properties making it one of the most popular materials for biomedical implants [1]. However, the implant-related infections, especially in dental applications, remain a major clinical problem [1], calling for the development of implant materials with antibacterial properties.

Copper (Cu) has been widely explored for its antibacterial property, as Cu ions can disrupt bacterial cell membranes and inhibit biofilm formation. When alloyed with Ti-6Al-4V, Cu could impart antibacterial functionality while maintaining the base alloy's favourable properties. A key factor in this behaviour is the formation of the Cu-rich intermetallic phases such as Ti₂Cu, which are primarily responsible for the antibacterial effect [1].

This contribution presents the first results of the ongoing research [2] focused on the development and characterization of a novel Ti-6Al-4V-4Cu alloy fabricated using the DED-LB AM process. Namely, the DED-LB of metal powder process can not only be used for 3D printing, cladding and repairing metal parts, but its in-process material mixing ability makes it also suitable for production of functionally graded materials (FGM) and fabrication of novel alloys. The present study includes different DED-LB build strategies and heat treatment to investigate their influence on the microstructure, Cu-rich phase content, and mechanical properties.

Materials and methods

To fabricate Ti-6Al-4V-4Cu alloy, plasma-atomized Tekmat Ti6Al4V Grade 23 and inert gas-atomized Oerlikon Metco 55 Cu powders were used with a nominal particle diameter range of 40 µm to 145 µm and 38 µm to 120 µm, respectively. As substrate material, wrought Ti-6Al-4V plates of dimension L × W × D = 90 mm × 15 mm × 3 mm were used.

An experimental DED-LB system [3] with a patented annular laser beam (ALB) deposition head [4] was used. The schematic of the setup is shown in Fig. 1a, which consists of a two-channel disk feeder that delivers the powders in the desired powder mixture to the axial nozzle. The ALB forms a melt pool on the surface of the substrate where the incoming powder melts and, by feeding the substrate, a deposited layer is fabricated. The entire process is carried out in an argon-atmosphere build chamber to prevent oxidation. Using a layer-by-layer deposition (Fig. 1b) Ti-6Al-4V and Ti-6Al-4V-4Cu alloys were fabricated in the form of a thin wall of dimensions 70 mm × 20 mm × 3 mm (Fig. 1c).

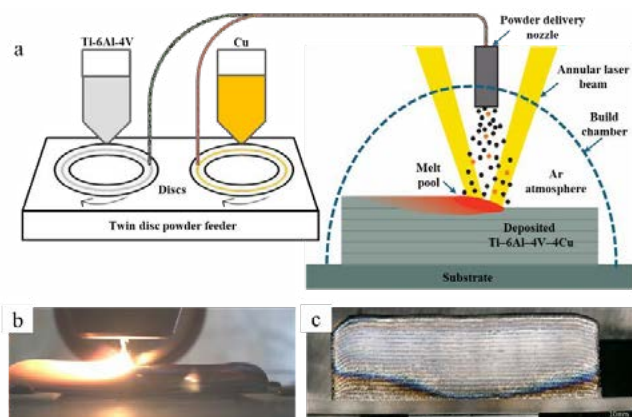


Figure 1: (a) Schematic of the ALB DED-LB system. (b) DED-LB deposition process. (c) Fabricated Ti-6Al-4V-4Cu thin wall

The factors of the investigated DED-LB build strategies were the deposition path, ALB power and heat treatment. Two deposition paths were used: unidirectional (Fig. 2a), where each layer is deposited in the same direction, and bidirectional deposition (Fig. 2b), where the deposition direction alternates between successive layers. To prevent overheating and melt pool instability due to cumulative heat buildup, using the ring laser beam intensity distribution [5], the laser power was set to 1250 W for the first layer and reduced by 10 W for each consecutive layer. The heat treatment was performed by the following procedure in an Ar atmosphere: solution annealing at 900°C for 1 hour, quenching in water, aging at 600°C for 4 hours, and slow cooling in the furnace.

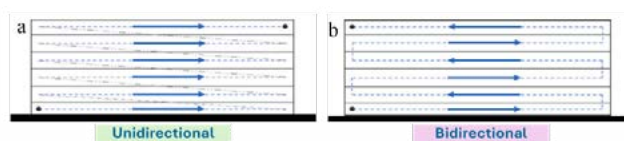


Figure 2: (a) Uni- and (b) bi-directional deposition path.

The deposited walls were machined into shapes suitable for different analyses, including metallographic and microstructural analysis by SEM and XRD, and different types of mechanical testing.

Results and discussion

SEM imaging of the Ti-6Al-4V-4Cu sample (Fig. 3a) showed the distribution of the Ti- α (dark grey region), Ti- β (light grey region), and Cu-rich intermetallic Ti₂Cu phase (bright features distributed along the α/β phase interface) [6]. Using image segmentation, as illustrated in Fig. 3b, an approximate relative content of the Cu-rich phase was estimated, yielding values of about 2% or less. In future, a systematic XRD characterization will be conducted to quantify the Ti₂Cu phase content, and additionally, the influence of different deposition paths on the formation and distribution of Ti₂Cu phases will also be investigated to identify the optimal build strategy, resulting in the highest Ti₂Cu phase fraction.

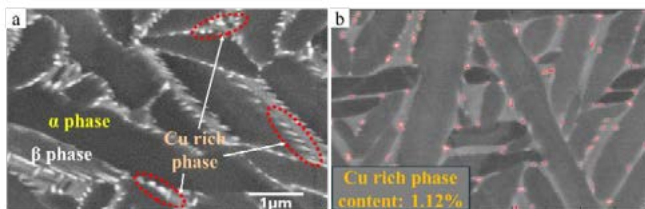


Figure 3: An example of a) SEM image of a typical Ti-6Al-4V-4Cu microstructure, b) Cu-rich phase content analysis by image segmentation.

From the mechanical testing, the preliminary tensile strength results comparing the properties of DED-LB fabricated Ti-6Al-4V and Ti-6Al-4V-4Cu are shown in Fig. 4. Here, the bars represent the mean values and whiskers the two measured values. As can be seen, the tensile strength values are within 9% of the wrought Ti-6Al-4V reference value, denoted by the green dashed line. The statistically significant influences of material composition and heat treatment are presented by solid arrows. The blue arrows show the influence of material composition, where the tensile strength increases from Ti-6Al-4V to Ti-6Al-4V-4Cu in both as-printed and heat-treated cases. The orange arrow shows the influence of heat treatment, which results in a reduction in tensile strength across all material compositions. In contrast, the influence of the

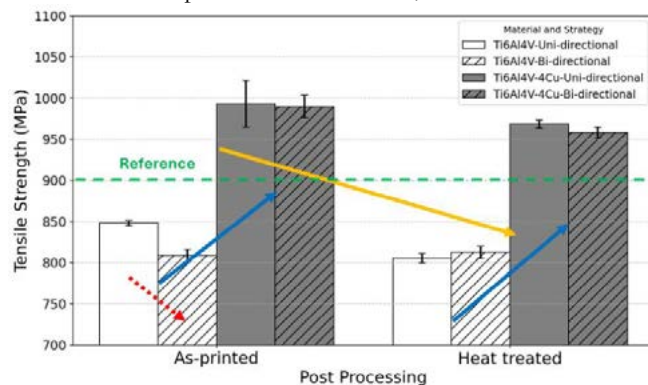


Figure 4: Tensile strength values dependence on composition, heat treatment, and deposition path.

deposition path was insignificant, observed only in the case of as-printed Ti-6Al-4V, as highlighted by the red dashed arrow.

SEM analysis of the fractured surfaces indicated that, while a purely ductile fracture (dimpled rupture surface) is typically expected for Ti-6Al-4V alloys [6], the addition of Cu led to a mixed ductile-brittle fracture mode characterized by the regions of localized plastic fracture (Fig. 5). In future work, impact toughness, bending strength and hardness will also be examined to gain a comprehensive understanding of the alloy's mechanical behaviour.

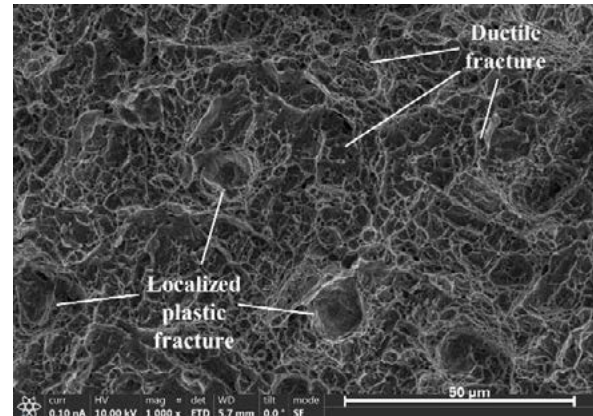


Figure 5: SEM image of a fractured surface.

Conclusions

The ongoing research focuses on the development and characterization of a novel Ti-6Al-4V-4Cu alloy fabricated using the DED-LB. Different build strategies were investigated to understand their influence on the microstructure, Cu-rich phase formation, and mechanical properties. Preliminary mechanical testing and SEM analysis revealed a mixed ductile and localized plastic fracture mode in Cu-containing samples, while image analysis of SEM micrographs confirmed the presence of Ti₂Cu precipitates. Future XRD studies will provide quantitative validation of these findings. In addition, in vivo biocompatibility tests in mice have been conducted demonstrating the alloy's biological response [7]. Overall, the results highlight the potential of the DED-LB Ti-6Al-4V-4Cu alloy for biomedical implant applications, combining structural integrity with antibacterial functionality.

ACKNOWLEDGEMENTS. The authors acknowledge the financial support from the Slovenian Research and Innovation Agency (BIOAD project funding No. J7-4639 and research core funding No. P2-0241). The authors acknowledge the technical assistance of the Laboratory for Cutting at the Faculty of Mechanical Engineering, University of Ljubljana, for machining of test samples from the DED-LB-fabricated Ti-6Al-4V-4Cu alloy walls.

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A Practical Approach to Modelling Evaporation in 3D CFD Simulations of Domestic Ovens for EN60350 Testing

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An experimentally fitted 0D evaporation model from previous literature was implemented into a 3D CFD-based digital twin of a domestic oven to enhance the physical fidelity of heat transfer predictions. Incorporating the evaporation model markedly improved agreement between simulations and experiments, particularly during moisture-driven transients. The study demonstrates that evaporation is a key mechanism influencing thermal load heating behaviour and provides a simple and practical approach for integrating accurate evaporation modelling into 3D CFD simulations of domestic ovens for numerically performing the EN60350 tests, thereby reducing reliance on experimental measurements.

Introduction

The accurate numerical prediction of heat and mass transfer within domestic ovens is essential for assessing cooking performance and optimizing energy efficiency. Evaporation plays a crucial role in the transient thermal response of porous materials and in the overall thermal balance inside the oven cavity. Neglecting phase change processes leads to systematic discrepancies between simulated and experimental temperature profiles, particularly during the moisture-driven heating phase. As a result, oven simulations tend to overpredict surface and core temperatures, compromising their predictive accuracy and limiting their applicability for standardized performance evaluation.

To address this, the present study introduces a practical and physically consistent approach for modelling evaporation within 3D CFD simulations of domestic ovens. The approach integrates an experimentally fitted evaporation model into a full-scale CFD representation of the oven cavity, capturing the latent heat effects. This work aims to demonstrate that a simple, yet experimentally grounded evaporation model can substantially improve the fidelity of digital twins used for EN60350 testing, reducing dependence on costly physical experiments while maintaining numerical efficiency.

Materials and methods

Experimental method. The experimental procedure followed the EN60350 standard for evaluating the energy consumption and performance of domestic ovens. Tests were conducted using a forced convection heating mode at set-point temperatures of 200 °C. A clay brick (230 × 114 × 64 mm, 920 ± 75 g) was used as the thermal load. Prior to each test, the brick was soaked in cold water for at least 8 hours, reaching a mass of 1050 ± 50 g and a core temperature of 5 ± 2 °C. A

Pt500 thermocouple was placed at the centre of the brick to measure its internal temperature.

The brick was then placed at the centre of the oven cavity and heated until its core temperature increased by 55 K. After heating, the mass loss of the brick was determined to quantify water evaporation. These measurements provided the experimental reference data for validation of the CFD-based digital twin, allowing direct comparison of temperature evolution and evaporation rate.

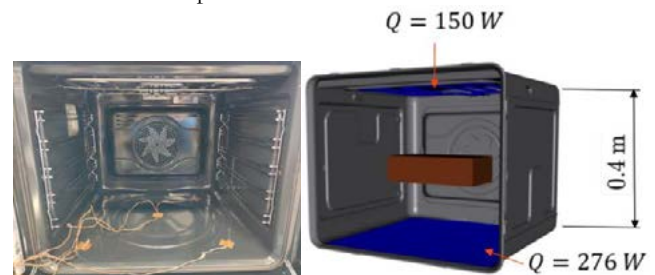


Figure 1: Experimental oven setup (left), the numerical twin of the oven cavity, used in the simulation (right).

Numerical model. The numerical simulations were performed using open-source code OpenFOAM v11 [2], solving the compressible, turbulent flow inside the oven cavity coupled with heat transfer in both fluid and solid domains. The air flow was modelled using the compressible Navier–Stokes equations with the RANS $k-\omega$ turbulence model, coupled to the enthalpy equation (1) for temperature prediction,

$$\frac{\partial(\rho h)}{\partial t} + \nabla \cdot (\rho u h) = \nabla \cdot \left(k \nabla \frac{h}{c_p} \right) + \nabla \cdot (\underline{\tau} \cdot \underline{u}). \quad (1)$$

In equation (1), h is the enthalpy, k the fluid thermal conductivity and c_p the fluid's specific heat capacity. Heat conduction within the clay brick was resolved using the transient heat diffusion equation,

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T, \quad (2)$$

where T is the brick temperature and α is the solid thermal diffusivity, defined as $\alpha = \frac{k_{solid}}{\rho_{solid} c_{p, solid}}$. The fluid–solid interface coupling ensured continuity of heat flux and temperature. To account for moisture evaporation, a boundary condition based on the experimentally-fitted model of Lucchi et al. [1] was implemented, along with the radiation, linking the surface temperature and experimentally measured water loss to the latent heat flux, $\dot{q}_{evap} = \dot{m} R_{lat}$, in form

$$\dot{m} = D A_{brick} (p_{sat, brick} - p_{v, air}), \quad (3)$$

where p_{sat} is the polynomial-fitted temperature-dependent water saturation pressure on the brick's surface and $p_{v, air}$ is the vapour pressure of water in the air. Similarly to [1], we assume

that the oven's steam evacuation system ensures a constant relative humidity of 50%. Parameter D is defined as

$$D = \frac{m_{tot}^{exp}}{A_{brick} \int_t^{t_{end}} (p_{sat,brick}^{exp}(t) - p_{v,air}) dt}, \quad (4)$$

Where superscript *exp* denotes the experimentally measured values, A_{brick} the brick surface. m_{tot}^{exp} is the experimentally measured amount of evaporated water. The p_{sat}^{exp} value was measured indirectly, by measuring the surface temperature of the brick. Parameter D (4) basically ensures the water vapour mass conservation during simulation.

The forced convection produced by the oven fan was modelled through a pressure jump condition representing the fan's momentum source, avoiding the computational cost of simulating the rotating region directly. The oven's thermostatic regulation and thermocouple (tc) response dynamics,

$$\frac{\partial T_{tc}}{\partial t} = \frac{1}{\tau_{tc}} (T_{tc}(t) - T_{cell}(t)) \quad (5)$$

were also incorporated to reproduce the control behaviour and thermal inertia of the physical system. In equation (5), T_{cell} is the actual temperature in the finite-volume cell, where the thermocouple is located, T_c the delayed thermocouple temperature and τ_{tc} the thermocouple response time.

A mesh and time-step sensitivity study ensured numerical stability and convergence. The reported timestep uncertainty by Celik's method [3] amounts to 0.3% for the fine time discretization and 2.7% for coarse time discretization, with a timestep order of convergence of 1.48, indicating a first- to second-order accuracy in time.

Results and discussion

Figure 2 shows the simulated instantaneous flow field. The baffle surrounding the fan promotes a uniform distribution of airflow across the heating surfaces, thereby ensuring consistent forced convection within the oven cavity.

Figure 3 compares the transient temperature evolution at the surface and core of the brick under two modelling conditions: with evaporation and neglecting evaporation, alongside experimental temperature data measured at the brick core.

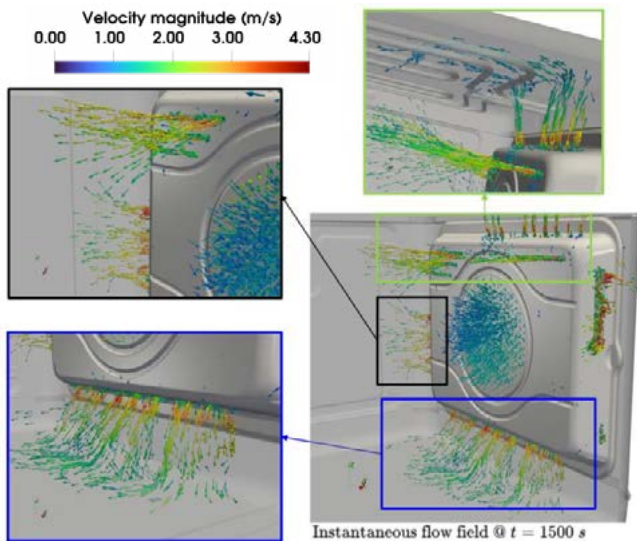


Figure 2: Instantaneous flow field, induced in the oven cavity by the fan.

At the surface, the simulation neglecting evaporation predicts a rapid temperature rise exceeding 150 °C within approximately 1000 s, followed by a gradual approach to steady state around 175 °C. In contrast, the case with evaporation exhibits a markedly lower steady-state surface temperature (~100 °C). This difference reflects the strong cooling effect of phase change, where latent heat consumption during moisture evaporation limits further surface temperature increase despite continuous external heating. The core temperature rises almost linearly over time in both cases; however, the evaporation-inclusive model consistently predicts lower core temperatures, aligning more closely with the experimental data. The negligible-evaporation model overestimates the core temperature by more than 30 °C at later times, indicating that ignoring evaporative cooling leads to significant overprediction of heat transfer into the brick interior.

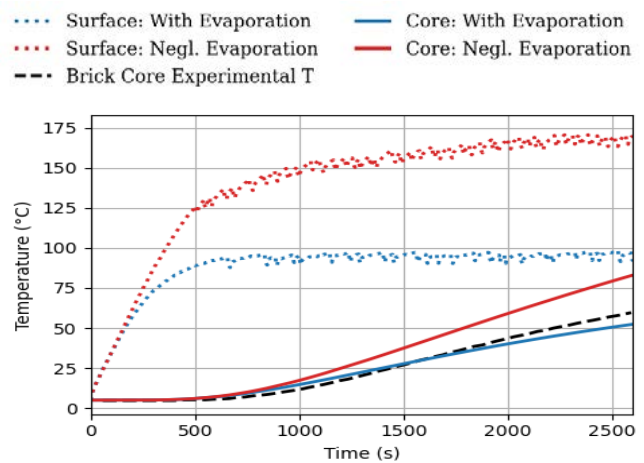


Figure 3: Numerical results with evaporation and with evaporation neglected are compared against experimental data.

Conclusions

Incorporating the experimentally fitted evaporation model into the 3D CFD-based digital twin significantly improved agreement between simulations and experimental measurements. The results demonstrate that evaporation is a key mechanism governing heat transfer in moist porous materials, where latent heat effects limit surface temperature rise and delay core heating. Importantly, this study provides a simple and practical approach for integrating accurate evaporation modelling into 3D CFD simulations of domestic ovens, thereby improving the physical fidelity of numerically performing the EN60350 standardized tests.

ACKNOWLEDGEMENTS. The authors wish to thank the Slovenian Research and Innovation Agency for the financial support in the framework of the Programme P2-0196: Research in Power, Process and Environmental Engineering and project J7-60118.

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Investigation of parameters affecting energy savings during cooking

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Households contribute approximately one fifth of final energy consumption in Slovenia. This paper describes the methodology of a survey designed to assess energy-efficient behaviour in Slovenian households. To analyse the impact of small behavioural changes on reducing energy consumption, survey respondents will be asked about their energy efficient cooking practices. Informative material will be prepared based on the most influential parameters affecting energy use during cooking. This study experimentally identifies several key factors, mainly related to consumer behaviour while cooking. Results show that using a lid while boiling can reduce heat losses by up to six times, allowing for lower heating power. Another important parameter is pot size, which influences the amount of water used when no measuring method is applied.

Introduction

In final energy consumption, there are three main sectors that impact the end-use of energy significantly; transport (42 %), manufacturing and construction (24 %), and households (22 %)[1]. Households account for approximately one fifth of final consumption, with cooking representing about 4 % of household energy use. Although this share may seem small, it includes everyday activities where potential for energy savings can be found. Cooking methods vary among individuals - for example, in the amount of water used for cooking, whether a lid is used while cooking, and so on. So-called "small actions" have an impact on energy use and importantly, we can implement them without major financial investments. Understanding behavioural choices is the key to promote sustainable habits and increase the energy literacy. In Slovenia a knowledge gap in this area was identified [2], confirming the need for further research. Therefore, a survey about general energy efficiency behaviour and more detailed cooking habits will be conducted.

Materials and methods

The survey for households will be divided into two parts. First part will include various concepts of home energy use and also energy efficiency behaviour that will help us gain insights whether these aspects coincide with efficient energy use. Main goal is to determine if individual's values and sustainability mindset affect energy use. The results will help us identify different user profiles based on their behavioural characteristics.

The second part will include concepts that will address cooking habits. In order to identify whether individuals can contribute to efficient energy use in cooking the survey will also include a section of questions addressing attitudes including cooking habits [3] and attitudes relevant to energy efficient cooking

practices [4]. The results of cooking habits will be later on used to evaluate the energy consumption for cooking. In addition, the participants will be divided into two groups where only one group receives additional informative materials on how to cook energy efficiently. Main goal is to determine if individuals who received the informative materials chose cooking techniques that indirectly led to lower energy consumption. In order to determine the energy use of participant in the survey a tool will be designed. The tool will base on a sensitivity analysis including influencing parameters that affect heat losses while cooking. The results could also be used more broadly and will allow to identify areas where more education and information is needed.

In order to prepare informative material for survey respondents, and to **determine influencing parameters** for energy consumption to cook 250 g of pasta, two different experiments are conducted.

Firstly, heat losses of a system water-pot-lid at different water temperatures are evaluated. For this purpose, water in three different pots (2 l, 3 l and 5 l) and three different water levels ($\frac{1}{4}$, $\frac{1}{2}$, and $\frac{3}{4}$ of pot capacity) was heated on induction hob up to boiling point and then cooled down to 60 °C. In the meantime, water temperature was measured with a K-type thermocouple and logged each second with Extech SDL400 temperature logger. Uncertainty of measured temperature is 0.4 % of measured value + 0.5 K.

Energy balance can be simplified and written as equation (1):

$$mc_p \frac{dT}{dt} + hA(T - T_\infty) + \frac{dm_w}{dt} h_v = 0, \quad (1)$$

where first term is associated with system's change in internal energy, second term with convective heat transfer and third term with heat transfer due to water evaporation. In the case when pot is covered with lid, latter term can be omitted and only convective heat losses are assumed. In this study, temperature gradient over temperature is more of an interest then over time, so energy balance can be simplified and written as differential equation (2):

$$\frac{dT}{dt} = a - cT, \quad (2)$$

where a and c are constant fitting factors. When pot is not covered with lid, simultaneous heat and mass transfer can be assumed. In this case energy balance is written as differential equation (3):

$$\frac{dT}{dt} = -K_1(T - T_\infty) - K_2 \frac{p_s(T)}{(T+273)} + K_3, \quad (3)$$

where K_1 , K_2 and K_3 are constant fitting factors, and $p_s(T)$ is saturation pressure of water vapour in the air, calculated with equation (4) [5]:

$$p_s(T) = 610,94 e^{\frac{17,625 T}{T+243,04}}. \quad (4)$$

Non-linear ordinary differential equation is solved numerically with Runge-Kutta method, adjusting to experimental data on cooling curves. In both cases, uncertainty of parametric model is estimated with Monte Carlo simulation with 10^5 iterations and represents 95 % confidence interval. Calculated temperature derivative is multiplied by mass and specific heat of a system, representing heat losses, and plotted against temperature difference between the system and environment. Parametric model's derivative is compared to experimental derivative which is obtained using a moving linear regression method, where a 1st-degree polynomial was locally fitted to a sliding window of data points.

Secondly, volunteers ($N = 28$) were asked to fill each of three pots with amount of water they think was sufficient to cook 250 g of pasta. They poured water directly from tap without any measuring. Mass of water was measured and data were used to analyse mean value, standard deviation and uncertainty for each case, while normal distribution was assumed.

Results and discussion

Figure 1 presents heat losses of 1.5 l of water in a pot over temperature differences between the system and environment, estimated with parametric model and experimental derivative.

At boiling, heat losses are greatest in the case without lid; 443 W for bigger pot and 336 W for smaller pot, respectively. When pot is covered with lid, heat transfer due to evaporation is neglected, therefore heat losses are reduced up to 6 times (75 W and 62 W, respectively). Heat losses in both cases are greater in bigger pot, which can be explained by greater surface for heat exchange, as well as higher unwetted part of the pot, which acts as a cooling fin.

The results in Figure 2 and Table 1 show that when volunteers poured water into pot without any measuring device, the mean value of water mass and its standard deviation increased with pot size, indicating greater variation for larger pots. Similarly, the uncertainty of the results was highest for the 5 l pot and lowest for the 2 l pot. This suggests that participants were less consistent when filling larger pots. These findings highlight the importance of using appropriate measuring method, like measuring cup.

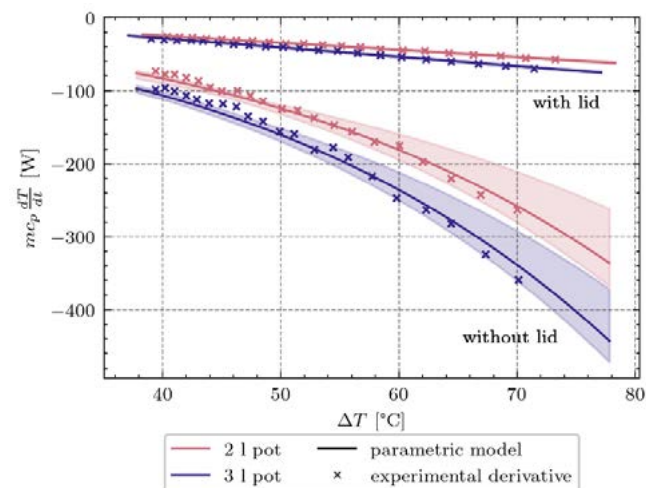


Figure 1: Heat losses of a system water-pot-lid over range of temperature differences between the system and environment. In all cases 1,5 l of water was used.

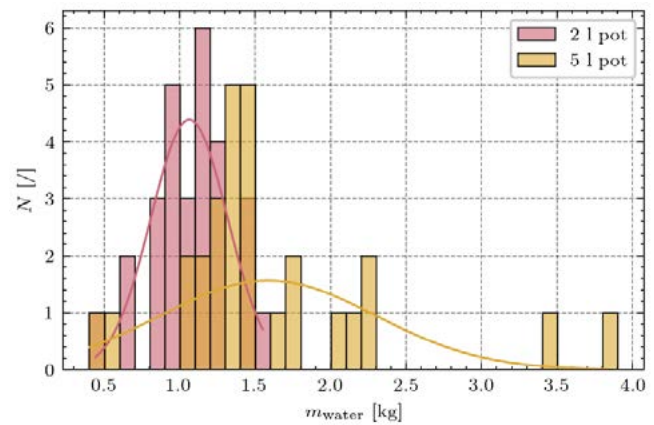


Figure 2: Histogram of water mass volunteers poured in 2 l and 5 l pots directly from tap. Solid line represents normal distribution.

Table 1: Mean value μ , standard deviation σ and uncertainty u of water mass m_w volunteers poured in 2 l, 3 l and 5 l pots to cook 250 g of pasta directly from tap without measuring.

pot	μ_{m_w} [kg]	σ_{m_w} [kg]	$u(m_w)$ [kg]
2 l pot	1.06	0.26	0.05
3 l pot	1.33	0.41	0.08
5 l pot	1.59	0.73	0.14

Conclusions

According to results, three influencing parameters are defined and classified by importance:

- Lid; while cooking without lid, energy consumption to maintain boiling can be up to six times higher compared to cooking with lid.
- Power reduction; highest heating rate of domestic hobs can be several kW, while to maintain boiling less than 500 W without lid and less than 100 W with lid is enough.
- Size of pot; too big pot can increase mass of water when no measuring method is used. It should fit for amount of water used as well, to reduce heat losses.

Findings provide a basis for preparation of informative material for survey respondents, where so called “small actions” to reduce energy consumption while cooking will be promoted.

In the future work, results from the survey will be analysed and compared between two groups, one informed and one uninformed, to estimate if informing can have any impact on energy consumption. Additional influencing parameters, like mass of water and hob type, will be studied as well.

ACKNOWLEDGEMENTS. This research was supported by LIFE IP CARE4CLIMATE (LIFE17 IPC/SI/000007).

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Fotonapetostne ozelenjene strehe: energijska bilanca in raba vode

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Integracija fotonapetostnih (PV) modulov in ozelenjene strehe predstavlja obetavno tehnologijo za doseganje ciljev trajnostne gradnje. Sinergijski učinki vključujejo povečan izkoristek PV modulov zaradi hlajenja vegetacije, hkrati pa zmanjšanje porabe vode in izboljšanje toplotne stabilnosti ovoja stavbe zaradi senčenja. V raziskavah smo razvili podroben model toplotne in vodne bilance, ki vključuje natančen izračun geometrijskih faktorjev senčenja in sevanja ter dolgovalovne sevalne izmenjave. Meritve so pokazale več kot 100 W/m² višje dolgovalovno sevanje pod PV moduli v primerjavi s prostim nebom. Rezultati so pokazali, da zanemarjanje podrobnega modeliranja dolgovalovne izmenjave vodi do 18 % podcenitve evapotranspiracije, kar potrjuje ključno vlogo natančne obravnave toplotnih tokov, vključno z dolgovalovno sevalno izmenjavo.

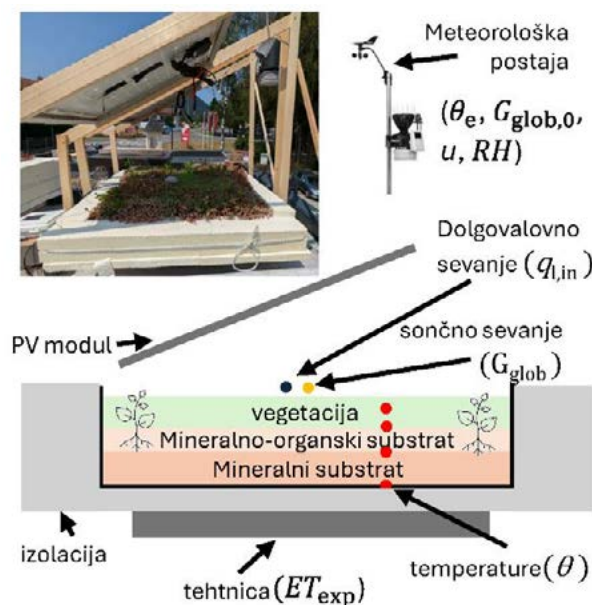
Uvod

Vse večja potreba po energetski učinkovitosti stavb povečuje potrebo po večnamenskih in trajnostnih gradbenih rešitvah. Ozelenjene strehe so že uveljavljene kot učinkovit način blaženja mestnih toplotnih otokov, izboljšanje toplotne stabilnosti ovoja in zadrževanje padavinskih voda. Fotonapetostni (PV) module se uporablja za lokalno proizvodnjo električne energije, vendar v mestnem okolju zmanjkuje prostora za njihovo namestitvev. Integracija fotonapetostnih modulov na ozelenjeno streho prinaša dodatne sinergistične učinke. Povečana učinkovitost PV modulov zaradi hlajenja zelenih površin z mehanizmom evapotranspiracije (izhlapevanjem vode) je že dobro raziskana [1]. V naših raziskavah smo se osredotočili tudi na obratni učinek: vpliv fotonapetostnih modulov na energijsko in vodno bilanco ozelenjenih streh. Dosedanje raziskave so poenostavljeno obravnavale pomembne vidike, kot je na primer zanemarjanje dolgovalovne sevalne izmenjave [2] z moduli in poenostavljeno obravnavano senčenja s kalibracijskimi faktorji [3].

Metodologija

Razvit model temelji na energijski bilanci površine in vodni bilanci sestave ozelenjene strehe. Z znanimi energijskimi tokovi na površini lahko posledično tudi izračunamo količino izhlapele vode (evapotranspiracijo) površine s FAO Penman-Monteith metodo [4]. Energijska bilanca vključuje kratkovalovno (sončno) sevanje, dolgovalovno sevanje, konvekcijo, prevod in latentni toplotni tok. Za izračun podrobne dolgovalovne sevalne izmenjave je bil razvit geometrijski model faktorja senčenja (SF) in faktorja vidnega dela neba (VF) na urnem nivoju. Ti faktorji omogočajo natančen izračun direktnega in difuznega sončnega sevanja, ki

doseže vegetacijo pod moduli. Skupaj s prilagojenim modelom temperature PV modulov na ozelenjeni strehi pa omogočajo tudi natančen izračun dolgovalovne sevalne izmenjave. Vodna bilanca temelji na vsebnosti vode v substratih in vključuje padavine, izhlapevanje, transpiracijo rastlin in zadrževanje vode. Model je bil razvit v Python okolju in validiran z eksperimentalnimi meritvami na zunanjem preizkuševališču LOTZ v Gameljnah. Slika 1 prikazuje eksperimentalno postavitve in merjene veličine. Zasnova eksperimenta omogoča različne postavitev PV modulov z različnimi faktorji senčenja in vidnimi faktorji. Dodana vrednost raziskave je posredna meritev in validacija latentnega toplotnega toka s pomočjo gravimetrične metode.



Slika 1: Shema eksperimentalne postavitve na zunanjem preizkuševališču LOTZ v Gameljnah z merjenimi veličinami.

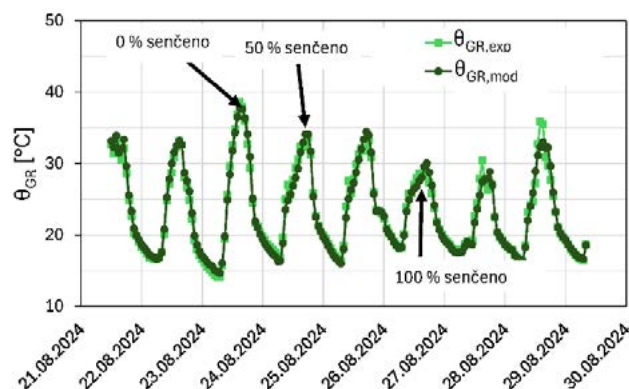
Rezultati in razprava

Temperatura PV modulov in ozelenjene strehe. Izmerjene temperature PV modulov nad ozelenjeno površino so v povprečju nižje za 2°C v primerjavi z referenčnim modulom na navadni strehi. Temperatura PV modulov je še vedno dovolj visoka, da ima pomemben vpliv na energijsko bilanco ozelenjene površine. Na osnovi meritev dolgovalovnega sevanja, smo razvili parametrični model temperature fotonapetostne zelene strehe, ki je odvisen od temperature okolice (θ_{amb}), globalnega sončnega sevanja ($R_{s, glob, 0}$) in faktorja senčenja (SF) [5]:

$$\theta_{GR} = 0.935 \cdot \theta_{amb} + 0.011 \cdot R_{s, glob, 0} \cdot (1 - SF) \quad (1)$$

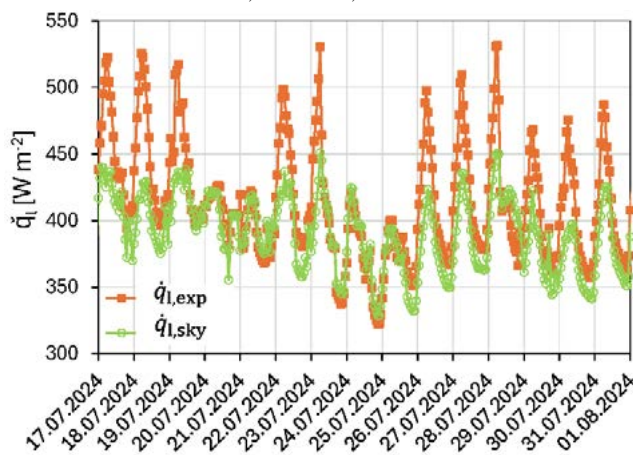
V obdobju validacije, ki vključuje različne postavitve, je bila normalizirana napaka kvadratov modela (NRMSE) 2,43 %. Slika 2 prikazuje izmerjeno in modelirano temperaturo ozelenjene strehe pri različnih geometrijskih postavitvah. Pri

nesenčeni ozelenjeni strehi na dan 23.8. temperatura površine doseže 37,2°C, medtem ko pri 100 % senčeni postavitvi na dan 26.8. temperatura doseže maksimalno vrednost 30,4°C.



Slika 2: Primerjava izmerjene ($\theta_{GR,exp}$) in modelirane ($\theta_{GR,mod}$) temperature zelene strehe pri različnih geometrijskih postavitvah (faktorjih senčenja).

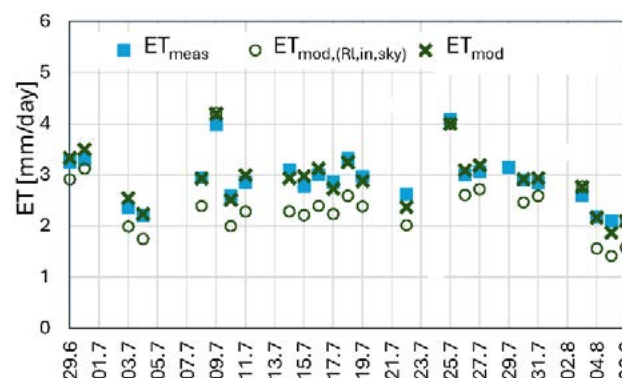
Dolgovalovna sevalna izmenjava. Dolgovalovna sevalna izmenjava med PV moduli in ozelenjeno površino se je izkazala kot ključni element energijske bilance za natančno modeliranje [6]. Meritve so pokazale do 100 W/m² višji dolgovalovni toplotni tok proti strehi pod PV moduli v primerjavi s prostim nebom (slika 3), kar pomeni, da ta toplotni tok ne smemo zanemariti. Poleg temperatur PV modulov in ozelenjene strehe pod PV moduli, za urno modeliranje potrebujemo tudi natančna geometrijska modela faktorja senčenja in vidnega faktorja površine, ki sta bila sta bila validirana pri različnih postavitvah, s faktorji senčenja od 0-100 %. Natančen model je v primerjavi z meritvami dosegel normalizirano srednjo napako kvadratov 5 % v obdobju validacije.



Slika 3: Primerjava izmerjenega vpadnega dolgovalovnega sevanja na površino zelene strehe v primeru meritve pod PV moduli ($\dot{q}_{l,exp}$) in pod jasnim nebom ($\dot{q}_{l,sky}$).

Evapotranspiracija (raba vode). Na osnovi izračunanih toplotnih tokov na ozelenjeni strehi, lahko izračunamo tudi količino evapotranspiracije. Primerjava med izmerjenimi in modeliranimi vrednostmi je pokazala dobro ujemanje, kar potrjuje ustreznost natančnega modeliranja. Pri tem se je izkazalo, da bi bila evapotranspiracija, če bi pri izračunu uporabili le dolgovalovno sevanje neba brez PV modulov, podcenjena. Slika 4 prikazuje izmerjene (ET_{exp}), modelirane (ET_{mod}) in modelirane vrednosti z uporabo dolgovalovnega

sevanja neba brez PV modulov ($ET_{mod,sky}$). Za urne vrednosti evapotranspiracije znaša srednja napaka kvadratov (RMSE) 0,06 mm/h in normalizirana srednja napaka kvadratov (NRMSE) 24 %, kar je delno posledica negotovosti meritev pri tehtanju. Pri dnevni vrednostih, kjer se relativna merilna napaka zmanjša, se natančnost bistveno izboljša, RMSE je 0,13 mm/dan, NRMSE pa 4,4 %. Če bi se za model uporabilo samo sevanje neba brez vpliva PV modulov, bi bila povprečna dnevna evapotranspiracija podcenjena za približno 0,5 mm/dan (18 %), kar poudarja pomen natančnega modeliranja dolgovalovnega sevanja pri napovedi vodne bilance.



Slika 4: Primerjava rezultatov izmerjene (ET_{meas}), modelirane (ET_{mod}) in modelirane z upoštevanjem sevanja jasnega neba ($ET_{mod,(Rl,in,sky)}$).

Zaključki

- Razvili smo integriran model toplotne in vodne bilance fotonapetostne ozelenjene strehe, ki vključuje natančen izračun dolgovalovne sevalne izmenjave na osnovi geometrijskih faktorjev senčenja in vidnega faktorja.
- Vpadlo dolgovalovno sevanje pod PV moduli smo izmerili do 100 W/m² višje kot dolgovalovno sevanje neba, kar potrjuje pomembnost natančnega modeliranja.
- Poenostavljen model brez dolgovalovne izmenjave z moduli podceni dnevno evapotranspiracijo v povprečju za 18 %.
- Model se je izkazal kot zanesljivo orodje za analizo vpliva PV modulov na energijsko in vodno bilanco ter za načrtovanje optimalne geometrije in postavitve fotonapetostnih zelenih streh glede na podnebne razmere.

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Effect of mixing speed on the thermo-mechanical properties of glass fibre reinforced polypropylene composites

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The study focuses on effect of mixing speed on thermo-mechanical properties of glass fiber reinforced polypropylene (PP) composites. Composites mixtures containing 30 wt% of glass fibres were processed using a micro-compounder at various rotation speeds, i.e., 25, 50, 100 and 200 rpm. The degree of fibre fragmentation and its influence on fibre length distribution, thermal and mechanical response were analysed using optical microscopy, differential scanning calorimetry (DSC) and dynamic mechanical analysis (DMA). The results revealed that increasing mixing speed led to shorter fibres and enhanced fragmentation, which significantly affected both thermal and mechanical performance of composites. Increased mixing speed (decreasing fiber length) weakens composite stiffness and thermos-mechanical stability. Additionally, it also influences thermal response, slightly effecting melting and crystallization kinetics.

Introduction

Polymer composites have gained increasing importance since the 1940 with the introduction of fibreglass-polyester matrices. Due to their benefits, i.e., high strength-to-weight ratio, tuneable mechanical properties, corrosion resistant, etc. [1] Their application expanded rapidly in the 1960s and continues to grow across various engineering sectors, including aerospace, automotive and construction.

The present work focuses on a composite system consisting of polypropylene (PP) reinforced with glass fibres. Polypropylene is a semi-crystalline polymer, with the smallest density (lightest synthetic polymer), relatively good impact resistance and chemical stability with excellent processing properties. It is the second most widely used polymer in volume by production volume (after polyethylene) and is commonly used in automotive components, packaging, textiles, medical devices and electrical housing due to its cost and manufacturing efficiency [2].

Glass fibres represent the most frequently used reinforcement in polymer composites because of their favourable combination of high tensile strength, elastic modulus, low density and excellent temperature resistance. Among various glass fibre types, alumino-borosilicate is the most common due to its low cost and good mechanical performance, while high-strength magnesium-aluminosilicate provides superior stiffness and fatigue resistance [3].

Glass fibre reinforced polymeric composites during the mixing phase are exposed to a variety of different mechanical stresses,

such as high shear forces during the extrusion process, which can result in fibre breakage and a reduction in their length. Processing-induced changes in fibre length and dispersion affect the thermo-mechanical performance of polypropylene composites. Lower screw speeds preserve fibre length, which enhances stiffness and increases thermo-mechanical stability due to more efficient load transfer. On the other hand, higher screw speeds improve a better fibre distribution and homogeneity, but result in a decrease in stiffness as a result of higher fibre breakage [4].

The aim of presented research is to demonstrate the influence of various mixing speeds during compounding on thermal thermo-mechanical properties of glass fibre reinforced polypropylene composites.

Materials and methods

Composite specimens were prepared using a micro-compounder (Xplore, MC15, Netherlands) coupled with an injection moulding system (Xplore, IM12, Netherlands). Polypropylene granules were first premixed for 5 min at 50 rpm, to ensure complete melting and homogenization. Subsequently, 30 wt% of short glass fibres were added and the blend was homogenised for an additional 5 minutes at different mixing speeds, i.e., 25, 50, 100 and 200 rpm. The compounded materials were injection-moulded into a rectangular shaped specimens measuring 60 x 10 x 1 mm, then cut to 40 mm in length for measurements.

Dynamic mechanical analysis (DMA) was performed on an Anton Paar MCR 702 rheometer under a nitrogen atmosphere. DMA measurements were conducted test at a constant stress of 0,1 MPa (within linear viscoelastic domain) and a frequency of 1 Hz while heating from -10°C to 100°C at a 3°C/min (heating) rate. The storage modulus - G' , loss modulus - G'' , loss factor ($\tan \delta$) and glass transition temperature - T_g were recorded to quantify the elastic and viscous components of the material response as well as its glass transition.

Thermal analysis was conducted using differential scanning calorimetry - DSC (Q2500, TA Instruments, USA). Test were performed from -25°C to 200°C with a heating and cooling rate of 10°C/min under a nitrogen atmosphere. From the resulting thermograms, glass transition temperature, melting - T_m and crystallisation - T_c temperatures were determined using standard procedures, while T_g was discarded from the analysis due to weak transition.

Results and discussion

Dynamic mechanical analysis (DMA).

Prior to the DMA analysis, the samples were examined under an optical microscope, revealing a significant reduction in fibre length from the initial 3 mm before mixing to approximately 390 μm after 5 minutes at 25 rpm and a further reduction in length to 220 μm at 200 rpm, confirming severe shear-induced fibre breakage during compounding.

The dynamic mechanical behaviour of neat polypropylene (PP) and PP composites with 30 wt% glass fibres (PP30GF) homogenized at different mixing speeds was evaluated by temperature-dependent DMA (Fig. 1). All samples exhibit elastic like behaviour throughout observed temperature range ($G' \gg G''$), Fig. 1A). At ambient temperature, the neat PP exhibited a G' value of approximately 600 MPa, whereas PP30GF composites showed significantly higher stiffness (1364 MPa for 25 rpm and 1261 MPa for 200 rpm). The observed twofold increase in modulus demonstrates the strong reinforcing effect of the glass fibres. The glass transition temperature (T_g), determined from the peak of $\tan \delta$ occurred at 8,4°C for neat PP and shifted to lower values with addition of glass fibres to 5,4°C at 25 rpm and 7,4°C at 200 rpm indicating increase of chain mobility, Fig. 1B. Above T_g both G' and G'' gradually decrease with temperature, however slightly bigger drop of G' was observed at higher mixing speed attributed to enhanced fibre degradation under higher shear, which produced shorter fibres and reduced load transfer efficiency.

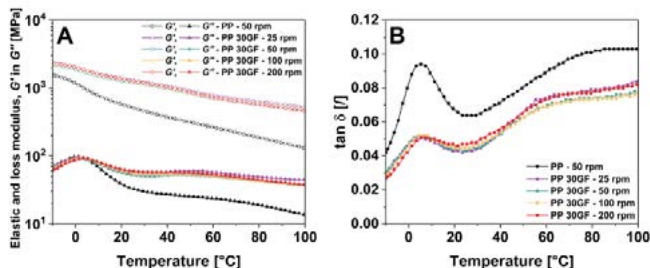


Figure 1: (A) Temperature dependence of G' and G'' of neat PP and PP30GF processed at different mixing speeds. (B) Temperature dependence of $\tan \delta$ showing the effects of fibre reinforcement and processing conditions on the relaxation behaviour.

Differential Scanning Calorimetry (DSC).

All samples exhibited a single endothermic peak upon heating, corresponding to the melting of the crystalline α -phase of polypropylene. During the cooling cycle, all PP30GF samples displayed a distinct exothermic crystallisation peak (T_c) that systematically shifted toward higher temperatures with increasing mixing speed, Fig. 2A. This shift indicates that shorter glass fibres generated at higher shear rates act as an effective heterogeneous nucleation site [5], facilitating faster polymer crystallisation upon cooling. Consequently, T_c increased from approximately 118°C at 25rpm to 121°C at 200 rpm. On the other hand, the opposite may be observed through T_m , which lightly decreased with increasing mixing speed, from 164.7°C at 25 rpm to 162.5°C at 200 rpm, Fig. 2B. The reduction of T_m can be attributed to the increased degree of fibre fragmentation and the resulting change in the

crystalline morphology of the polymer matrix, where increased number of fragments restrains crystal growth by promoting smaller, less perfect crystallites, which melt at lower temperatures [6, 7]. This inverse correlation between T_m and T_c indicates that although higher shear induces crystalline disorder, it simultaneously enhances the overall crystallisation kinetics.

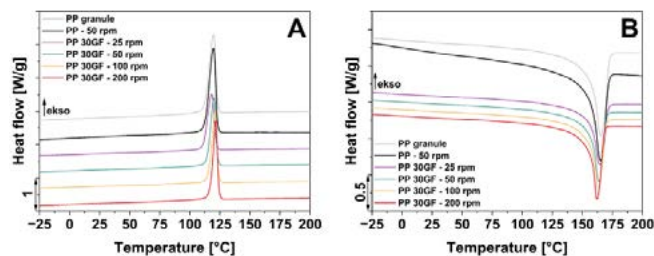


Figure 2: Differential scanning calorimetry (DSC) results of neat PP and PP30GF processed at different mixing speeds. (A) First cooling cycle demonstrating changes in crystallisation, and (B) second heating cycle indicating transition of melting peaks due to fibre fragmentation.

Conclusions

This study confirms that the mixing speed during compounding strongly influences the fibre morphology and thermo-mechanical behaviour of glass fibre reinforced polypropylene. Combining the results from DMA and DSC allows a comprehensive interpretation of the structure property relationship in glass fibre reinforced polypropylene. At lower shear conditions, the fibre length is better preserved, leading to higher stiffness and improved thermo-mechanical stability, while higher shear enhances fibre dispersion, while reduced stiffness of the composite due to fibre breakage.

- The twofold increase in storage modulus confirms the dominant contribution of glass fibres compared to neat polypropylene.
- Increased shear conditions during compounding yields a decrease in storage modulus across the temperature range due to progressive fibre breakage and decreased load transfer efficiency.
- The shift of peak of $\tan \delta$, i.e., T_g , to a lower temperature indicating increased chain mobility within the composite compared to the neat material.

These results demonstrate that both the microstructural evolution and molecular mobility of polypropylene are strongly affected by the processing parameters, therefore, optimising the mixing speed offers a viable strategy for tailoring of thermo-mechanical behaviour in fibre-reinforced composites.

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Using the Effect of Oxygen Enrichment to Boost the Performance of a PEMFC Stack Integrated into an Aerobatic Aircraft

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This paper investigates integration of a low-temperature Proton Exchange Membrane Fuel Cell (LT-PEMFC) onboard an aerobatic aircraft. Experiments examined the effects of increased oxidant concentration, temperature, and pressure on its performance. Results were used to model a PEMFC system capable of providing sufficient power for regular flight and aerobatic manoeuvres. To meet peak power while minimizing stack mass, pure oxygen use at the cathode was explored. A numerical model simulated stack operation with 100% oxygen versus ambient air, estimating mass and energy fluxes for an eight-minute variable power profile. The study confirms the feasibility of hydrogen-powered aerobatic aircraft but also indicates that commercial off-the-shelf components would be too heavy. Collaboration with suppliers would yield optimized, lighter components. With innovative aircraft design and optimized balance-of-plant systems, total mass can be reduced, demonstrating PEMFC potential in advanced aviation.

Introduction

This study is driven by the potential to replace internal combustion engines (ICE) with a more sustainable electric propulsion system. Energy for electric propulsion can be stored either in batteries or hydrogen-based via proton exchange membrane fuel cells (PEMFCs). Both approaches offer distinct advantages and challenges in terms of energy density, system complexity, and environmental impact, and are actively being investigated for application in aviation.

Decarbonizing aviation using hydrogen fuel cell aircraft is a promising but still technically challenging pathway. While the frequency of first flights involving hydrogen-powered aircraft has increased in recent years, the majority remain small-scale, one-off demonstrators. Experimental flight testing would need to increase substantially to make hydrogen aircraft viable in the near future. By converting conventional aircrafts to use fuel cell systems – based on hydrogen produced from renewable energy sources – it is expected to reduce lifecycle emissions by more than 85% compared to fossil fuel-powered planes [1].

Materials and methods

A test station built in-house was used to measure the performance characteristics of a single PEMFC under various operating conditions, with particular emphasis on the impact of oxygen enrichment. The tested membrane electrode assembly (MEA) had a symmetrical platinum loading on both electrodes (0.5 mg/cm²), a 0.002" thick membrane, 410

microns thick woven carbon cloth gas diffusion layers, and an active area of 50x50 mm². For the tests, the MEA was placed in the fixture that includes integrated electric heaters for precise temperature regulation. The contact pressure on the MEA is controlled using a pneumatic system to ensure consistent pressure across the membrane. All system components are integrated with a custom-built LabVIEW program, enabling precise parameter regulation, real-time monitoring, and data collection, as shown in Figure 1.

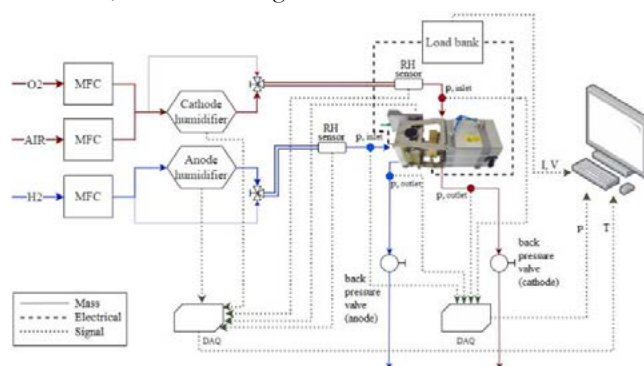


Figure 1: Schematic of the experimental setup for PEMFC testing.

The actual aerobatic aircraft considered in this study is the Ultimate 20-300 [2], which is powered by a piston ICE specifically designed for aerobatics that runs on aviation gasoline and produces 225 kW of power. Its empty weight (excluding fuel, passengers, and baggage) is 522 kg. An indicative aerobatic flight profile includes take-off (1 min) at maximum power (225 kW), followed by cruise to the aerobatic area (1.5 min) at reduced power of 100 kW. The aerobatic manoeuvres require 4 min at maximum power, and the return to the hangar takes 1.5 min at reduced power.

To replace the ICE powertrain, the hydrogen-based aircraft requires a PEMFC stack and several balance-of-plant (BoP) components, including a humidifier, hydrogen recirculation pump, gas storage tanks, and a cooling system. It is assumed that the modified hydrogen-based aircraft uses ambient air as the cathode reactant during low-power flight and switching to onboard oxygen when peak power is needed. Additionally, an electric motor with its controller and a lithium-ion battery are needed to manage rapid power fluctuations. Among commercial products, the NM12 TwinStack PEMFC system developed by EKPO [3] was selected. It operates on hydrogen and ambient air and delivers up to 225 kW. Building on this data, the effect of oxygen enrichment was incorporated to estimate the stack's power output when operating with pure oxygen.

Results and discussion

A power curve was measured on a single cell using both air and pure oxygen at absolute pressures of 1 bar and 1.5 bar, since realistic systems operate at elevated pressures. The nominal operating point for air was defined at current density slightly below the peak power, at which a 33% performance improvement was observed when pure oxygen was used (see Figure 2). This improvement was then extrapolated to the stack level, under the assumption that similar performance gains would raise the stack's nominal power output to 300 kW.

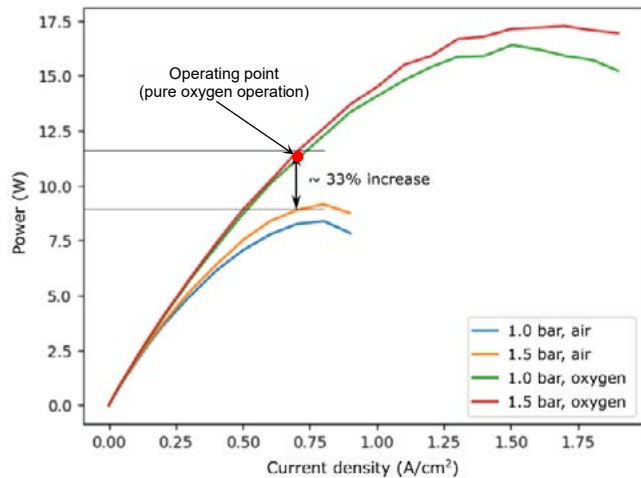


Figure 2: Measured improvement in the performance of a single PEMFC due to oxygen enrichment.

Due to the number of BoP components required for the operation of the PEMFC stack, it was presumed that the overall aircraft mass would be higher compared to a conventional ICE configuration. To compensate for the increased mass, and maintain a comparable specific power ratio, the BoP components were sized based on the maximum power delivered to the electric motor. The masses of all BoP components, the PEMFC stack, and the empty airframe are summarized in Table 1.

Table 1: Components and corresponding masses of a hydrogen-based aircraft for two design configurations.

Component	Baseline mass (kg)	Optimised mass (kg)
electric motor	30	20
EM controller	13	9
batteries	33	17
electronics cooling system	36	18
electronics cooling pump	2	2
PEMFC stack	125	93
H2 recirculation pump	3.5	3.5
cathode humidifier	6	6
stack cooling system	80	53
stack cooling pump	7	5
cooling fluid	20	20
H2 tank	36.5	36.5
O2 tank	40	20
basic airframe weight	270	270
empty aircraft	702	573

As shown, the empty aircraft in the hydrogen-based configuration is approximately 180 kg heavier than the ICE configuration. However, this baseline design was based on commercial off-the-shelf components and was not optimized. Therefore, a second optimized configuration was designed, which was based on discussions with component suppliers, literature review, and our own experience.

For comparison, a conservative assumption is made that an ICE aircraft has negligible own consumption for its BoP components, whereas a hydrogen-based aircraft has about 15% own consumption for its BoP components. Using these assumptions, the specific power of the empty aircraft was calculated: the existing ICE aircraft achieves 0.43 kW/kg, the hydrogen-based baseline configuration reaches 0.36 kW/kg, and the optimised design achieves 0.44 kW/kg.

Table 2 presents the calculated values for the optimized system in both power modes during the flight. The total hydrogen consumption over the entire flight is approximately 1.5 kg, while 16.7 kg of oxygen is required only for the maximum power mode.

Table 2: Mass and energy balances for the optimized configuration of the hydrogen-based aircraft.

Parameter	Max. power mode	Low power mode	Unit
stack power	300	128	kW
electric current	625	290	A
H2 mass flow	0.0039046	0.001812	kg/s
O2 mass flow	0.0557807	/	kg/s
time	5	3	min
H2 mass	1.17	0.33	kg
O2 mass	16.73	/	kg
stack efficiency	0.640	0.589	
system efficiency	0.544	0.501	

Conclusions

The study demonstrated that building a hydrogen-powered aerobatic aircraft is feasible. However, assembling the aircraft using off-the-shelf components would likely result in excessive weight. By collaborating with component suppliers and introducing innovative aircraft design approaches, particularly in the optimization of BoP components, these parts could be made lighter and less energy-consuming. This would enable the aircraft to achieve the desired specific power-to-weight ratio, demonstrating the potential of PEMFC technology in a unique aviation application.

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Mehka robotika v fluidni tehniki

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V današnjem času si ne moremo predstavljati industrije brez robotike, ki nadomesti težavno, monotono in ponavljajoče-se delo ter, kar je najpomembneje pokriva primanjkljaj delavne sile. V robotiki je ena izmed zelo pomembnih operacij zanesljivo in varno prijetanje predmetov za manipulacijo. Predmeti pravilnih oblik in večje trdnosti niso problematični, težave pa nastopijo, ko želimo prijeti predmete nepravilnih in naključnih oblik. Za lahke premete so rešitve na trgu znane, pri težjih pa teh ni. Prispevek predstavlja raziskave vpliva različnih geometrijskih oblik mehkih prijemal na kot in silo prijemanja. Testirana prijemala so bila natisnjena po postopku FDM ter po postopku SLA iz elastičnih poliuretanov. Izkazalo se je, da imajo geometrijske karakteristike prijemala ključen vpliv na njihovo prijemno silo in kot prijemanja.

Uvod

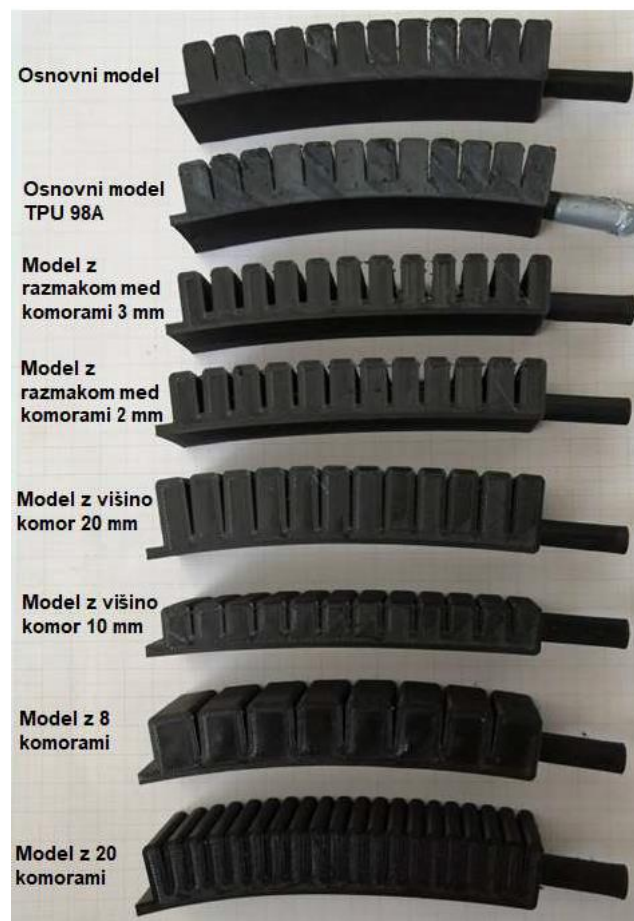
Povečanje industrijske proizvodnje in pomanjkanje delovne sile nas vodi v vedno večjo uporabo robotov. Ena izmed pomembnejših robotskih operacij je varno in zanesljivo prijemanje različnih predmetov. Ti so različnih oblik in različno občutljivi na način prijemanja. Mehanska, kovinska prijemala so v večini primerov ustrezna in primerna. Obstaja pa tudi veliko predmetov, ki jih, kljub natančnemu in nadzorovanemu prijemanju z različnimi mehanskimi kleščami ne moremo prijeti. Takih predmetov so lahko različni prehrabni izdelki od jajc, sadja, tankih lončkov, pa vse do različnih plastičnih, lesenih in steklenih predmetov. V ta namen se po vsem svetu izvajajo številne raziskave. Večina, do sedaj razvitih prijemal, ki se najpogosteje aktivirajo z energijo komprimiranega zraka, je namenjena za prijemanje lahkih predmetov [1].

Do sedaj so se mehka prijemala uporabljala pri manjših silah, kar pomeni, da smo lahko prijemali le lažje predmete. Področje mehkega prijemanja za večje sile je še neraziskano, saj se pri tem uporabljajo predvsem klasična - mehanska prijemala. Ker imajo mehka prijemala zaradi svoje prilagodljivosti uporabe na terenu velik potencial, smo se odločili, da bi mehka prijemala premo sorazmerno povečali.

Metodologija raziskave

Mehka prijemala so izdelana iz elastičnih materialov, najbolj pogosto so 3d natisnjena, ulita ali pa vulkanizirana v stiskalnici. V Laboratoriju za fluidno tehniko Univerze v Ljubljani se s tematiko mehke robotike ukvarjamo že več let. V tem času smo raziskovali vplive različnih oblik na prijemalno silo in deformacijske oblike v odvisnosti od tlaka. S sodobnim programskim orodjem smo izvedli številne simulacije deformacij elastičnih prijemal pod tlakom [2]. V raziskavi smo

najprej zasnovali različne oblike prijemal, ki jih je mogoče 3d natisniti. Raziskovali smo vplive različnega razmaka med komorami, vplive različne višine in različnega števila komor. Prijemala smo natisnili iz termoplastičnega poliuretanskega polnila TPU98A s trdoto 98 po Shoru A in premerom nitastega polnila 1,75 mm. Slika 1 prikazuje 3d natisnjene oblike prijemala po postopku s plastenjem staljenega elastomera (FDM). Slika 2 prikazuje 3d natisnjeno obliko prijemala, ki je bilo v več različnih izvedbah natisnjeno s postopkom stereolitografije (SLA).



Slika 1: Tri-dimenzionalno, s FDM natisnjena oblika prijemala z različnimi geometrijskimi lastnostmi [2].

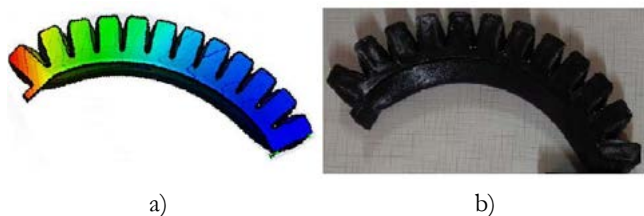


Slika 2: Tri-dimenzionalno, s SLA natisnjena oblika prijemala [3].

Natisnjenim prototipom mehkih prijemal smo pri različnih tlakih merili radij upogiba ter pritisno silo.

Rezultati in diskusija

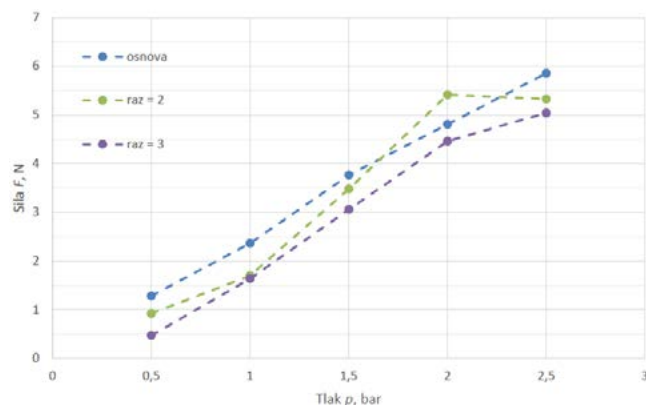
Na sliki 3a je prikazana deformirana FDM oblika numerično preračunanega prijemala, na sliki 3b pa 3d natisnjeno mehko prijemalo pod tlakom stisnjenega zraka 0,25 MPa.



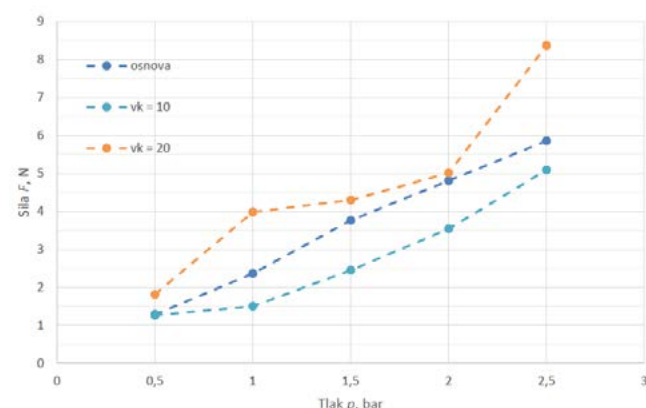
Slika 3: Slika deformacije s FDM natisnjenega mehkega prijemala, a) numerično preračunano, b) fotografija elastično deformiranega prijemala pod tlakom 0,25 MPa.

Na sliki 4 so prikazani rezultati meritev prijemne sile mehkega prijemala FDM, ko smo imeli razmak med komorami 1 mm (osnova), 2 mm in 3 mm. Največjo silo prijemala, 5,8 N smo dobili pri 0,25 MPa v primeru prijemala z najmanjšim razmakom med komorami (1 mm). Najmanjšo prijemalno silo, 5 N smo dobili v primeru prijemala z razmakom med komorami 3 mm.

Slika 5 prikazuje rezultate meritev prijemne sile FDM prijemala v odvisnosti od višine komor prijemala, najnižja višina komor je bila 10 mm, vmesna je bila 15 mm (osnova) ter največja 20 mm. Največjo silo prijetanja, 8,4 N smo dobili v primeru najvišje komore (20 mm), najmanjšo, 5 N pa v primeru najnižje višine komor 10 mm, oboje pri tlaku 0,25 MPa.

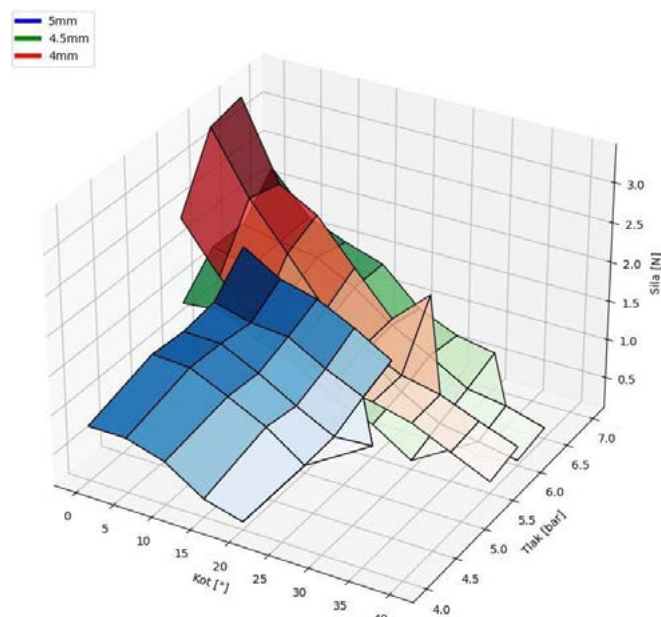


Slika 4: Rezultati meritev sile prijetanja FDM prijemala v odvisnosti od tlaka in razmaka med komorami [2].



Slika 5: Rezultati meritev sile prijetanja FDM prijemala v odvisnosti od tlaka in višine komor [2].

Slika 6 prikazuje eksperimentalno določen vpliv treh različnih debelin stene SLA mehkega prijemala na silo in kot prijetanja. Največja izmerjena sila prijetanja je bila 3 N pri debelini stene 4 mm. Iz slike je jasno razvidno, da večja debelina stene pomeni več vložene energije v elastično deformacijo prijemala in manj v silo prijetanja. Največjo silo prijetanja pri debelini stene 5 mm smo izmerili 1,5 N pri tlaku 6 bar, kar je ravno pol manj, kot smo dobili pri debelini stene 4 mm.



Slika 6: Izmerjen vpliv debelin stene SLA prijemala na silo in kot prijetanja [3].

Zaključki

V raziskavi smo razvili novo mehko prijemalo in preučevali geometrijske dejavnike, ki vplivajo na kot in silo prijetanja. Največjo silo, 8,5 N, smo dosegli pri največji višini komore (20 mm). Ugotovili smo, da najmanjši razmak med komorami zagotavlja največjo prijemno silo. Analiza vpliva debeline sten je pokazala, da večja debelina zahteva več energije za elastično deformacijo, kar vodi v manjšo prijemno silo.

Zahvala

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Modification of the Stöber process for the formation of sub-micron and micron-sized silica particles

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We present a simple and versatile approach for the synthesis of spherical silica particles based on the systematic modification of classical Stöber process parameters, without using surfactants or advanced techniques such as spray pyrolysis. By carefully tuning the reaction conditions, we first demonstrated that controlled nucleation and growth can occur in seed-free protocols, leading to highly uniform particles with tuneable diameters ranging from ~17 nm to ~800 nm. These particle variants were subsequently employed as seeds in further two-step seed-growth experiments, with fine-tuned precursor hydrolysis and condensation kinetics.

Further work will focus on optimizing the seed-assisted growth process to improve yield and reproducibility, aiming to establish a scalable route for the controlled production with potential applications in the development of advanced coating materials.

Introduction

The Stöber process is an effective and widely used method for preparing spherical silica nanoparticles, offering several advantages, including controllable particle size, high purity, and easy surface functionalisation. It relies on the controlled hydrolysis and condensation of tetraethyl orthosilicate (TEOS) in an ethanol medium, with water and ammonia acting as reagents. The particle size is governed by nonlinear interactions between sol-gel conditions and parameters, which affect hydrolysis, condensation, and subsequent particle growth [1,2]. Since its introduction, many studies have adapted this method by varying reagent concentrations and conditions to produce micron-sized silica particles. This kind of particles present several interesting engineering applications in coatings [3], catalysis [4] and as biomedical devices [5]. The approaches for their production typically rely on temperature regulation [6], the use of surfactants [7], and spray pyrolysis techniques [8,9], involving repeated addition, separation, and redispersion cycles. While effective, such methods are inherently more complex and less practical for straightforward or scalable synthesis.

The goal of this work is to develop a simple and reproducible strategy to obtain large, monodisperse, spherical silica particles with diameters exceeding 1 μm , without relying on advanced techniques or multiple separation and redispersion cycles. To this end, we initially designed and tested seed-free protocols,

which led to the formation of silica sub-micron particles. Further optimisation is still in progress to achieve even larger particle sizes in this seed-free approach. In parallel, the particles obtained from these current seed-free methods are being used as seeds in seed-assisted growth reactions to promote controlled particle growth beyond 1 μm . Although the formation of particles with a diameter above this threshold was successful, we are still addressing challenges associated with uncontrolled nucleation, low yield, interparticle bridging, and aggregation. Further optimization of these protocols remains ongoing, driven by the scientific and practical relevance of developing a reliable controlled synthesis of multi-micron-sized silica particles in a two-step method.

Materials and methods

Silica particles were synthesized via the Stöber process using TEOS (Thermo Fisher), ethanol, aqueous ammonia (25%), and distilled water. Reactions were conducted under magnetic stirring (350 rpm) at room temperature. After synthesis, samples were left to age for 24 hours and then purified by repeated centrifugation and redispersion in distilled water, followed by sonication. Three seed-free protocols were developed (see SI, SEED 2 and 3), of which:

- **SEED 1 (~882 nm):** 35 mL of ethanol, 3 mL of ammonia, and 0.5 mL of water were mixed and stirred for 30 min before the dropwise addition of a *FEED* solution (6 mL of ethanol and 2.5 mL of TEOS) using a syringe pump at a rate of 0.5 mL/h.

The particles obtained from seed-free syntheses were subsequently used as seeds for secondary growth reactions (see SI Protocol 3). In particular:

- **Protocol 1 (~818 nm):** The reaction mixture contained 35 mL of ethanol, 3 mL of ammonia, 250 μL of 146 nm particle suspension (see SI, SEED3), and 250 μL of water. After 30 min stirring, the *FEED* solution (the same as in SEED 1) was added at 0.5 mL/h.
- **Protocol 2 (~1449 nm):** 35 mL ethanol, 3 mL ammonia, and 1 mL of Protocol 1 were mixed, without additional water. After 30 min stirring, the *FEED* solution (the same as in SEED 1) was added at a rate of 0.5 mL/h.

Supporting information:

<https://www.zveza-zsis.si/2025/10/29/svet-strojnistva-akademija-strojnistva-2025-november-2025/>

Results and discussion

Seed-free synthesis of silica particles

The first stage of this study was focused on developing seed-free procedures to achieve controlled nucleation and growth of silica particles. By varying the ammonia concentration, suspensions of spherical silica with mean diameters of ~ 17 nm and ~ 146 nm were obtained (see Supplementary information), confirming that catalyst concentration directly governs particle size while maintaining good colloidal stability. Building on these results, in SEED 1, a controlled addition of TEOS via syringe pump enabled gradual hydrolysis and condensation, yielding uniform silica spheres with an average diameter of ~ 882 nm (Figure 1). The absence of secondary nucleation and the narrow size distribution indicate that the reaction kinetics were well controlled, favouring progressive particle growth, without the presence of seeds, surfactants, or advanced synthetic techniques. These findings demonstrate that simple tuning of ammonia content and TEOS feed rate enables the classical Stöber process to sustain particle growth at a sub-micron scale, providing a straightforward and reproducible high-yield route.

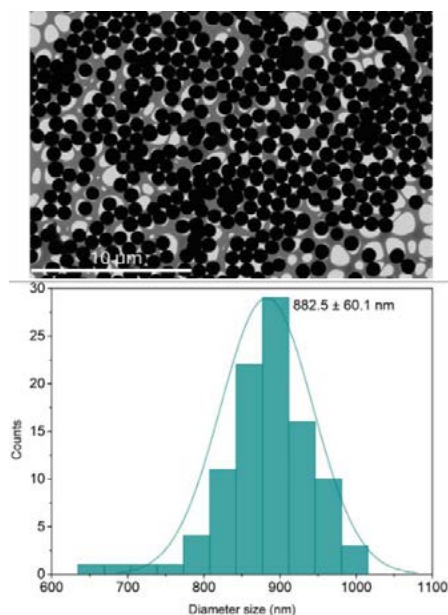


Figure 1: Top: STEM image of the spherical particles from SEED 1. Below: statistical size distribution of particles with average diameter and standard deviation.

Seed-supported growth

To demonstrate particle growth from the seeds, silica nanoparticles obtained from the initial seed-free procedures were employed as seeds in the second step, seed-supported growth. A series of systematic experiments was conducted, varying individual parameters of the Stöber process to isolate their respective effects on particle growth and stability. Under optimised conditions, Protocol 1 led to well-dispersed particles with uniform size, reaching ~ 818 nm, starting from seeds of ~ 146 nm (see SI, SEEDS 3), confirming the feasibility of controlled heterogeneous condensation and hence particle growth. In contrast, a Protocol 2 with seeds from SEED 1 yielded a bimodal size distribution, consisting of two particle populations with diameters of ~ 557 nm and $\sim 1.4 \mu\text{m}$ (see Figure 2). A similar bimodal distribution was observed in the particles obtained using Protocol 3, as reported in the

Supplementary Information. This outcome indicates that, alongside successful seed growth, new nucleation events occurred, likely driven by an excess of reactive hydrolysed TEOS species. These results demonstrate that a significant size increase can be achieved through seed-assisted strategies. The systematic variation of reaction parameters has provided valuable insight into the interplay between growth and nucleation, which will guide further optimization to achieve fully uniform multi-micron-sized silica spheres.

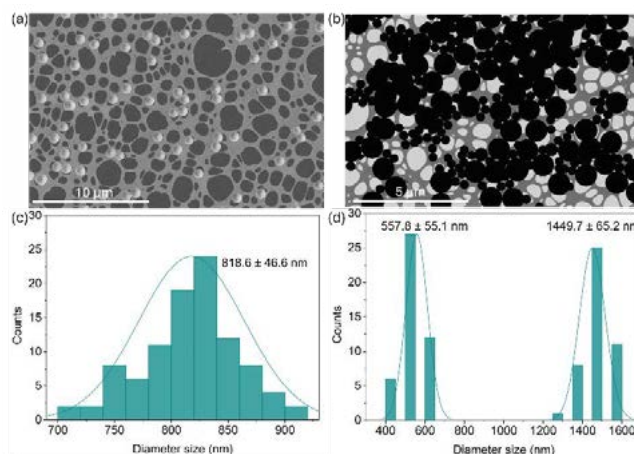


Figure 2: Panels (a) and (b): SEM-STEM images of the spherical particles from Protocol 1 and 2, respectively. Panels (c) and (d): statistical size distributions of particles with mean diameters and standard deviations from Protocol 1 (c) and Protocol 2 (d), respectively.

Conclusions

The obtained results illustrate a progressive understanding of silica particle formation, from seed-free nucleation to larger microspheres synthesized by seed-assisted growth, achieved without relying on advanced techniques or complex systems. In particular, the growth process was successfully optimized, yielding a particle diameter of $\sim 1.4 \mu\text{m}$. The work is still in progress, focusing on improving yield and preventing secondary nucleation and particle aggregation, to establish a robust and straightforward strategy for synthesising silica microspheres through the combined use of optimised seed-free and seed-assisted reactions.

SUPPLEMENTARY INFORMATION. Available at: <https://www.zveza-zsis.si/2025/11/10/svet-strojninstva-akademija-strojninstva-2025-november-2025/>

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Razvoj računskih orodij za napoved toplotnih obremenitev sten fuzijskih reaktorjev

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Ena glavnih omejitev pri razvoju fuzijskih reaktorjev je toplotna obremenitev prve stene reaktorja, specifično divertorja. Za izračun toplotnega toka moramo upoštevati geometrijo posode, konfiguracijo magnetnega polja in transportne lastnosti plazme. Razvili smo dve računski kodi, ki upoštevata 3D geometrijo posode in magnetnega polja ter gibanje delcev v plazmi vključno s ciklotronskim radijem. Koda smo uspešno validirali na realnih eksperimentalnih podatkih.

Uvod

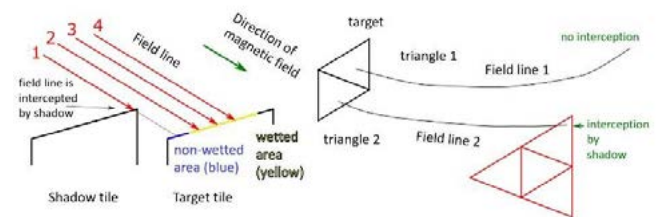
Uporaba reakcije zlivanja lahkih jeder za namen pridobivanja električne energije je eden od najobetavnejših pristopov k pridobivanju vremensko neodvisne čiste energije. Trenutno najnaprednejši tip fuzijskega reaktorja je t.i. "tokamak", ki je toroidalne oblike. Fuzijske reakcije potekajo pri zelo visokih temperaturah goriva, več kot 100 milijonov kelvinov, zato je gorivo v stanju plazme, ki jo zadržujemo s pomočjo magnetnega polja, saj zaradi Lorentzove sile nabiti delci plazme krožijo okoli magnetnih silnic. Silnice so znotraj reaktorja v večini sklenjene same vase. Ker zadrževanje ni popolno, del silnic "odpremo" neposredno na omejujočo steno reaktorja, saj imamo na ta način nadzorovan izpuh/izpust odvečne toplote in neželenih delcev. Temu delu reaktorja na dnu reaktorske posode, pravimo divertor. Magnetno polje v divertorju oklepa s površino zelo majhen kot, manj kot 5°, saj se na ta način toplotni tok razporedi po večji površini.

V sodobnem dizajnu divertorjev je površina sestavljena iz t.i. monoblokov, kvadrov čistega volframa, ki so nanizani na hladilne cevi skozi katere teče voda. Volfram je bil izbran kot najbolj obetaven material saj ima najvišje tališče med vsemi snovmi, čeprav ima sicer nekoliko slabše mehanske lastnosti ter ob eroziji z visokim atomskim številom Z precej vpliva na razmere v plazmi. Tak dizajn je bil vpeljan tudi za največji eksperimentalni fuzijski reaktor na svetu ITER (International Thermonuclear Experimental Reactor), ki je trenutno v gradnji na jugu Francije. Monobloki so v prevladujoči smeri magnetnega polja postavljeni tako, da glavna ploskev predhodnega monobloka ščiti vodilni rob oz. ploskev naslednjega monobloka. Na ta način se izognemo vpadu silnice magnetnega polja oz. delcev blizu normale na površino in posledično dvigu temperature in erozije na tej ploskvi. Pred časom je pri dizajnu prišlo do spoznanja, da ima na toplotne obremenitve velik vpliv tudi ciklotronski radij kroženja delcev okrog magnetnih silnic. Ciklotronski radij ionov je lahko namreč pri višji temperaturah dovoljšen, da omogoči ionom

preboj v razdelek med dvema monoblokoma. Rob takšnega monobloka postane termično precej bolj obremenjen, kar lahko v navezavi s slabšim hlajenjem robov rezultira v pregrevanju, rekristalizaciji in celo taljenju, kar za dolgotrajno obratovanje elektrarne ni zaželeno. V laboratoriju LeCAD se ukvarjamo z modeliranjem plazme in toplotnih procesov v stenah tokamakov in bomo v nadaljevanju predstavili dve računski orodji, ki smo ju razvili za te potrebe. Orodji sta namenjeni različni stopnji zajemanja detajlov.

Metoda sledenja silnicam (FLT)

Za grobo oceno gostote toplotnega toka je zadosti, če uporabimo metodo sledenja silnicam [2]. Površino divertorja pomrežimo s trikotno mrežo nato pa na podlagi predpisanega 3D zunanega magnetnega polja izračuna krivuljo silnice iz vsakega trikotnika navzven. Če silnica seka steno divertorja, štejeemo da je tak trikotnik v senci, kot prikazuje slika 1.



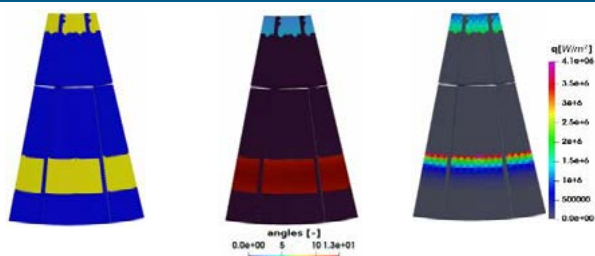
Slika 1: Shema metode FLT.

Če pa je silnica dovolj dolga, da pride do ekvatorialne ravnine tokamaka, potem je trikotnik omočen. Zdaj lahko s pomočjo projiciranja gostote toplotnega toka iz ekvatorialne ravnine na divertor izračunamo prostorsko odvisno toplotno obremenitev.

Pri izračunu krivulje silnic v prostoru uporabljamo metodo Runge-Kutta-Fehlberg (RKF45) z adaptivnim korakom. Za hitro iskanje preseka med silnicami in objekti v našem 3D modelu smo uporabili t.i. drevesni particijski k-d algoritem. Projekcijo gostote toplotnega toka q opravimo s sledečo enačbo:

$$q = \frac{F P_{loss}}{2\pi R_m \lambda_m B_{pm}} B \cdot N \cdot e^{\left(\frac{\psi - \psi_m}{\lambda_m R_m B_{pm}}\right)} \quad (1)$$

Primer izračuna z porabo naše FLT kode je podan na sliki 2. Razvita koda RIPTRACE je sposobna obravnave tako 3D CAD geometrije stene tokamaka, kot 3D magnetno polje, kar nam omogoča obravnavo problemov aksialne nesimetrije, npr. v tokamaku MAST-U, kot je prikazano na sliki 2.

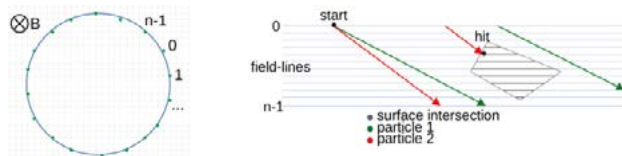


Slika 2: Izračun toplotnega toka v divertorju tokamaka MAST: omočenost stene (levo), vpadni kot silnic (sredina), gostota toplotnega toka (desno).

Balistična metoda izračunave trajektorij delcev

S sledenjem zgolj silnicam s kodo RIPTRACE ne moremo popisati problematike končne velikosti ciklotronskega radija, nam pa na hiter način poda porazdelitev gostote toplotnega toka po vsej površini tokamaka. Če želimo razvozlati problematiko dodatne obremenitve vodilnih robov monoblokov [3,4], moramo izračunati dejanske trajektorije delcev okrog magnetnih silnic.

V ta namen smo razvili kodo GYROHIT, ki je sposobna s statističnim pristopom ovrednotiti vpliv kroženja delcev okrog silnice. Pri izračunih se osredotočamo predvsem na prispevek ionov, saj imajo zaradi večje mase znatno večji ciklotronski radij, za elektrone pa lahko vzamemo kar optično aproksimacijo. Tudi tu izračunavamo trajektorije od tarče navzgor, vendar ne vse do ekvatorialne ravnine, saj je to računsko preveč potratno. Zanima nas le, če delec iz razdelka najde pot v prosto plazmo, kar ocenimo kot nekaj ciklotronskih radijev oddaljenosti od vrhne površine monobloka. Pristop izračunavanja od tarče navzgor prinese znatno boljše prostorsko resolucijo distribucije gostote toplotnega toka, v primerjavi npr. s kodo HEAT [5].



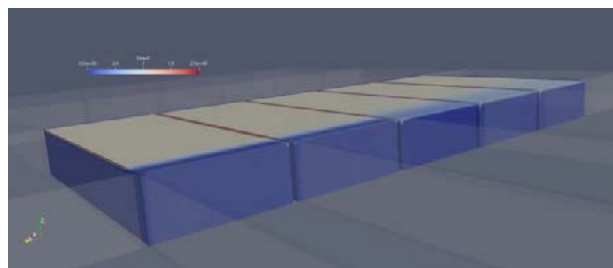
Slika 3: Shema iskanja preseka s steno v kodi GYROHIT.

V kodo lahko uvozimo poljubno CAD geometrijo, kar je zelo pomembno zaradi velike občutljivosti transporta delcev na ploskev od uspešnosti magnetnega senčenja. Delce vbrizgavamo po poljubni hitrostni porazdelitveni funkciji, od hladnejši plazem, do nestabilnosti ELM (Edge Localized Mode) tipa I, ki so najbolj kritičen primer obremenitve. Eksperimentalne vrednosti večinoma aproksimiramo z maksvelsko porazdelitvijo, premaknjeno za potencialni padec v plazemskem plašču.

To pot za iskanje preseka med trajektorijo delca in omejujočimi površinami nismo uporabili algoritma k-d particije, pač pa smo razvili lasten algoritem, ki temelji na funkcijskem preverjanju preseka med objekti in premicami, ki popisujejo ciklotronsko gibanje ob upoštevanju predpisanega koraka vzdolžnega gibanja in je predstavljen na sliki 3.

Tarčno geometrijo običajno opišemo z do 10^6 trikotniki, iz vsakega od trikotnikov pa pošljemo do 10^5 delcev iz izbrane porazdelitvene funkcije, kot npr. za tokamak WEST na sliki 4.

Koda je paralelizirana z uporabo knjižnic OpenMP, običajno izračun razdelimo na do 100 niti in poganjamo na 1 računskem vozlišču, tako da celoten izračun traja nekaj deset sekund.



Slika 4: Stopnjujoča obremenitev monoblokov s senčenjem za temperature $T_i=50-2000$ eV.

Koda je sposobna obravnave tudi zelo zahtevnih geometrij, kot je npr. ionski energijski analizator oz. RFA, ki smo ga nedavno vstavili v tokamak WEST. Pri tem nas zanima tudi prepustnost mrežic, ki odbijajo elektrone ter diskriminirajo ione v odvisnosti od njihove energije, kar je predstavljeno na sliki 5. Prepustnost je pomembna saj je ionski signal nizek z relativno slabim SNR, in mora zajemati signal skozi več velikostnih razredov ionskega toka.



Slika 5: Mreženje ionskega energijskega analizatorja (levo) in izračun prepustnosti mrežic (desno).

Zaključek

Uspešno smo razvili in validirali računski kodi RIPTRACE in GYROHIT, ki omogočata preračun toplotnih tokov na steno fuzijskega reaktorja. Kodi delujeta na različnih principih in na različnih stopnjah ločljivosti. RIPTRACE lahko učinkovito ugotovi omočenost površine s plazmo s pomočjo algoritma sledenja silnicam ter poveže toplotni tok na ekvatorialni ravnina tokamaka z obremenitvijo na divertorju. Koda GYROHIT pa je sposobna višje ločljivosti in obravnava posamezne monobloke ter upošteva končno velikost ciklotronskega polmera delcev v plazmi.

Acknowledgement

The authors acknowledge the financial support from the Slovenian Research Agency research through core funding P2-0405 (Fusion Technologies) and the project NC-25005 (Heat loads on tokamak divertors).

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Viscoelastic Properties and Surface Hardness of Bio-Based HDPE and Used Coloured HDPE Bottle Caps

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Bio-based HDPE polymer and two different used green and pink-coloured HDPE bottle caps were used in this study. The results show that the complex viscosities of the polymer melts decreased as the measuring temperature increased from 140 to 200 °C. The results obtained for the bio-based HDPE polymer differed significantly from those of the coloured bottle caps. The nanoindentation results showed that green coloured bottle caps exhibit the highest elastic modulus and hardness, while bio-based HDPE and pink coloured bottle caps had approximately 45% lower elastic modulus and 30% lower hardness values.

Introduction

Today, new environmentally sustainable polymers derived from natural and renewable sources (bio-based) are emerging as alternatives to traditional fossil-based polymers. In particular, polyethylene (PE), one of the most widely used thermoplastics in the world, can also be synthesised in bio-based form; however, it is currently produced only in small quantities. Although bio-based PE has similar mechanical properties to conventional PE, it is more environmentally friendly, with a lower CO₂ footprint than PE derived from fossil fuels. Bio-based PE is increasingly used in the packaging industry for bottles, films, containers, and caps [1].

Plastic bottle caps are among the five most common litter items found on beaches worldwide. It has also been shown that the pigments and additives used in bottle caps significantly affect environmental degradation caused by various factors such as UV irradiation, moisture, heat, and abrasion, leading to embrittlement and the formation of microplastics. Findings indicate that black or white pigmented plastic bottle caps can withstand over 30 years with relatively little environmental degradation, as carbon and titanium dioxide colourants provide good protection for the HDPE polymer against photolytic degradation. In contrast, red pigmented bottle caps showed significant degradation already after 3 years, followed by green and blue pigmented bottle caps. For the latter, it is presumed that the blue caps decompose into microplastics after 20 years. Pigments that exhibit low UV absorption do not protect the polymer from UV radiation, resulting in faster degradation and consequently production of microplastics [2].

The bio-based HDPE polymer has a melting temperature of 130.7 °C and a degree of crystallinity of 63.6%. Typically, the temperatures used for the extrusion process of HDPE are above 180 °C and up to 230 °C, depending on the polymerisation and additives used. PE polymers have long linear chains with long or short branches and varied molecular weight and molar weight distribution, which can affect its

density, properties, and rheological behaviour in its molten state. It was observed that by blending of different PE polymers, even small amounts of high molecular weight fraction can lead to flow anomalies that negatively impact final polymer properties [3]. Therefore, to properly assess the polymer behaviour during processing, rheological tests must be performed in the molten state, above melting temperature (T_m).

The surface characterisation using the nanoindentation technique was performed on HDPE plaque samples before and after four weeks of simulated solar exposure (according to ISO 4892 cycle 4). The study performed by Zhang et al. [4] showed that the increase in elastic modulus is smaller when HDPE polymer density is higher. The modulus increases after exposure from 1.97 GPa to 2.94 GPa. A faster increase in the modulus suggests that the polymer is becoming more brittle, due to photooxidation affecting the crystalline regions of the polymer. This trend was significantly more pronounced in linear low-density polyethylene (LLDPE) compared to high-density polyethylene (HDPE).

The aim of this research was to determine the viscoelastic properties of bio-based HDPE and two different types of used coloured HDPE bottle caps at various temperatures between 140 and 200 °C. Since various pigments and additives are used in the production of bottle caps, understanding their rheological properties is very important, especially if the bottle caps are to be recycled after use. In addition, nanoindentation measurements were conducted to determine the elastic modulus and hardness of the bio-based HDPE polymer and the surfaces of the used bottle caps.

Materials and methods

In our study, we used commercially available bio-based high-density polyethylene (HDPE) from Braskem Idesa without additives. For comparison, we also used green and pink-coloured HDPE bottle caps obtained from Radenska and Lissa bottled water.

The viscoelastic properties of polymer melt samples were measured using an Anton Paar MCR302 (Anton Paar, Graz, Austria) rheometer, equipped with a plate-plate sensor system (PP 25) and 1 mm measuring gap. Frequency tests were carried out at $\tau = 1$ MPa (within the LVR) by decreasing the frequency from 100 to 0.01 Hz. All rheological measurements were performed at four different temperatures i.e. 140, 160, 180 and 200 °C.

The hardness and elastic modulus of the surface of the used bottle caps and bio-HDPE disc shaped samples, prepared by injection moulding process (Xplore IM12 micro injector, Xplore Instruments) to obtain a smooth surface (injection moulding parameters: $T_{melt}=190$ °C, $T_{mould}=50$ °C, $P_1=8$ MPa, $t_1=10$ s, $P_2=10$ MPa, $t_2=10$ s) were determined from

nanindentation measurements carried out with an Agilent (USA) G200 XP nanoindenter equipped with a standard three-sided pyramidal Berkovich probe. For each sample, 40 indents were made to a depth of 4000 nm, and the average value from 1000 to 4000 nm depth was used for data analysis.

Results and discussion

The viscoelastic properties such as storage modulus (G') and loss modulus (G''), as a function of the frequency (f) of characterised polymer melts were determined at four constant temperatures (Figure 1). The results indicate that for all samples at lower frequencies, viscous effects dominate and the materials behave like a liquid. At higher frequencies, elastic effects prevail ($G' > G''$), and the polymer behaves more like a solid, which is typical for molten polymers. Moreover, for bio-based HDPE polymer at 140 and 160 °C, at frequencies below 0.1 Hz, the storage modulus (G') shows a plateau, indicating that the linear polymer molecules are entangled indicating stability of the polymer.

The crossover point in dynamic oscillatory measurements provides information about the molecular weight, molecular weight distribution, and molecular mobility of the polymer. The crossover frequency (ω_{CO}), defined as the point where the storage and loss moduli intersect ($G' = G''$), is inversely proportional to the longest relaxation time. This is because polymer chains can move more freely as the temperature increases, which accelerates relaxation processes. The time required for the polymer to respond to stress decreases, so the material behaves more fluid-like at higher frequencies. Consequently, the ω_{CO} of bio-based HDPE polymer increases from approximately 44 to 100 Hz as the melt temperature is increased from 140 to 180 °C, while at higher temperatures, no cross-over point has been observed. In contrast, the ω_{CO} of coloured bottle caps increases with increasing temperature slower than for bio-based HDPE polymer, yet the increase is for both samples show almost the same values from ~13.2 to ~43.1 Hz, respectively (Fig. 1D).

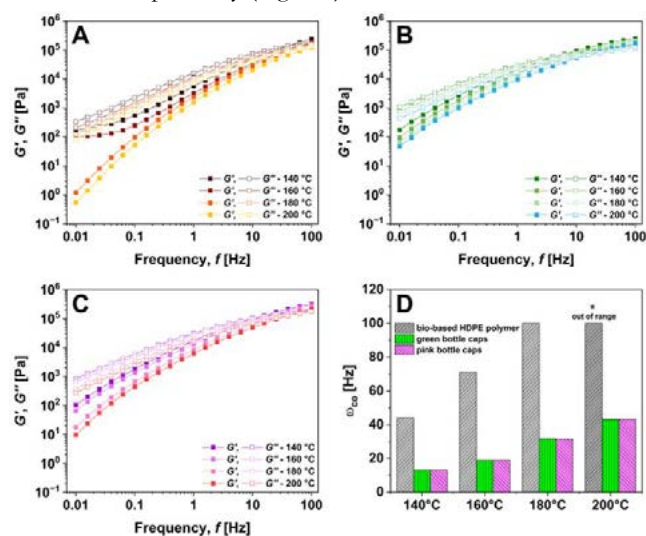


Figure 1: Storage (G') and loss (G'') modulus as a function of frequency (f) for: A) bio-based HDPE polymer, B) green and C) pink bottle caps and D) cross-over frequencies at different temperatures.

Figure 2 presents the complex viscosities (η^*) determined at $f = 0.01$ Hz for different temperatures. The highest η^* values were observed at the lowest measured temperature (140 °C), as the elastic component becomes more pronounced, restricting the movement of polymer chains and consequently increasing the complex viscosity. The highest η^* values were obtained for green bottle caps compared to pink bottle caps, while η^* values for bio-based HDPE were half a decade lower at all measured temperatures.

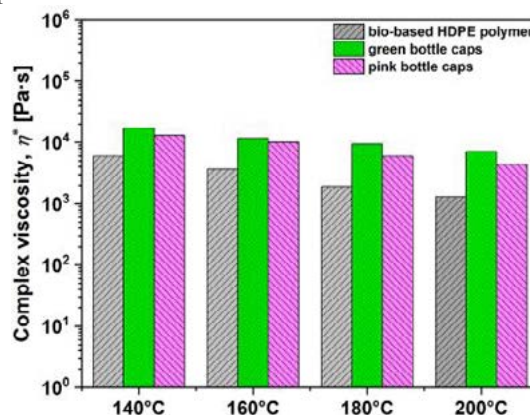


Figure 2: a) Complex viscosity (η^*) determined at $f = 0.01$ Hz for bio-based HDPE polymer, green and pink bottle caps at different temperatures.

Nanoindentation is a versatile technique used to investigate the surface mechanical properties of a wide range of materials. The surface of bottle caps should provide protection while remaining flexible enough to allow easy opening of polymer water bottles. The results show that the elastic modulus (E) and surface hardness (H) are the highest for green bottle caps, 1.72 ± 0.15 GPa and 0.063 ± 0.012 GPa, respectively. The surface of pink bottle caps and bio-based HDPE polymer showed significantly lower, but similar, E and H values ($E = 1.20 \pm 0.03$ GPa and $H = 0.036 \pm 0.001$ GPa). In addition, a high H/E ratio suggests that a greater load is needed to deform the surface of the sample, indicating the improvement of wear resistance. The highest H/E ratio of 0.035 was observed for green bottle caps, at measuring depth of 4 μ m, it was higher by 20.3% and 16.3% than that of bio-based HDPE and pink bottle caps, respectively.

Conclusions

The results of viscoelastic behaviour in the melt showed that bio-based HDPE behaves differently from the green and pink-coloured bottle caps. The nanoindentation results showed that green coloured bottle caps provide better wear protection and consequently less degradation of microparticles. In addition, the rheological and mechanical changes in coloured bottle caps can be ascribed to the use of different pigments and/or additives in their production.

ACKNOWLEDGEMENTS. This research was funded by Slovenian Research Agency: grant number P2-0264.

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Segment zaščitnega panela z odzivno geometrijo in samopopravljivimi lastnostmi

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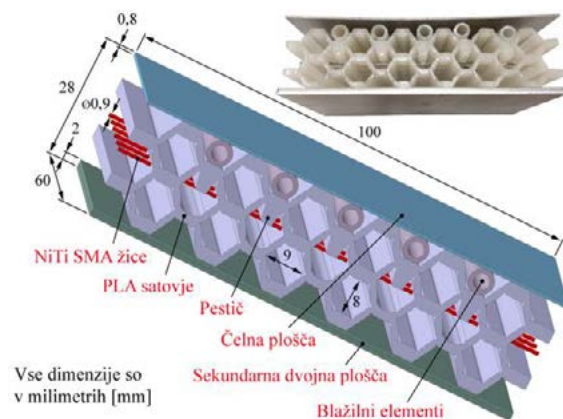
Prispevek obravnava zasnovo ultralahkega segmenta zaščitnega panela. Sestavljen je iz kombinacije tankih jeklenih čelnih pločevin, 3D-tiskanega satovja, izdelanega iz polimlečne kisline (PLA) ter osrednje armature iz NiTi-zlitine z oblikovnim spominom SMA (*shape memory alloys*), ki omogoča regeneracijo strukture po prizadejani poškodbi. Struktura temelji na konceptu izkoriščanja dinamičnih lastnosti materialov, zasnovanih za učinkovito prestrezanje srednje hitrih izstrelkov in letečih fragmentov (do 50 m/s). V eksperimentalnem preizkusu je segment panela uspešno zaustavil letečo jekleno kroglo kalibra $\varnothing 16$ mm, kar potrjuje njegov potencial za uporabo v naprednih zaščitnih aplikacijah.

Uvod

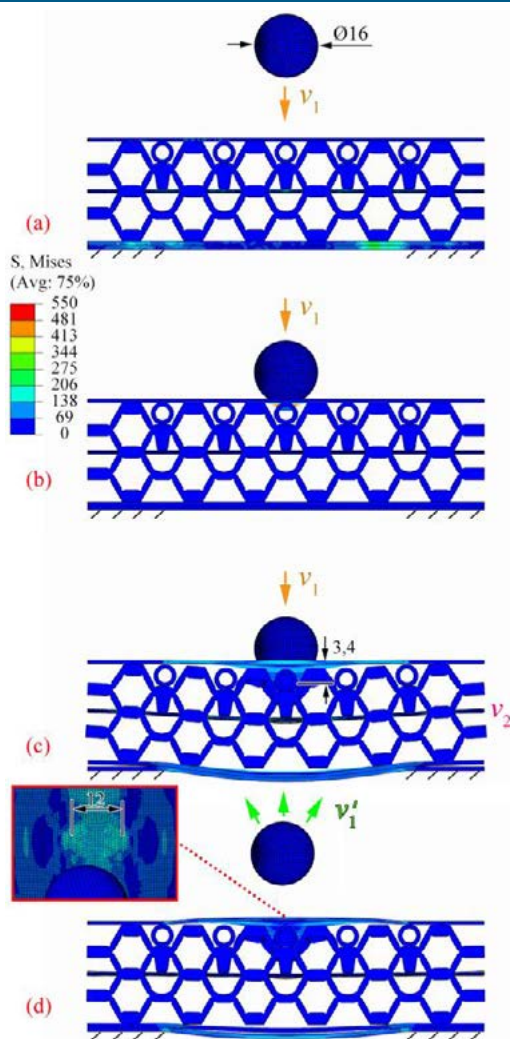
Klasične zaščitne strukture temeljijo na masivnih oplatah visoke gostote, kot so jeklene plošče, kjer kinetično energijo izstrelka prevzame predvsem masa in trdnost materiala [1]. Naprednejši sistemi, kot so keramični in kombinirani oklepi, združujejo materiale z različnimi mehanskimi lastnostmi ter tako dosegajo učinkovitejšo disipacijo energije ob nižji skupni masi, vendar so precej togi in posledično tudi bolj krhki. Novejše raziskave se vse bolj usmerjajo v razvoj lahkih zaščitnih panelov s celično oziroma satasto strukturo, kjer energijo udarca ne absorbira masa, temveč kontrolirana deformacija geometrije. Tak pristop omogoča učinkovito disipacijo energije ob minimalni masi na enoto volumna strukture ter predstavlja obetavno alternativo klasičnim gostim oklepom. V nadaljevanju predstavljeni koncept razvoja zaščitne strukture temelji na disipaciji energije znotraj celične strukture sataste oblike, ki se ob udarcu kontrolirano deformira in s tem porablja kinetično energijo izstrelka. Ključna novost pri tem je integracija mehanizma samoobnavljanja v kompozit, ki se sproži naknadno z aktivacijo nikelj-titanovih žic (NiTi) z oblikovnim spominom (SMA). Sama ideja je nastala na osnovi naših preteklih raziskav [2,3] o delovanju aktivacijskih mehanizmov prilagodljivih struktur, kjer so se proučevali različni pristopi transformacij strukturnih celic pod obremenitvijo. Za omogočanje regeneracije po poškodbi je satovje oblikovano tako, da na mestih največjih upogibnih razponov žic tvori posebne pestiče, ki ob trku letečega delca (npr. izstreljene krogle) reakcijsko pritisnejo na vgrajeno NiTi-SMA armaturo [4]. Ta se pod obremenitvijo kontrolirano upogne in s tem prevzame tudi del udarne energije, predvsem pa se naknadno ob segrevanju povrne v prvotno izravnano obliko. S tem se lahko ponovno vzpostavi začetna geometrija celične matrice, kar omogoča polno ali vsaj delno regeneracijo poškodovanega kompozita ter ponovno vzpostavitev njegove funkcionalnosti pri morebitnem naslednjem prestrezanju udarcev.

Zasnova fleksibilnega kompozita z SMA žicami

V izhodišče so bili postavljeni glavni cilji razvoja lahke in mehansko učinkovite zaščitne strukture, namenjene prestrezanju udarcev in letečih fragmentov, pri čemer je bila v zasnovo hkrati vključena funkcija samoobnavljanja, dosežena z uporabo NiTi-žic z oblikovnim spominom (SMA). Delovanje zasnove temelji na sestavljeni konfiguraciji, kjer tanka (0,8 mm) trda vrhnja plošča iz konstrukcijskega jekla S235, izbranega zaradi ustrezne mehanske zmogljivosti in ugodne cene, sprejme udarec in prenese obremenitev naprej na satasto jedro iz PLA, kot je prikazano na sliki 1. To jedro se kontrolirano deformira in s tem disipira energijo udarca. Na zadnji strani zaščitnega segmenta je nameščena sekundarna dvojna plošča, prav tako iz jekla S235, ki služi kot podloga in podporni sloj za namestitev celotnega zaščitnega elementa. Znotraj satastega jedra so oblikovani pestiči, ki ob udarnem obremenjevanju načrtovano deformirajo vgrajene SMA-žice. Med pestiči in čelno ploščo so vstavljeni še blažilni elementi (cevke), ki posredujejo mehansko energijo v satasto strukturo in s tem povečajo učinkovitost disipacije. SMA-žice se pri tem pasivno deformirajo kot posledica lokalnega preoblikovanja, po segrevanju pa se aktivno povrnejo v prvotno obliko, kar zagotavlja regenerativne lastnosti kompozita in njegovo pripravljenost na naslednjo udarno obremenitev. Geometrija je bila najprej oblikovana v AutoCAD-u, nato modelirana v CATIA V5, analiza udarnega odziva pa izvedena z ABAQUS-om 2024. Cilj je bil razviti eksperimentalno podprt in kalibriran numerični model, ki bo služil za zanesljivo napoved mehanskega odziva ter razvoj novih učinkovitih vrst zaščitnih struktur. Simulacija streljanja, izvedena na osnovi metode končnih elementov (MKE), je prikazana na sliki 2. Uporabljena hitrost izstrelka $v_1 = 46$ m/s je ustrezala kasnejšemu preizkusu s pnevmatskim topom kalibra $\varnothing 16$ mm, kjer je bil preizkušanec bočno vpet 20 mm globoko, z aktivno površino 60×60 mm, skladno s standardoma ASTM D5420 in D3763.



Slika 1: Sestav ultralahkega segmenta zaščitnega panela z načrtovanimi naknadnimi samopopravljivimi lastnostmi.



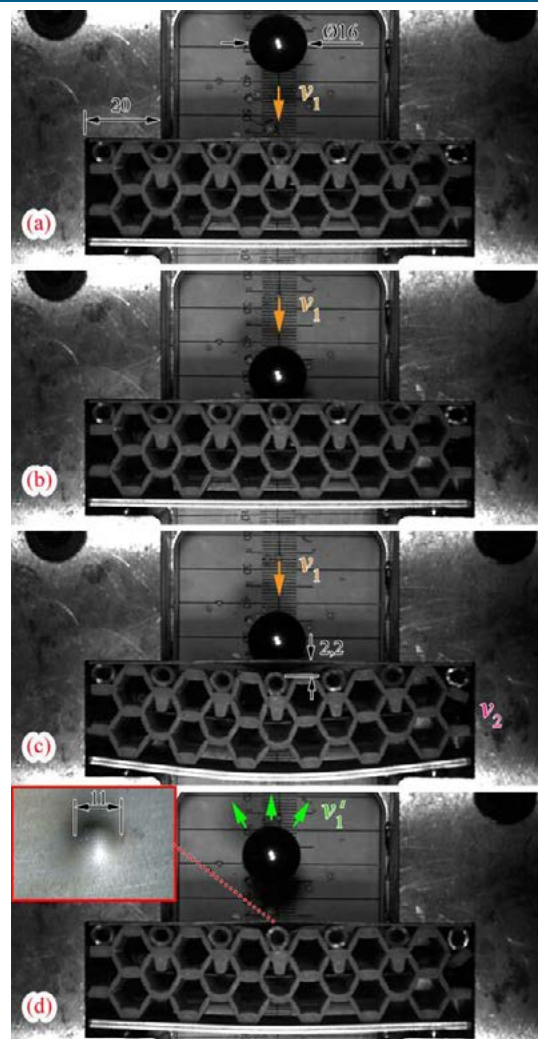
Slika 2: Simulacija zaščitnega efekta segmenta panela s prikazi: a) prileta krogle s hitrostjo v_1 , b) dotika in c) vtiska v strukturo ter d) končnega odboja krogle s hitrostjo v'_1 .

Rezultati in diskusija

Sliki 2 in 3 prikazujeta primerjavo simulacije in realnega rezultata prestrežanja leteče krogle. Iz razmerja hitrosti prileta krogle ($v_1 = 46$ m/s) in njene hitrosti po odboju ($v'_1 = 2$ m/s), lahko z izračunom po enačbi (1) ugotovimo, da gre za izrazito plastični odboj ($e \approx 0$), z veliko disipacijo energije. Specifična absorbirana energija (SEA) zaščitne strukture pri tem znaša 50 J/kg. Ker je panel med testom miroval, velja $v_2 = v'_2 = 0$ m/s.

$$e = \frac{v'_2 - v'_1}{v_1 - v_2} = \frac{2}{46} = 0,043 \quad (1)$$

Iz testov in simulacij je razviden zelo skladen odziv zaščitne strukture, s podobnim razmerjem koeficienta restitucije e . Krogla povzroči pri realnem testu le manjšo lokalno vdolbino v čelni pločevini $\phi 11$ mm in globino vtiska 2,2 mm, medtem ko je pri simulaciji zaznan vtisek $\phi 12$ mm globine 3,4 mm. V globljih slojih strukture ni bilo zaznanih lomov PLA, temveč le kontrolirana deformacija nekaj stisnjenih celic satovja, ki se poravnajo, če strukturo segrejemo na 50 °C, ker takrat aktiviramo NiTi SMA material žic z oblikovnim spominom. Struktura kaže dober tako zaščitni kot regeneracijski efekt. Glede na zaznano stopnjo poškodbe ima potencial za učinkovito prestrežanje tudi pri večjih hitrostih izstrelkov.



Slika 3: Eksperimentalni preizkus zaščitnega efekta segmenta panela s prikazi: a) prileta krogle s hitrostjo v_1 , b) dotika in c) vtiska v strukturo ter d) končnega odboja krogle s hitrostjo v'_1 .

Zaključki

Iz doseženih rezultatov lahko strnemo naslednje ugotovitve:

- Zasnova učinkovito absorbira udarno energijo pri nizki masi
- Dosežena je dobra skladnost med simulacijami in eksperimentalnimi testi. Simulacije kažejo nekoliko konzervativnejše rezultate z večjo poškodbo, kar pomeni napovedi na varni strani z dodatnim zaščitnim potencialom.
- V prihodnje je predviden preizkus uporabe kevlarja namesto pločevine ter nadgradnja satovja z dodatnimi plastmi celic in SMA-armaturo žic v dveh ravninah za večji zaščitni učinek.

ZAHVALA

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Examination of thermo-mechanical properties of TPU based MWCNT nanocomposites

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Evaluating the thermo-mechanical performance of a nanocomposite is crucial for its potential applications in flexible sensing. In the present study, TPU and TPU/MWCNT samples of varying compositions were produced by melt processing and characterized for their thermo-mechanical properties using dynamic scanning calorimetry and dynamic mechanical analysis. The results showed that TPU has a unique block structure, where blocks separate into microphases with different thermal properties. The material further showed increased polymer chain mobility upon glass transition, visible by the Gibb's free energy released by the chains. Finally, both characterisation methods showed that glass transition temperature and improved thermo-mechanical stability are highly dependent on the MWCNT concentration. Moreover, it was shown that the existence of fully established MWCNT network is a pre-requisite for noticeable performance improvements.

Introduction

The usage of thermoplastic polyurethane (TPU) has increased significantly in the last decade, especially in flexible sensing as a polymer base for nanocomposite sensing materials. The advantages of using TPU flexible sensing come from the ease of processing (similar to thermoplastics), as well as the structure created in the polymer post cooling (similar to elastomers). Therefore, the material obtains higher flexibility, combined with ease of processing [1].

The favourable properties of TPU are inherently linked to its structure. The polymer is made up of hard segments (HS) and soft segments (SS), which act as distinct microphases in the bulk material. SS represent the main polymer chains, while HS are shorter chains that connect the SS phases into a distinct, quasi-elastomeric structure upon solidification. Moreover, the inclusion of different nanofillers, such as multi-walled carbon nanotubes (MWCNTs), greatly improves the polymer's thermo-mechanical and electrical performance [1, 2].

In this work, pure TPU and TPU/MWCNT samples were produced via a melt processing method, and final shapes were obtained via injection moulding. Afterwards, the thermo-mechanical properties of the samples were examined, to connect the materials' thermal performance to their structure.

Materials and methods

Thermoplastic polyurethane pellets (Desmopan 9370AU, Covestro AG, Germany) were used in subsequent processing steps. The polymer had a producer-specified density of 1.06

g/cm³, Shore hardness A of 70, and melt flow rate of 45 cm³/10 min at 190 °C. TPU/MWCNT masterbatch with 10 % wt. MWCNT (Nanocyl, Belgium) was used as nanofiller. The masterbatch had a producer-specified density of 1.06 g/cm³, and melting point of 122 °C.

The sample production consisted of two steps: melt compounding, followed by injection moulding. Granule batch weights were carefully weighted (precision balance WTC 2000, Radwag, Poland), and further pre-dried, to remove surface moisture, at a temperature of 60 °C for 8 hours in a nitrous atmosphere (furnace SP-190 C, Kambič, Slovenia). The granules were then compounded (twin-screw micro compounder MC-15, Xplore Instruments, the Netherlands), with a batch capacity of 15 mL, in co-rotating mode. The compounding temperature was set to 210°C, and screw speed of 25 rpms. First, TPU was mixed for 5 min at screw speed of 50 rpm. After that the masterbatch was added and additionally mixed for 5 min at 75 rpm. Injection moulding was used to obtain the final sample shape, with melt temperature of 210°C, mould temperature of 60°C and pressures below 9 bar. The samples used in further characterisation were rectangular (dimensions 60 mm x 10 mm x 1 mm).

Calorimetric analysis was performed (differential scanning calorimeter DSC2500, TA Instruments, USA) in temperature range from -90 to 250 °C, with a heating/cooling rate of 10 K/min under an inert (nitrogen) atmosphere. For evaluation, the results of 2nd heating were observed.

Thermo-mechanical stability analysis (dynamic mechanical analyser MCR 702, Anton Paar, Austria) was conducted using temperature sweep tests. The tests were performed in extension mode of loading, in temperature range from 0 to 60°C, with a heating rate of 3 °C/min, at fixed frequency of 1 Hz and strain levels within the LVE domain (preliminary determined by amplitude sweep tests).

All results presented show an average of three repetitions. The error bars, where applicable, show the maximum deviation from the corresponding average value presented in the figure.

Results and discussion

The dataset of the obtained thermograms via DSC for the temperature range between 0 and 60 °C is shown in comparison to the temperature sweep obtained via DMA, Fig. 1. From the thermogram, it can be noticed that a sharp, endothermal peak is visible at a temperature $T \approx 20$ °C. Such transitions, when observed through DSC, are commonly associated with melting of crystalline polymers [3], suggesting that TPU has a semicrystalline structure. In order to specify the behaviour of the polymer in this range, dynamic mechanical analysis (DMA) was performed as the polymer loses its integrity at higher temperatures.

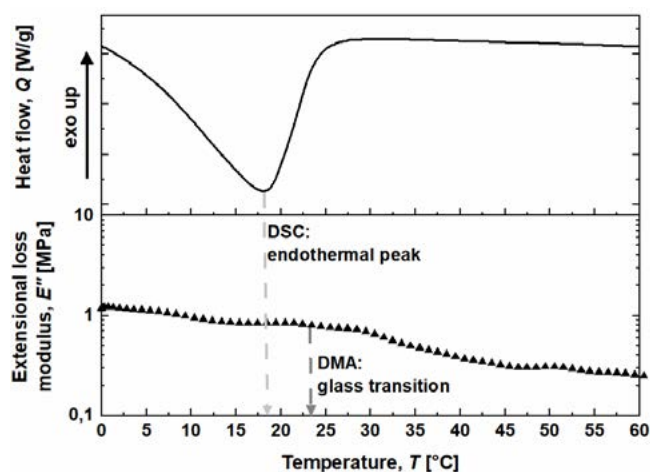


Figure 1: DSC thermogram (top graph) compared to a DMA temperature sweep (bottom graph) for pure TPU in measurement temperature range of 0-60 °C.

Based on the dataset for the extensional loss modulus (E''), Fig. 1, it can be noted that a maximum in the temperature sweep of E'' is visible at $T \approx 25$ °C. Such maximum, correlating to a drop in the value of the corresponding extensional storage modulus (E') for the same temperature range, suggests the presence of glass transition in the material. When such transition occurs in a polymer, an increase in mobility of polymer chains is visible, as the polymer's mechanical properties shift significantly, leading to mechanical destabilisation [4].

Based on the data provided, it can be summarised that the thermal transitions recorded with both methods can be characterised as glass transitions, as they occur at a similar temperature. Moreover, expanded calorimetric analyses of the same material [2] have shown that two distinct glass transitions occur in TPU, relating them to TPU's soft segments (SS) and hard segments (HS), respectively. Moreover, it has been pointed out in previous literature [2] that TPU has a specific structure with distinct amorphous SS and HS microphases, solidifying at different temperatures. The sharp endothermic peak in this study has been discussed and being equally characterised as glass transition with Gibb's free energy of the segments noted as the reason of the sharp peak.

Glass transition data, determined from both methods, were analysed also for TPU based MWCNT nanocomposites, Fig. 2, where it is clear that glass transition temperature (T_g) increases with the addition of MWCNTs. This increase suggests that the added filler influences the thermal properties, and with that, the mechanical stability of TPU.

The significant increases in T_g , Fig. 2, were recorded at $\phi_{V,crit}^{CP} \approx 1\%$. In accordance with [1], where it was shown that nanocomposite performance have a direct correlation with the CNT network that is established in the polymer matrix, it can be concluded that this upward shift can also be attributed to already established MWCNT networks. This signifies that finalised MWCNT network formation leads to improvements in glass transition temperatures, and with that, increased mechanical stability of the material.

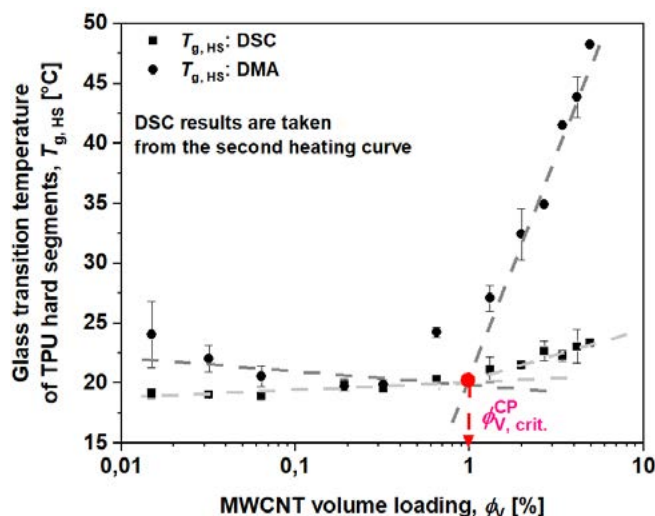


Figure 2: Glass transition temperatures recorded via DSC (squares) and DMA (circles) as a function of MWCNT volume loading. The dataset obtained via DSC was determined from the second heating curve, while the DMA dataset was calculated according to DIN 65583 [4].

Finally, it can be noted that the rates of change of T_g as characterised by the two methods, are very distinct. This can be attributed to the different conditions of the methods used. Namely, the temperature transitions recorded via DSC stem from the recorded heat output of the sample, occurring prior to and during glass transition. The temperature transitions observed through DMA, on the other hand, are an indirect calculation, based on the change of mechanical properties (i.e., extensional storage modulus, extensional loss modulus) over a certain temperature range, and therefore show the change in properties, which occurs after the actual energy exchange of the glass transition process [3].

Conclusions

In this study, it was shown that the thermal performance is highly dependent on the structure of TPU. The polymer's building blocks separate into microphases with separate glass transitions, which possess a high value of Gibb's free energy, greatly increasing chain mobility upon glass transition. Furthermore, the mechanical stability of the TPU/MWCNT nanocomposites increases with the addition of MWCNTs, however, a crucial component for the increase is the finalised MWCNT network formation (network establishment), which for this system occurs at $\phi_{V,crit}^{CP} \approx 1\%$.

ACKNOWLEDGEMENTS. The presented research was supported by funding provided by the Slovenian Research and Innovation Agency (ARIS), grant no. P2-0264.

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The influence of a signal jammer on UAV navigation

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The increasing occurrence of GNSS interference represents a growing threat to aviation safety and unmanned aerial vehicles (UAV). This study investigates the influence of a signal jammer on UAV navigation under controlled flight conditions. A quadcopter equipped with dual-source navigation (GNSS and inertial reference system) was tested at different altitudes, and the number of connected satellites was analysed using Mission Planner software. Results show a clear correlation between jammer proximity and the reduction in satellite visibility, which directly affects navigation accuracy. The presented findings provide an empirical basis for developing interference detection and mitigation strategies in small UAV systems.

Introduction

Global Navigation Satellite Systems (GNSS) provide essential positioning data for modern aviation. Their precision and reliability are crucial for safe operation, route tracking, and autonomous flight control. However, intentional interference, or jamming, has become increasingly common, particularly in conflict zones and in regions of high military activity. Civilian aviation and UAV operations are unintentionally affected, resulting in positional uncertainty, control loss, or complete signal denial [1,2].

Previous studies have analysed GNSS jamming effects primarily in military or controlled environments, focusing on frequency disruption and loss of service. Recent reports emphasize the need for empirical data from real UAV operations, where dynamic flight conditions and altitude changes can significantly alter signal quality [2]. This research aims to experimentally evaluate how GNSS signal jamming impacts the number of tracked satellites and positional accuracy in UAV operations.

Materials and methods

Tests were conducted on an open field without physical obstructions that could interfere with signal propagation. A UAV equipped with a Here 4 GNSS module [CubePilot Global Pty Ltd., Vic, Australia] and an open-source autopilot Cube Orange+ [CubePilot Global Pty Ltd., Vic, Australia] system shown on figure 1 was used. The Here 4 receiver can track multiple GNSS constellations (BeiDou, Galileo, GLONASS, GPS) on L1 (1575.42 MHz) and L5 (1176.00 MHz) bands. The Cube Orange+ also functions as an Inertial Management Unit (IMU) with triple accelerometers, gyroscopes, redundant barometers, and a magnetometer for high-precision navigation.

The jammer used was a Skyner Raptor SJ jammer operating at 900 MHz, 1.5 GHz, 2.4 GHz, 5.2 GHz, and 5.8 GHz bands, delivering ~20 W of power into each ~20 MHz wide band. The operating regime was set to GNSS jamming. It jams the drone's GNSS receiver by overpowering the GPS satellite signal, so that it can no longer operate. It supports combined narrow band low-power precision jamming and wide band high-power jamming. Jammer can detect and position UAVs at a distance of over 3 km and jam them at a distance of over 2 km [9]. Jammer was positioned approximately two meters above ground and directed in a fixed direction across the field and parallel to the ground (as shown with the red arrow in figure 2). The UAV was

flown to different locations, where it loitered while jamming was in progress. Each jamming event lasted 10 seconds. Different altitudes were chosen, to assess the influence of the jammer in 3 planes. The UAV was tested at altitudes of 5 m, 60 m, and 120 m, moving horizontally in the rows across the jammer's field. Flights were interrupted when the batteries needed to be replaced. After the replacement, the next location was measured.

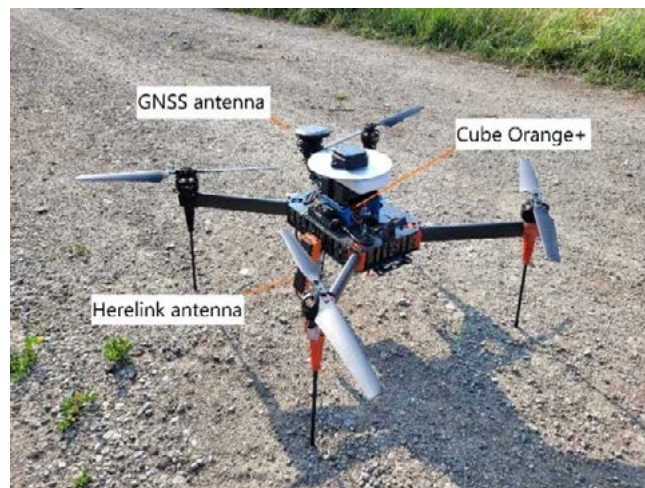


Figure 1: Custom built UAV, with GNSS and IMU positioning capabilities Here 4 RTK GNSS module, open-source autopilot Cube Orange+ and Herelink telemetry and video transmission module.

GNSS telemetry was recorded through the Mission Planner interface [10]. Parameters such as number of satellites (NSat), horizontal dilution of precision (HDop), and positional accuracy (HAcc) were analysed. While the first two parameters are dimensionless, the third parameter, HAcc, describes the expected radius of a circle in meters within which the GNSS receiver estimates the true position of the UAV is. A larger value indicates greater uncertainty.

Results and discussion

Presented partial results of the measurement campaign, show the impact of a GPS jammer on a drone's ability to navigate at an altitude of 60 m above ground level.

The recorded data confirmed a strong influence of the jammer on satellite availability, especially in the vicinity of the jammer as shown in figure 2. As expected, a significant drop in the number of visible satellites was observed during active interference when the UAV was within the jammer's line of sight. Apart from the locations which were aligned to the orientation of the jammer, location with the reduction of 9 satellites show the maximum value at this altitude. This could be due to the leakage of the jamming signal in other directions, or due to the misalignment of the jammer for that measurement. Along with the drop of connected satellites in the jamming event, the HDop value increased correspondingly, indicating deteriorated positional geometry and reduced accuracy. Once the jammer was deactivated, the system gradually restored full satellite connectivity. Interestingly however, the number of connected satellites never fell below 23, indicating that the GNSS positioning was still possible.

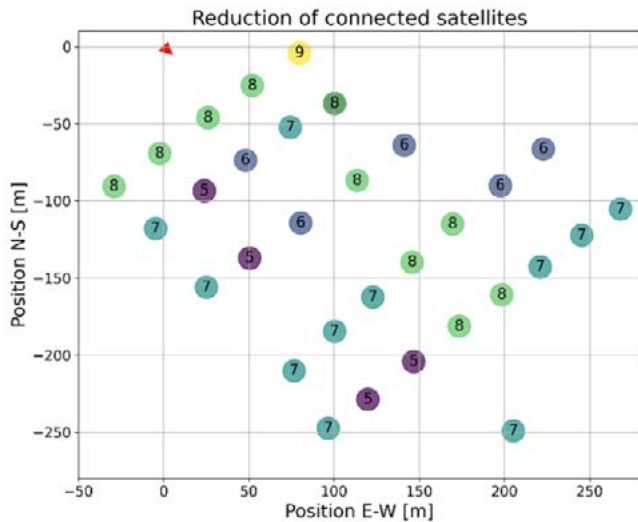


Figure 2: Measured reduction of number of connected satellites with the GNSS jamming at 60 m altitude AGL, depending on the location of the UAV. Numbers within the bubbles represent the reduction in the number of connected satellites. Position is measured from the jammer location, shown with a red arrow, which was at 45.9662510 N and 14.5521745 S.

The reduction in the number of connected satellites was affected by the altitude. While the average reduction at 5 m was 33 %, this percentage declined to 25 % at 120 m, indicating that more power is required at higher altitudes to achieve the same results.

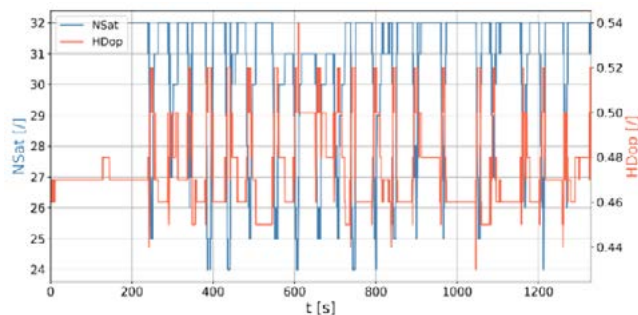


Figure 3: HDop parameter and number of connected satellites at 60 m altitude AGL in a single battery flight with multiple jamming events at different locations.

Figure 3 shows how HDop changed in comparison to the value of NSat at the time of jamming events. Initially, the HDop value changed due to the stabilization of the system, while subsequent changes (after 200 s) replicate the movement of NSat. For every decrease in NSat, there is an increase in HDop, indicating less favourable satellite dispersion through the sky, and vice versa. Although this parameter increased, it remained below value of one, which still indicates excellent conditions.

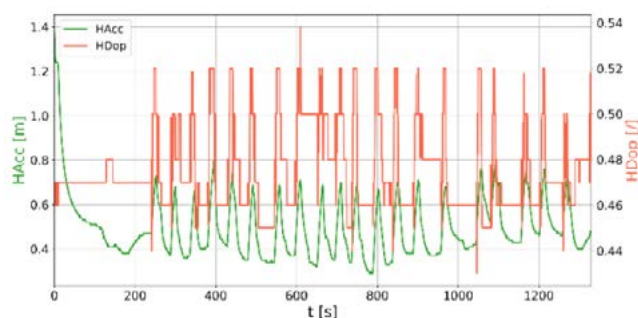


Figure 4: HAcc and HDop parameters at 60 m altitude AGL in a single battery flight with multiple jamming events at different locations.

Figure 4 shows the measurement of the HAcc and HDop values. An increase in HDop also results in an increase in the HAcc value because, with fewer satellites for navigation which results in them being less dispersed though the sky, the ability of GNSS receiver to precisely calculate a UAV's true position deteriorates. As illustrated in Figure 4, a similar trend to that observed in Figure 3 is evident. The HAcc reduces significantly as the system stabilises. Subsequently, its value fluctuates between approximately 0.24 and 0.75 m whilst GPS jamming is active. Despite GPS jamming, the value of 0.75 m is still relatively low, which indicates higher degree of confidence of GNSS receiver about its location.

These findings align with trends reported in recent literature. Morales-Ferre et al. [1] and the OPSGROUP report [2] described similar degradation patterns in manned aircraft environments. Radoš et al. [3] and Jiang et al. [5] emphasized that dual-frequency and multi-constellation receivers can partially mitigate jamming effects. The UAV used in this study demonstrated resilience due to its inertial navigation backup, like the hybrid sensor fusion models proposed by Zhou et al. [4].

It was noted in the experiment that even though the number of satellites was large enough for GNSS positioning, the jammer influenced the communication between the radio control and the UAV. This might be the influence of the wider frequency range of the jamming signal to the stated frequency range chosen on the Raptor and requires a further examination.

Conclusions

- GNSS signal jamming significantly reduced the number of connected satellites and increased the horizontal dilution of precision and positional uncertainty, with its maximum value being 0.75 m. Influence was strongly related to the relative distance between the jammer and the UAV.
- The Cube Orange+ inertial reference system employed on the UAV successfully maintained an acceptable level of navigation control during GNSS jamming.
- Future tests should determine the effective range of jamming in different environmental and operational conditions and, extensively characterise the effects of GNSS jamming on the positional accuracy and navigational capability of UAVs.
- Influence of the jammer on the command-and-control link must be further investigated since it represents a great safety risk for a possible loss of UAV.

ACKNOWLEDGEMENTS. The authors would like to acknowledge dr. Polona Pavlovčič Prešeren and her team for providing the tachometric measurements and Branimir Filovski for safely performed flights.

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Določitev enoosnega nateznega ter enoosnega tlačnega mehanskega odziva na podlagi upogibnega testa

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V prispevku je predstavljena metoda za določitev sigma-epsilon diagrama pri enoosnem nateznem in tlačnem obremenitvenem stanju, ki temelji na štiri-točkovnem upogibnem testu. Geometrija in deformacije preizkušanca so izmerjene z metodo korelacije digitalnih slik (DIC – Digital Image Correlation). Metoda upošteva deformirano geometrijo preizkušanca, kar omogoča karakterizacijo materialov, pri katerih lahko dosežemo tudi večje deformacije.

Uvod

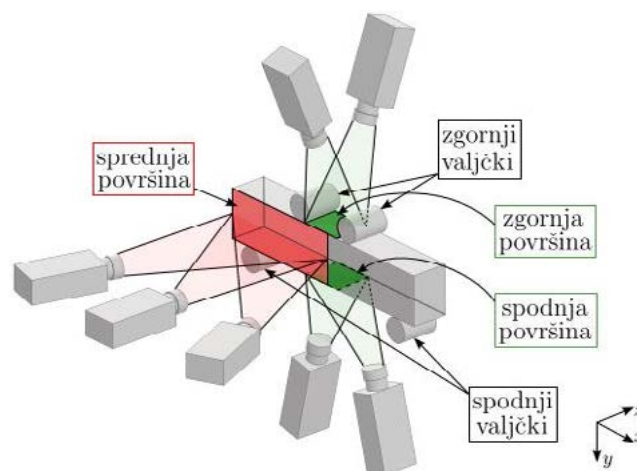
Koncept določanja σ - ϵ diagrama na podlagi upogibnih preizkusov brez predpostavljenega materialnega zakona je bil prvič predstavljen v [1]. Metoda temelji na čistem upogibu, kjer se razmerje med napetostjo in deformacijo določi iz upogibnega momenta in deformacij na zunanji površini vzorca. Kasneje so bile predstavljene tudi različne variacije slednje metode [2-4], kjer so za reševanje enačb problema uporabljeni različni numerični pristopi.

Te metode pa imajo omejitve, saj pri večjih deformacijah sprememba geometrije preseka zaradi Poisson-ovega učinka povzroča napako [5]. Kasnejše raziskave so predlagale korekcijske faktorje za izboljšanje natančnosti [6], vendar celovit teoretični model še vedno manjka.

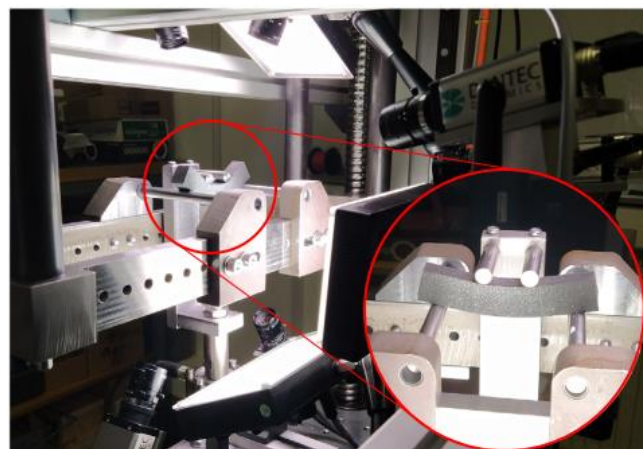
V tem prispevku je predstavljena nova metoda, ki omogoča določitev σ - ϵ diagrama brez pogoja čistega upogiba, z uporabo štiri-točkovnega upogibnega testa. Metoda upošteva ravnotežje na deformirani geometriji, pri čemer analitično vključuje tudi vpliv antiklastičnega upogibnega vzorca preko Poisson-ovega količnika. Celoten postopek je analitičen, brez potrebe po iterativnem reševanju ali mehanskih simulacijah. Rezultat metode je σ - ϵ diagram v diskretni obliki. Metoda omogoča določitev nateznih in tlačnih lastnosti materiala tudi pri velikih deformacijah.

Eksperiment

Za določitev σ - ϵ diagrama iz upogibnega testa potrebujemo poznan profil deformacij, notranjo osno silo N ter notranji upogibni moment M v osrednjem delu preizkušanca. Profil deformacij je v tem območju linearen, saj notranja prečna sila tu ni prisotna. Celoten profil lahko torej dobimo iz dveh poznanih vrednosti, ki so izmerjene na zgornji in spodnji površini preizkušanca. Za določitev osne sile in upogibnega momenta je bila merjena vertikalna sila na valjčke, ter deformirana oblika preizkušanca, ki je bila določena preko polja pomikov na sprednji površini preizkušanca. Slika 1 shematsko prikazuje upogibni preizkus z označenimi merjenimi površinami in postavitvijo kamer sistema DIC, slika 2 pa prikazuje še praktično izvedbo eksperimenta.



Slika 1: Shema štiri-točkovnega upogibnega preizkusa. Deformacije in geometrija so merjene s sistemom DIC na zgornji, spodnji ter sprednji površini preizkušanca.

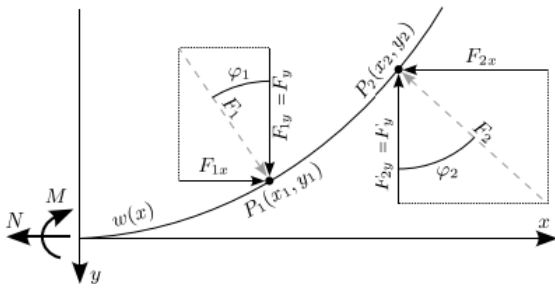


Slika 2: Praktična izvedba štiri-točkovnega upogibnega testa, z DIC merilnim sistemom.

Metodologija

Metoda temelji na poznanih vrednostih notranje osne sile N ter notranjega upogibnega momenta M . Ker notranjih veličin ne moremo direktno izmeriti, so določene posredno na podlagi izmerjene oblike upogibnice nosilca $w(x)$, ter izmerjene vertikalne komponente sile na valjčke F_y . S pomočjo slednjih lahko notranje veličine določimo z upoštevanjem ravnotežja sil na deformiranem preizkušancu, kot prikazuje slika 3.

Notranje veličine lahko izrazimo kot integral napetosti po višini kot $N = \int_A \sigma_{xx} \cdot dA$ ter $M = \int_A \sigma_{xx} \cdot y \cdot dA$, kjer je σ_{xx} funkcija napetosti po višini, ki jo želimo določiti. Za namen izpeljave smo namesto deformacij uporabljali raztezke λ , ki so definirani kot $\lambda = \exp(\epsilon_{log})$.



Slika 3: Shema štiri-točkovnega upogibnega preizkusa v deformirani konfiguraciji.

V slednjih enačbah lahko sedaj upoštevamo:

1. Upoštevanje deformirane geometrije prereza

Zvezo med nedeformiranim in deformiranim prečnim presekom lahko zapišemo kot $dA = \lambda_y \lambda_z dA_0$, kjer sta λ_y in λ_z raztezka v prečnih smereh. Ob predpostavki, da je vsak delček nosilca v osrednjem območju le enoosno obremenjen, lahko upoštevamo Poisson-ov efekt ter izraz zapišemo kot

$$dA = \lambda^{-2\nu} \cdot dA_0.$$

2. Upoštevanje linearnega profila raztezkov po višini

V osrednjem delu nosilca prečne sile ni, kar pomeni, da potek raztezkov po višini linearen, kar lahko zapišemo kot

$$\lambda = (\Lambda_+ + \Lambda_-)/2 + (\Lambda_+ - \Lambda_-)/h \cdot y,$$

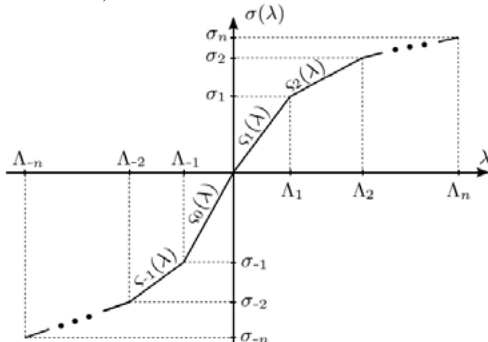
kjer sta Λ_+ ter Λ_- izmerjena raztezka na natezno (spodnji) ter tlačno (zgornjo) deformirani površini, h pa je višina nosilca.

Ob upoštevanju zgornjih zvez v izrazih za izračun notranje osne sile in upogibnega momenta, dobimo

$$N = \frac{bh}{\Lambda_+ - \Lambda_-} \int_{\Lambda_-}^{\Lambda_+} \sigma \lambda^{-2\nu} d\lambda \text{ ter}$$

$$M = \frac{bh^2}{(\Lambda_+ - \Lambda_-)^2} \left(\int_{\Lambda_-}^{\Lambda_+} \sigma \lambda^{1-2\nu} d\lambda - \frac{\Lambda_+ - \Lambda_-}{2} \int_{\Lambda_-}^{\Lambda_+} \sigma \lambda^{-2\nu} d\lambda \right),$$

kjer je b širina nosilca. S pomočjo dobljenih izrazov lahko izračunamo natezno ter tlačno napetost σ_+ ter σ_- ob predpostavki, da je σ - ε zveza linearna.



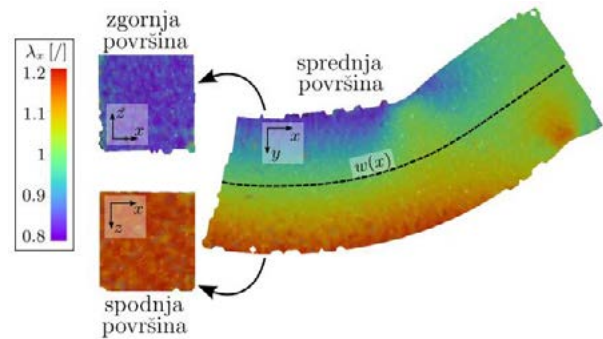
Slika 4: Diskretizacija σ - ε diagrama na posamezne točke, ki so med seboj linearno interpolirane.

Ključna lastnost te metode je diskretizacija upogibnega preizkusa na n obremenitvenih inkrementov. V vsakem inkrementu i lahko s pomočjo zgornjih izrazov določimo vrednost napetosti σ_{+i} ter σ_{-i} pri raztezkih Λ_{+i} ter Λ_{-i} , pri tem pa upoštevamo, da napetost σ na intervalu $\lambda \in [\Lambda_{-i+1}, \Lambda_{-i}]$ že poznamo, predpostavko o linearnosti σ - ε zveze pa je zato potrebno upoštevati le na območju med prejšnjim in trenutnim inkrementom. Na takšen način progresivno sestavimo celotno σ - ε krivuljo v nateznem in tlačnem območju, kot prikazuje slika 4.

Rezultati in diskusija

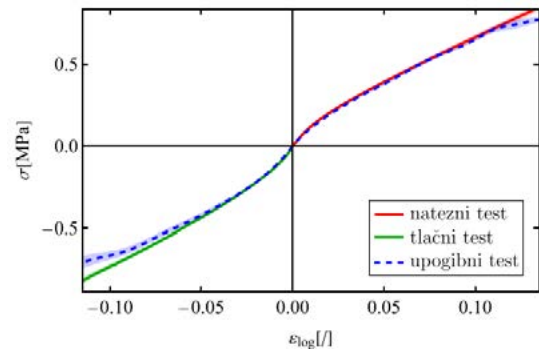
Izvedenih je bilo 5 upogibnih preizkusov, pri čemer smo za material izbrali SBR gumo. Za validacijo metode pa je bilo izvedenih tudi 5 nateznih ter tlačnih testov.

Slika 5 prikazuje izmerjena polja osnih raztezkov na zgornji, spodnji in sprednji površini. Iz zgornje ter spodnje površine sta izračunana raztezka Λ_{+i} ter Λ_{-i} . Iz izmerjene geometrije sprednje ploskve pa dobimo obliko upogibnice $w_i(x)$.



Slika 5: Izmerjena polja raztezkov s sistemom DIC.

Na sliki 6 je z modro barvo prikazan σ - ε diagram določen iz upogibnega preizkusa, zraven pa sta prikazani tudi krivulji dobljeni iz nateznih in tlačnih testov. V območju $\varepsilon_{log} \in [-0.09, 0.11]$ se odzivi med seboj dobro ujemajo, izven tega območja pa se pojavi nekoliko večje odstopanje. Slednje je posledica trenja med valjčki in upogibnim preizkušancem, ki spodnjo površino še bolj raztegne, zgornjo pa skrči, kar se odraža v prevelikih izmerjenih deformacijah v primerjavi z nateznim in tlačnim odzivom.



Slika 6: Primerjava mehanskih odzivov, dobljenih iz upogibnega, nateznega ter tlačnega preizkusa.

Zaključki

Predstavljena je analitična metoda za določitev σ - ε diagrama iz štiri-točkovnega upogibnega preizkusa, ki ne zahteva vnaprej predpostavljenega materialnega zakona. Metoda upošteva ravnotežje v deformirani geometriji, kar omogoča uporabo tudi pri večjih pomikih, ter upošteva vpliv antiklastične ukrivljenosti. V območju $\varepsilon_{log} \in [-0.09, 0.11]$ metoda podaja primerljive odzive v primerjavi z nateznimi in tlačnimi testi. Za verifikacijo metode tudi pri večjih deformacijah, pa je ključna odprava kontaktnega trenja med valjčki in preizkušancem.

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Digital twins in lyophilization modelling

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This work presents the development and validation of a comprehensive digital twin framework for pharmaceutical freeze-drying (lyophilization). The digital twin integrates a validated one-dimensional (1D) model of product drying kinetics, a three-dimensional CFD model of chamber and condenser flow, and a validated ice deposition model. The framework enables realistic simulation of the full freeze-drying cycle, incorporating the vacuum system through a measured pump performance curve at the condenser outlet. The model has been validated on laboratory and production-scale lyophilizers and is capable of predicting local hydrodynamic conditions, choked-flow phenomena, and deposition behavior. The modelling of heat transfer inside the shelf is currently under development and will further enhance predictive capability. This digital-twin approach provides a physically consistent and scalable tool for process design and optimization in pharmaceutical lyophilization.

Introduction

Digital twins are high-fidelity virtual representations of physical systems that combine mechanistic **modelling**, numerical simulation, and experimental validation. In pharmaceutical freeze-drying, the process is governed by tightly coupled heat and mass transfer, local pressure variations, and geometrical constraints. A digital twin offers the ability to simulate these interactions dynamically, enabling improved process understanding and optimization.

Traditional lyophilization models typically focus on a single representative vial and assume uniform chamber pressure and heat flux. Such simplifications neglect spatial variations that affect drying uniformity and product quality. Authors also often model only individual components of the system rather than the entire process. For example, vial stopper resistance was determined using CFD by Kamenik et al. [1], and the ice deposition model was developed in their subsequent work [2]. The multi-level model developed by Kamenik et al. [3] builds upon these foundations and integrates them into a comprehensive digital twin framework. The digital twin presented here overcomes previous limitations by coupling detailed CFD and 1D models, extended with a validated ice deposition model and realistic vacuum system boundary conditions.

Materials and methods

The digital twin consists of three principal components:

1. 1D Drying Model – The validated one-dimensional model simulates sublimation within each vial, accounting for resistance in the frozen product, stopper, and vial headspace. It also includes heat transfer by conduction, convection, and radiation. The model provides local product temperature, sublimation front position, and vapor mass flow rate.
2. CFD Chamber and Condenser Model – The CFD model calculates the flow, pressure, and temperature fields within the drying chamber and condenser. Local pressure over each vial is used as an input for the 1D model, while the vapor mass flow and temperature from the 1D simulation are imposed as inlet boundary conditions in the CFD domain. The two solvers are coupled through a TCP interface, ensuring robust transient data exchange.
3. Deposition and Vacuum System Model – A validated deposition model describes ice formation in the condenser as a volumetric mass sink. The model accurately reproduces deposition growth and associated flow resistance. The outlet boundary of the condenser is defined by the experimentally measured vacuum pump performance curve, providing a physically realistic representation of the vacuum system. The model can also identify and simulate choked-flow conditions in the connecting duct.

The modelling of heat transfer inside the shelf is currently in development. Once implemented, it will enable spatially resolved temperature distribution and improved prediction of heat flux to the vials. The whole model schematics is shown on Figure 1.

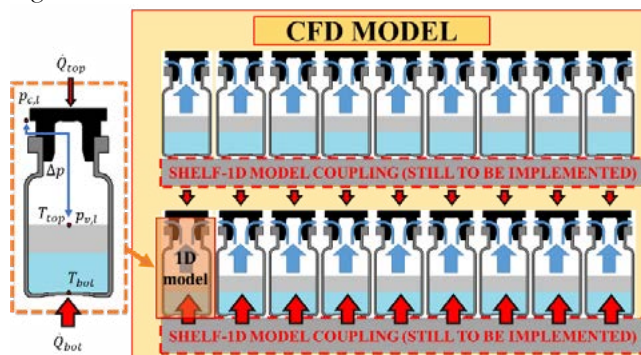


Figure 1: Multi-level model schematics.

Results and discussion

Simulations were carried out for fully loaded shelves with 15R vials at operating pressures of 6 and 22 Pa and shelf temperatures of -20°C and 10°C . The digital twin successfully reproduces pressure gradients across the shelves. Peripheral vials dry faster due to increased local heat flux, while off-center vials dry more slowly because of higher vapor pressure above them and reduced sublimation driving force. Slowest and fastest drying vial in the system is shown on Figure 2.

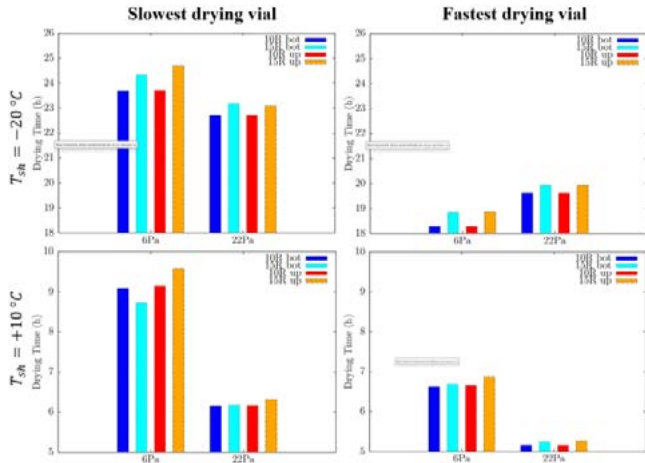


Figure 2: Fastest and slowest drying vial on each shelf at different process conditions.

Validation on laboratory and pilot-scale dryers confirmed the predictive accuracy of the developed ice deposition model. The ice deposition model correctly predicts the experimental condenser pressure and ice deposition distribution and can correctly predict the onset of choked flow under high vapor loads. Validation of the model on the pilot-scale device is shown on Figure 3 and for laboratory scale device is shown on Figure 4.

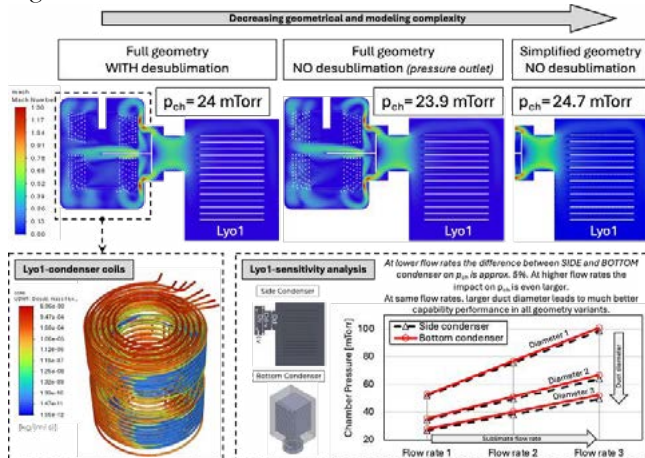


Figure 3: Ice deposition model validation for production scale device and simplification for determination of capability curves [4].

As observed in Figure 3, the ice deposition pattern on the condenser coils is highly nonuniform, with the highest deposition rate occurring on the outer surfaces of the coils. The lowest deposition rate is observed near the distribution plate, where the flow of water vapor from the drying chamber is

redirected toward the sides. In the laboratory-scale device shown in Figure 4, the ice deposition pattern is also nonuniform, with the highest deposition rate occurring at the top of the condenser along its circumference and decreasing toward the bottom. This is because the molar concentration of water vapor is highest at the top and decreases as the vapor is progressively removed from the system through ice deposition.

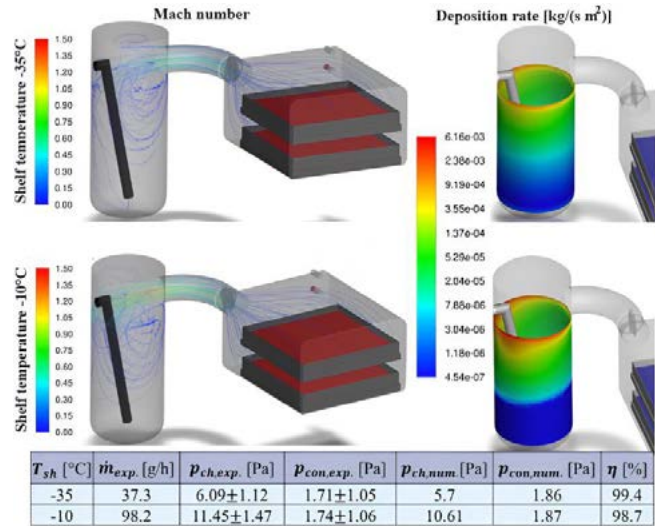


Figure 4: Ice deposition model validation on a laboratory scale device.

Conclusions

A validated digital twin for lyophilization has been developed, combining detailed CFD and 1D models with a physically based deposition module and realistic vacuum system boundary. The model provides insight into local drying kinetics, chamber hydrodynamics, and condenser behavior. The inclusion of the vacuum pump curve and the ability to detect choked flow make the framework robust for large-scale simulation and scale-up studies. The ongoing development of heat-transfer modelling inside the shelf will further enhance the digital twin's accuracy and predictive capabilities, paving the way for advanced process optimization and future integration with process analytical technologies (PAT).

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Analysis of pressure transients in steam generator blowdown piping with the AC²/ATHLET thermal-hydraulic code

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Transient pressure phenomena in the steam generator blowdown system of a pressurised water reactor were analysed using the AC²/ATHLET thermal-hydraulic code. The influence of valve closure time on pressure oscillations and potential two-phase flow formation was evaluated. Results demonstrate the capability of the model to predict transient behaviour and indicate the need for enhanced two-phase and heat transfer modelling.

Introduction

To achieve large-scale defossilisation of the primary energy sector, nuclear power plants remain the only available technology capable of delivering reliable and stable large-scale electricity supply [1]. However, construction of new nuclear power plants (NPPs) requires substantial capital investment, which remains a major obstacle to wider deployment. Therefore, long-term operation (LTO) of existing units plays a crucial role in supporting the energy transition.

LTO involves systematic modernisation of systems, components, and operating procedures, particularly to enhance nuclear safety following the Fukushima Daiichi accident. Under LTO conditions, several auxiliary systems experience increased operational demands [2]. One such system is the steam generator blowdown (BD) system, which maintains the chemical purity of feedwater (secondary working fluid) in pressurised water reactor plant, thereby reducing steam generator (SG) degradation. Although originally designed for intermittent use, the system often operates almost continuously under LTO conditions to protect major components and extend plant lifetime [2].

Increased operation alters the thermal-hydraulic loads in the blowdown piping and valves, potentially leading to structural damage of the piping supports. Such events have been reported in several nuclear power plants, including the Krško NPP [2]. Although these occurrences do not affect the nuclear safety of the plant, they are associated with increased maintenance costs due to more frequent snubber replacements, structural inspections, and related activities. Understanding and managing the underlying causes of the altered thermal-hydraulic loads are therefore of significant importance to NPP operators.

This paper presents an analysis of transient phenomena occurring in the BD system under various valve operation scenarios. The study is based on a hydraulic model of the BD piping system developed in the AC²/ATHLET thermal-hydraulic code [3]. The objective is to identify critical operating conditions that may lead to the formation of two-phase flow and the occurrence of condensation-induced water hammers. The analysis further aims to provide insight into the root causes

of increased dynamic loads on the BD piping supports and to evaluate whether alternative valve operation strategies can effectively mitigate these loads.

Simulated system and flow conditions

The BD system is an auxiliary system of the secondary circuit that maintains the chemical and radiological quality of the secondary working fluid. It prevents the accumulation of impurities and corrosion products in the SGs, thereby reducing the risk of heat transfer tube degradation [4]. Feedwater is extracted from both the hot and cold legs of SG and merged into a common pipeline with the flow control valve (FCV), as shown in Fig. 1. Operation of this valve could potentially induce pressure transients that may result in condensation-induced water hammer, a phenomenon caused by rapid steam condensation when steam contacts subcooled water, leading to sudden pressure rise and mechanical loading of the piping system. Therefore, the analysis focused on the flow conditions in pipeline between the SG and the FCV, marked in blue in Fig. 1.

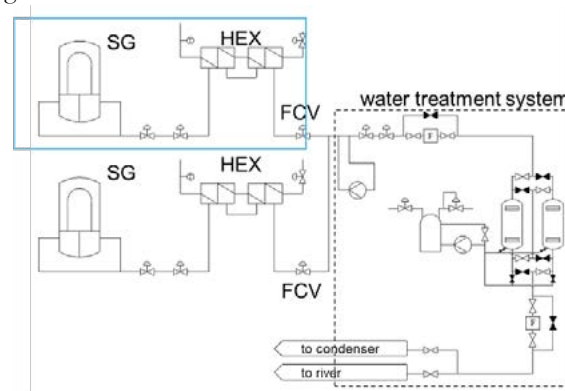


Figure 1: Scheme of the BD in typical two-loop PWR plant [4]

The water in the steam generator was assumed to be near saturation at 280 °C and 64.6 bar, while a pressure of 56.9 bar was prescribed downstream of the FCV. All valves upstream of the FCV were assumed to be normally open and to contribute negligibly to the total pressure loss. The heat exchanger (HEX) was represented by a constant pressure drop. The geometry of the piping between the steam generator and the FCV was defined according to the two-loop Westinghouse pressurized water reactor (PWR) design [5].

Hydraulic model

The model was implemented in the nuclear thermal-hydraulic system code AC²/ATHLET [3], developed and maintained by Gesellschaft für Anlagen- und Reaktorsicherheit gGmbH (GRS, Germany). The code is designed for the analysis of steady-state and transient behaviour of nuclear power plant

systems under normal and accident conditions. Its modular structure enables simulation of a wide range of thermal-hydraulic phenomena, including transient pressure behaviour, conjugate heat transfer, two-phase flow dynamics, and overall plant system response [3]. In this study, two modules were employed: the Thermo-Fluid Dynamics (TFD) module, used to model the flow in the BD piping, and the General Control System Module (GCSM), applied to define boundary conditions, simulate valve operation, and monitor key process variables. For the fluid thermodynamic properties, the AC²/ATHLET property library based on the IAPWS-97 tables was used [3].

The TFD module applies an Euler–Euler two-fluid approach with either a six- or five-equation formulation [3]. For the purposes of this study, the less computationally demanding five-equation formulation was used.

Spatial discretisation in the TFD module is based on one-dimensional and zero-dimensional Thermo-Fluid Dynamic Objects (TFOs), which are further discretised using the finite volume method [3]. In this study, two types of TFOs were used. The BD piping was modelled with standard pipe objects, while the boundary conditions, namely the SG and the system downstream of the flow control valve, were represented by time-dependent volumes (TDVs). At the end of pipe 1, a valve-type connection was implemented to simulate the operation of the FCV. The nodalisation scheme is shown in Fig. 2.

The boundary conditions and valve operation were modelled using control signals within the GCSM module [3]. For both the steam generator and the downstream system, the pressure and fluid enthalpy were defined as time-dependent signals. Although these boundary conditions were nominally constant, an initial ramp-up of pressure and enthalpy in SG was introduced to mitigate numerical non-linearities at the start of the calculation. The observation window for valve actuation was defined after the stabilisation of boundary conditions. Valve operation was controlled by a similar time-dependent signal, closing the valve linearly within a prescribed time interval. Several valve closure durations were analysed, ranging from 0.1 s to 1.0 s. Additionally, the GCSM module controlled the process signals used to record pressure, temperature, mass flow rate, and steam quality at the critical point in the BD piping, located at the highest elevation.

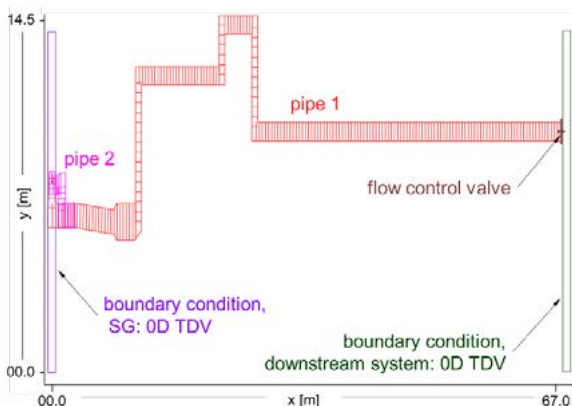


Figure 2: Nodalisation scheme of the simulated BD system piping in AC²/ATHLET. Pipe 1 was discretised into 200 control volumes and Pipe 2 into 20. The scheme is vertically scaled by a factor of 99.

Results and discussion

Results were evaluated at the critical point with the highest elevation in the pipeline. Figure 3 shows pressure transients for different valve closure times, with the saturation pressure at steam generator conditions indicated in red.

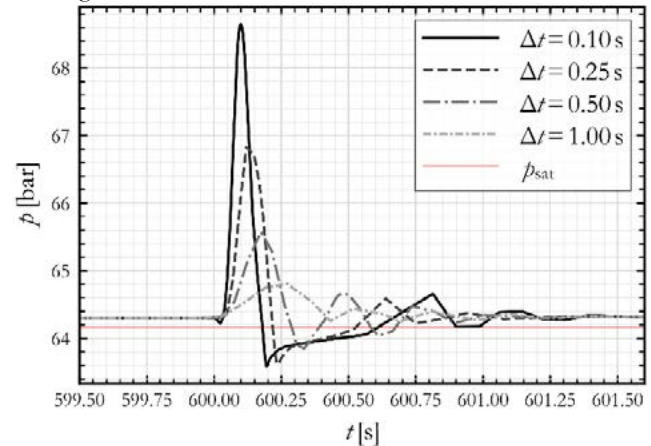


Figure 3: Simulated pressure transients at critical point for different valve closure times. Valve actuated at 600 s.

The valve closing speed has a strong influence on the magnitude of the pressure amplitude following closure. As expected, slower valve closure results in smaller pressure oscillations. Under near-saturation conditions, valve operation may promote the formation of two-phase flow at the critical location. However, in normal plant operation, valve closing times are between 0.25 s and 0.75 s do not produce significant pressure fluctuations in the simulation. Simulated fluid density and vapour quality were also examined, showing almost negligible vapour formation, particularly for longer closure times. These results may reflect numerical artefacts rather than physical phenomena.

Conclusions

The results confirm the applicability of the developed model for analysing transient pressure phenomena in the blowdown system. Further model improvement is recommended, particularly through inclusion of heat transfer surfaces and a more advanced two-phase flow model. These refinements are important at lower mass flow rates in SG, where liquid water in the outlet header may get saturated, evaporate in pipeline due to hydraulic losses and induce condensation-induced water hammer effects.

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Influence of Jet Impingement and Surface Modification on Pool Boiling Heat Transfer

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Efficient cooling of high-power electronics requires solutions capable of dissipating extreme heat fluxes while maintaining low surface temperatures. This work investigates the pool-boiling performance of a reference and a laser-textured microchannel surface, tested with and without submerged liquid jet impingement. Experiments were performed using saturated, twice-distilled water at atmospheric pressure and three mass fluxes delivered through a jet-impingement device. Embedding microtubes within the microchannels notably reduced surface superheat at high heat fluxes, while jet positioning strongly influenced the critical heat flux (CHF). Devices placed near the bottom surface achieved the highest CHF enhancement with increasing mass flux. At the highest tested mass flux, the reference surface outperformed the textured one by 20 %, reaching a maximum CHF of 9.1 MW m^{-2} .

Introduction

The continuous increase in power density of modern electronic and energy systems has pushed heat flux requirements beyond the capability of conventional cooling approaches [1]. Pool boiling offers high heat-transfer potential and near-isothermal surface operation. However, its performance is limited by the early formation of a vapor film that isolates the surface from the liquid and leads to CHF [2].

Surface micro- and nano-structuring can enhance nucleate boiling by increasing nucleation site density and improving liquid replenishment. Microchannel geometries add capillary-driven liquid supply and vapor removal, while surface texturing stabilizes bubble detachment [3]. To further improve performance, active techniques such as submerged jet impingement introduce localized forced convection that continuously renews the liquid in contact with the boiling surface [4,5].

The present study examines the combined influence of laser texturing and jet impingement on pool-boiling heat transfer in open microchannels. The effects of jet position, mass flux, and surface condition on CHF and heat-transfer coefficient (HTC) are evaluated using water at atmospheric pressure.

Materials and methods

Experiments were conducted on copper samples ($5 \times 5 \text{ mm}^2$) featuring machined open microchannels on the top. Each channel was 0.5 mm wide and 2 mm deep, separated by 200 μm fins. A laser-textured variant was fabricated using a nanosecond fiber laser ($\lambda = 1064 \text{ nm}$, 55.6 J cm^{-2} pulse fluence),

generating microcavities across the fin surfaces to increase nucleation site density and improve wettability.

Heating was provided by three cartridge heaters embedded in a copper block, controlled by a variable transformer. Four K-type thermocouples were inserted axially, with the uppermost sensor positioned 2 mm below the surface to calculate the surface temperature by linear extrapolation using Fourier's law. The boiling chamber, a 60 mm-diameter glass vessel filled with $\sim 160 \text{ mL}$ of twice-distilled water, allowed visual observation of bubble behavior.

A jet-impingement device containing stainless-steel microtubes (outer $\varnothing 0.4 \text{ mm}$, inner $\varnothing 0.2 \text{ mm}$) was positioned above or embedded within the microchannels. Each microtube featured ten $\sim 100 \mu\text{m}$ laser-drilled holes for localized jet discharge. The configuration is shown in Figure 1c). The flow was supplied by a syringe pump delivering mass fluxes of 0, 0.64, 3.22, and $6.44 \text{ kg m}^{-2} \text{ s}^{-1}$.

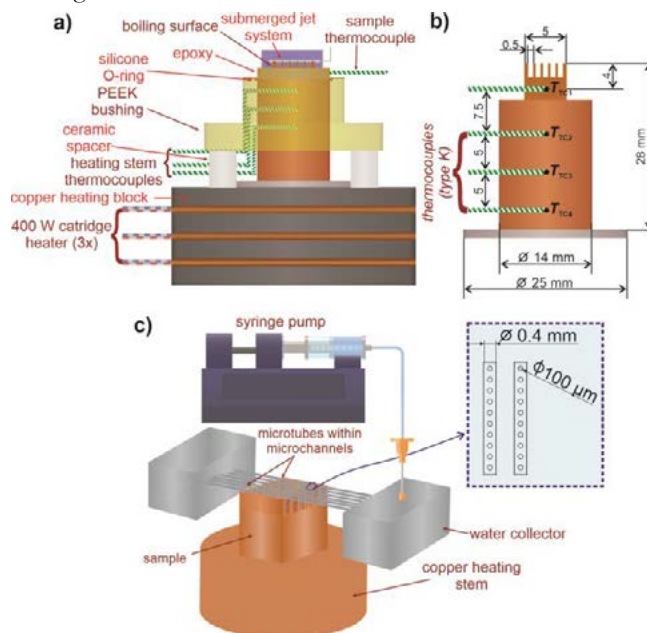


Figure 1: a) Depiction of testing assembly with a sample, c) sample and its characteristics, c) jet impingement system.

Temperature data was sampled at 10 Hz using a Dewesoft KRYPTON DAQ system. Surface superheat was defined as the difference between the extrapolated wall temperature and the saturation temperature of the liquid while heat flux was calculated from one-dimensional conduction through the copper stem, accounting for temperature-dependent thermal conductivity. Each test progressed from natural convection through nucleate boiling to CHF, defined by a sharp rise in wall superheat, with each measurement repeated three times to ensure repeatability.

Results and discussion

The introduction of microtubes within the microchannels shifted boiling curves toward lower surface superheats, even without active flow, due to enhanced liquid availability and vapor removal. Under submerged jet impingement, this effect became more pronounced, especially at higher heat fluxes. The onset of nucleate boiling occurred at approximately 50 % lower wall superheat on the laser-textured surface than on the reference, confirming that laser-induced microcavities act as preferential nucleation sites. Jet positioning had a significant impact on CHF behavior. When the microtubes were embedded at the bottom of the channels, CHF increased consistently with mass flux. In contrast, jets placed just above the surface produced nearly constant CHF, as vapor accumulation within the channels limited rewetting. Bottom-embedded jets improved local liquid replenishment, thereby suppressing vapor film formation and stabilizing bubble detachment. The enhancement achieved using the microchannel surface and the laser-textured microchannels surface at various flow rates in comparison with a plan surface is shown in Fig. 2.

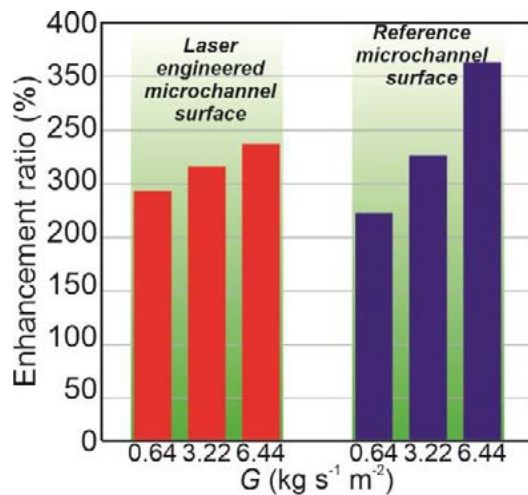


Figure 2: The enhancement ratio of the CHF for the two tested surfaces at different mass fluxes.

For the reference surface, CHF increased from approximately 5.1 MW m^{-2} at $0 \text{ kg m}^{-2} \text{ s}^{-1}$ to 9.1 MW m^{-2} at $6.44 \text{ kg m}^{-2} \text{ s}^{-1}$, corresponding to a 79 % enhancement. The laser-textured surface exhibited a 28 % higher CHF than the reference under pure pool-boiling conditions but showed little further improvement with increasing mass flux. This limitation is attributed to the oxidation layer generated during laser texturing, which introduced a thermal barrier and promoted localized dry-out. Despite this, the laser-textured surface maintained higher HTC across the entire boiling curve—up to 52 % greater than those of the reference—owing to higher nucleation site density and more frequent bubble release. The microjet configuration also mitigated large bubble coalescence, improving stability and delaying vapor film formation.

Figure 3 compares the present results with data from literature (see supplementary information). The combined surface and jet-impingement approach achieved one of the highest reported CHF and HTC values for saturated pool boiling of water, reaching 9.1 MW m^{-2} and $408 \text{ kW m}^{-2} \text{ K}^{-1}$ at CHF.

These findings demonstrate that integrating jet impingement within microchannels provides a synergistic enhancement, combining active fluid delivery with structured surface.

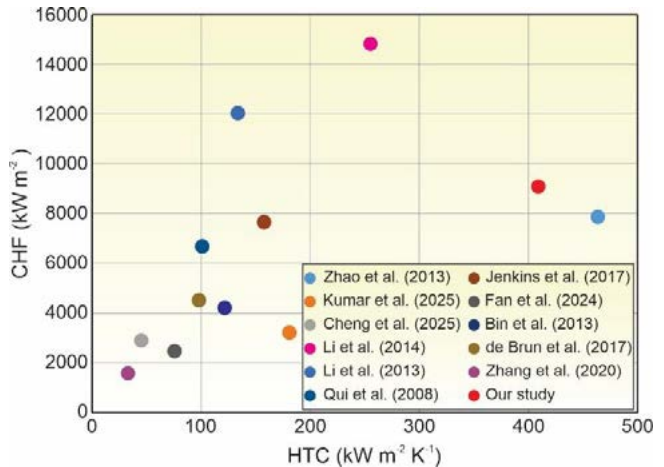


Figure 2: Boiling performance compared to literature-reported data [6–15].

Conclusions

Integrating direct jet impingement within microchannels significantly enhances pool-boiling performance. The embedded microtubes improve rewetting and delay vapor film formation, while laser texturing further increases HTC through microcavity-induced nucleation. The reference microchannel surface achieved the highest CHF of 9.1 MW m^{-2} at $6.44 \text{ kg m}^{-2} \text{ s}^{-1}$, representing a 79 % improvement over standard pool boiling. The findings demonstrate that combining hierarchical surface design with active jet impingement provides a powerful approach for compact, high-heat-flux thermal management, provided that oxidation and jet positioning are carefully controlled.

ACKNOWLEDGEMENTS.

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Corrosion protection of aluminium using zirconium conversion coating

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This study presents the enhanced corrosion protection of a freezer heat exchanger achieved through the application of a zirconium conversion coating. The focus was on the exchanger fins, whose surfaces were mechanically polished and treated by immersion in a conversion bath. The surface morphology was characterised using scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy (SEM/EDS). The corrosion performance after one hour of immersion was evaluated using potentiodynamic polarisation measurements. The results indicate that the formation of a Zr-based conversion coating increases the corrosion resistance of aluminium due to surface passivation.

Introduction

Aluminium and its alloys are widely used in the manufacturing of heat exchangers due to their excellent thermal conductivity and cost-effectiveness. But aluminium is highly susceptible to corrosion, particularly in humid or chloride-containing environments commonly encountered in cooling and air-conditioning systems. Corrosion can lead to material degradation and leakage [1]. Therefore, the development of effective corrosion protection methods is essential to ensure the long-term performance of aluminium heat exchangers. Traditional surface protection techniques, such as surface passivation, have increasingly focused on environmentally friendly alternatives. Among these, zirconium-based conversion coatings have emerged as a promising alternative due to their low environmental impact and good adhesion to aluminium substrates [1-4]. These coatings form thin, compact layers that enhance surface passivation and improve corrosion resistance. The formation mechanism typically involves three steps: (i) degreasing, (ii) desmutting and (iii) the deposition of Zr oxides or hydroxides [2-4]. This study investigates the potential of zirconium conversion coatings for improving the corrosion resistance of aluminium heat exchangers where the formed film provides a certain degree of protection against corrosive ions.

Materials and methods

The aluminium freezer heat exchanger, composed of tubes and fins, is shown in Figure 1a and is used by Gorenje d.o.o., Slovenia, in the manufacturing of refrigerators. The fin samples were initially ground mechanically with 1200-, 2400-, and 4000-grit SiC abrasive papers, followed by polishing with a 3 µm diamond paste. Ethanol served as a lubricant to ensure a smooth and homogeneous surface finish. Subsequently, the samples underwent ultrasonic cleaning in ethanol to remove

any residues, were rinsed with ethanol, and finally dried using compressed nitrogen.

Aluminium fin samples were treated using the three-step process provided by SurTec®: degreasing with an alkaline cleaner SurTec® 089 + SurTec® 132, acid desmutting with SurTec® 496 and conversion with hexafluorozirconic acid, H₂ZrF₆ (Figure 1b). The corresponding process parameters (immersion times and bath temperatures) were adopted from a previous study that optimized these conditions and are summarized in ref. [3].

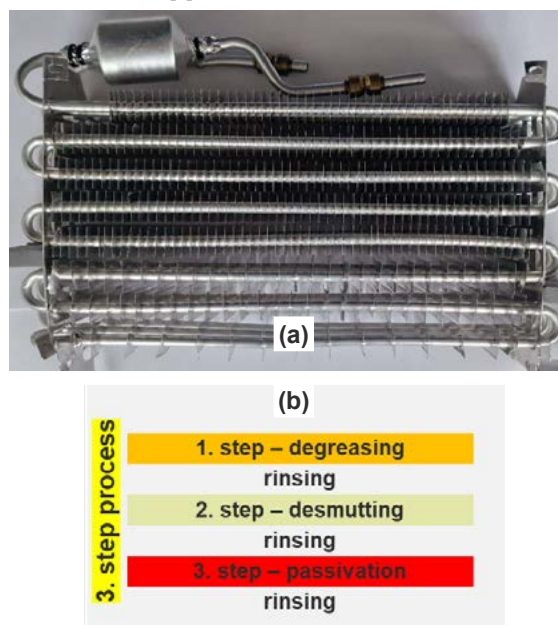


Figure 1: (a) Freezer heat exchanger heat and (b) three-step process for Zr-conversion coating formation.

SEM/EDS analyses were carried out to examine the surface morphology and elemental composition of both the uncoated alloy and the coated samples. Imaging was performed using secondary electrons (SE) captured with a through lens detector (TLD) and backscattered electrons captured with a concentric backscatter detector (CBS).

The corrosion performance was assessed using potentiodynamic polarisation measurements conducted in a custom-made polymethylmethacrylate three-electrode cell (250 mL volume) containing a 0.1 M NaCl solution. Before measurement, the samples were immersed at ambient temperature for 1 hour. The electrolyte was freshly prepared with deionised water (Milli-Q Direct, resistivity > 18.2 MΩ·cm at 25 °C; Millipore, Billerica, MA, USA), and its pH was adjusted to 5.8. The electrochemical setup consisted of a silver/silver chloride (Ag/AgCl) reference electrode, a carbon counter electrode, and the uncoated or coated aluminium fins serving as the working electrode.

Results and discussion

Figure 2 presents the SEM image of the polished aluminium captured using a CBS detector. The darker regions correspond to the Al-rich matrix, while the brighter regions correspond to heavier intermetallic phases composed of silicon (Si) and iron (Fe), as shown in Figure 2b. In aluminium alloys, the intermetallic phases are typically the initial area of corrosion due to microgalvanic coupling with the surrounding aluminium matrix. EDS analysis, given as a weight percentage (wt.%), confirms that the alloy contains more than 96.0 wt.% of Al (site X₁). Intermetallics are Fe-based, as evidenced by the EDS analysis, with a Fe concentration exceeding 20 wt.% (site X₂).

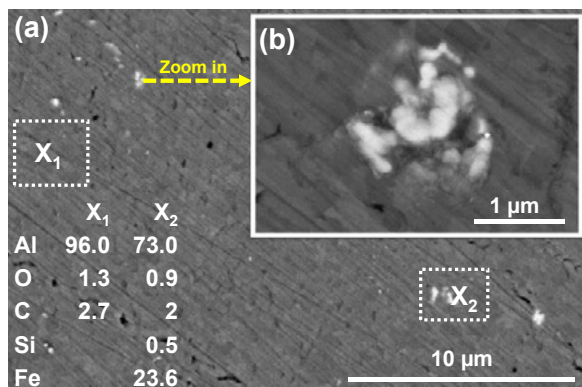


Figure 2: (a) SEM images of the polished aluminium recorded at two magnifications using a CBS detector. (b) The arrow presents the zoom in of the selected intermetallic in the aluminium matrix. The EDS values in weight percentages for X₁ and X₂ obtained from the selected area are given in the table.

Figure 3 presents the SEM/EDS analysis of the coated sample recorded in SE mode, confirming the presence of the zirconium coating on the aluminium surface. The cracks are present at intermetallic regions, where coating is preferentially deposited and cracks occur due to thickening. EDS analysis at the site X₃ confirmed a composition of zirconium (Zr, 6.9 wt.%), oxygen (O, 3.2 wt.%) and fluorine (F, 1.0 wt.%) as the main elements of the coating. A greater amount of these elements is present in areas of intermetallics (Zr 59.5 wt.%, O 24.6 wt.%, F 6.4 wt.%).

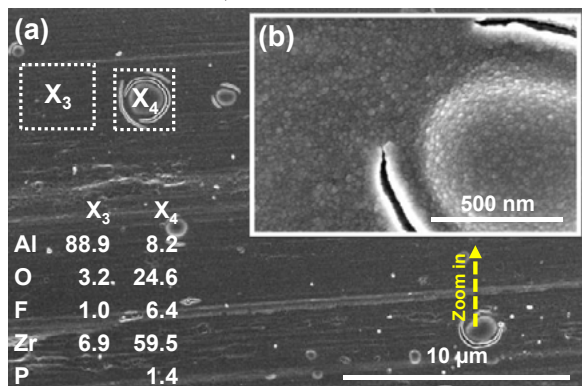


Figure 3: (a) SEM images of the aluminium coated with Zr conversion coating recorded at two magnifications using a TLD detector. (b) The arrow presents the zoom in of the selected intermetallic in the aluminium matrix. The EDS values in weight percentages for X₃ and X₄ obtained from the selected area are given in the table.

Figure 4 presents the potentiodynamic polarisation curves of uncoated and Zr-coated aluminium after 1 hour of immersion in 0.1 M NaCl. The corrosion current density (j_{corr}) is reduced for almost one order of magnitude to lower values for Zr coated ($7.6 \times 10^{-8} \text{ A cm}^{-2}$) compared to polished aluminium ($5.9 \times 10^{-7} \text{ A cm}^{-2}$). Additionally, a shift in potential breakdown (E_{bd}) from -0.66 V to -0.41 V was also noticed. The improved corrosion protection is related to the formation of a Zr conversion coating on the aluminium surface, which protects the surface against Cl^- ions in the corrosion medium.

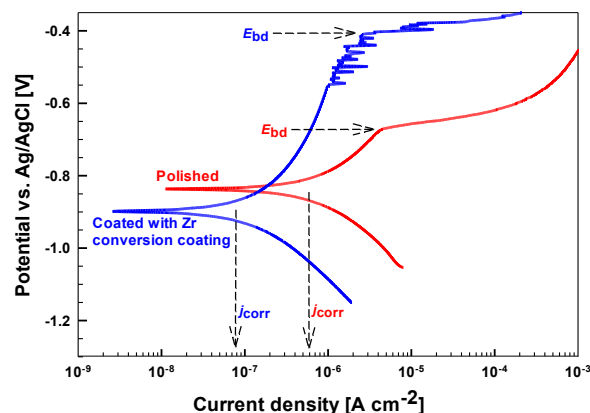


Figure 4: Potentiodynamic polarisation curves for ground aluminium, and protected with Zr conversion coating after 1 hour of immersion in 0.1 M NaCl.

Conclusions

This study showed the microstructure and enhanced corrosion protection of aluminium fins. Key findings are:

- The aluminium surface shows an Al-rich matrix with Fe- and Si-rich intermetallics that act as corrosion initiation sites due to microgalvanic effects.
- The Zr-based conversion coating formed mainly on intermetallic areas, containing Zr, O, and F, providing good surface coverage despite minor cracking.
- The coating reduced corrosion current density and shifted the breakdown potential positively, confirming strong protection against chloride attack.

Future studies will focus on testing after longer immersion times and additional protection with polymer coating, as proposed in the ARIS applicative project L2-60141.

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Flow analysis of green transition materials

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In this study the global trends in the production of critical materials necessary for the green transition were analysed. A multi-source flow analysis of the eight key materials reveals moderate growth and sharp increases linked to rapid growth of technologies for exploitation of RES and storage of electricity in last 10 years. In the pursuit of increasingly efficient energy systems, rare metals, heavily dispersed in the Earth's crust, are increasingly used, which may place disproportionate burden on nature during production. In this context, the need for a new methodology has been identified for the overall burden on nature impact assessment throughout the life cycle.

Introduction

The green transition in all sectors, especially in energy systems, is crucial for a global sustainable future. Its success depends on a stable supply of materials, often rare or difficult to extract, that are essential for manufacturing renewable energy technologies (RES), energy storage systems, and electric vehicles [1]. The International Energy Agency [2] has specified Aluminium (Al), Copper (Cu), Cobalt (Co), Graphite, Lithium (Li), Nickel (Ni), and Rare Earth Elements (REE - 15 elements, commonly referred to as the lanthanides + Yttrium) as critical materials for the green transition between 2020 and 2050, needed for deep decarbonisation of energy systems. Their reserves and supply chains may be disrupted if production or consumption patterns change [3]. Further, Iron (Fe) is fundamental for infrastructure development, and its extraction rate is closely associated with that of critical materials. Prolonged mining has led to the depletion of high-grade deposits, declining ore quality, and increasing energy requirements, thereby intensifying environmental impact and fossil fuel emissions. These interlinked tendencies underscore the need to comprehend how material extraction evolves in regard to economic and technological change. Studying long-term patterns supports identifying potential risks of supply instability, assessing sustainability, and quantifying environmental implications of persistent extraction. While previous studies often focus on individual materials or specific sectors, this research addresses the existing gap by simultaneously analysing eight key materials over four decades, emphasizing their extraction dynamics and interdependencies within the context of the global green transition.

Materials and methods

The primary source of data for this research is a literature examination to collate relevant papers, books, and industrial reports that address the trends in critical materials production

and international databases, such as the United States Geological Survey (USGS) [4], the British Geological Survey (BGS) [5], and World Mining Data (WMD) [6]. The scope of the flow analysis of green transition materials encompasses the temporal boundary of 1984 to 2022, assessed for global material flows, explicitly referring to the metal content of mined materials. Data from those sources were combined and expressed as a means of excavation volume growth of critical virgin materials from the Earth's crust. Those data were compared to the data [7,8] of the growth of the most used technologies for exploiting and storing renewable energy sources to compare mutual relations between them.

Results and discussion

Analysis of the data [4-6] shows that there is a high level of consistency between databases used for most of the materials, except for the Graphite (Gr). The main reason found is that the BGS reported higher values for graphite mine production in China. In contrast, the USGS reported estimated quantities.

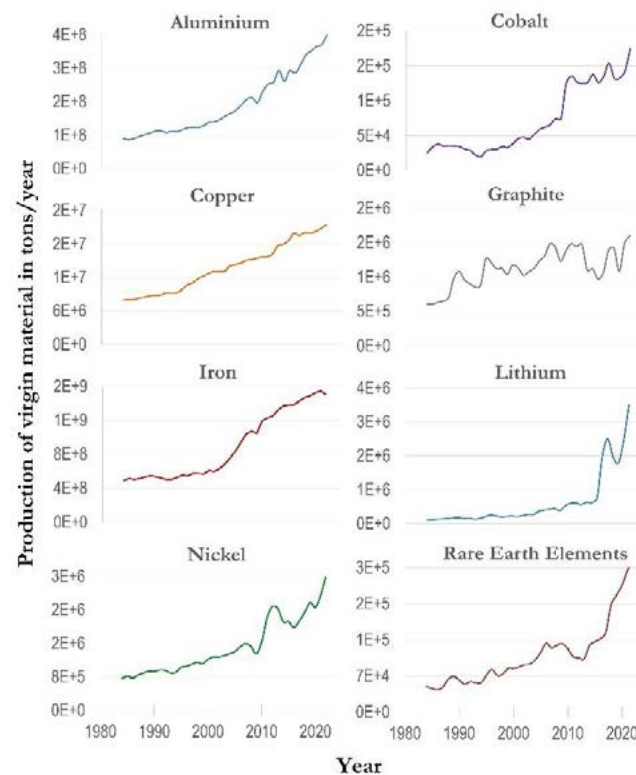


Figure 1: Trends of production, expressed in mass of virgin material in excavated ore, for critical materials in the last four decades. Data sources [4-6].

Yearly production of critical virgin materials in the period from 1984 to 2022 is presented in Fig. 1. The early period depicts average expansion, while the post-2000 period marks

accelerated production caused by globalization, industrial growth, and rising demand from emerging economies. All materials observed follow global recessionary trends in the metallurgical sector and decreased in 2008. In 2010, global demand increased due to improved global economic conditions, causing growth in mined ores. Overall, the recent production peaks align with global population growth, technological advancement and the expansion of green energy systems, electric mobility, and energy storage technologies, emphasising the growing importance of critical materials in achieving global decarbonisation objectives.

In the analysed period, production of the most used metals - Al, Fe and Cu - shows relatively steady growth with an increase of 343, 203 and 171 % respectively. These metals are traditional materials for mature technologies for the construction of infrastructure, buildings, wiring and means of transport, the growth of whose production is to some extent also linked to technologies for the green transition of energy systems. Production of Co (+597%), Li (+3.156%), Ni (+324%), and REE (+491%) increased sharply after 2010. The increase in their production is closely linked to the expansion of technologies for the exploitation and storage of RES, as presented in Fig. 2.

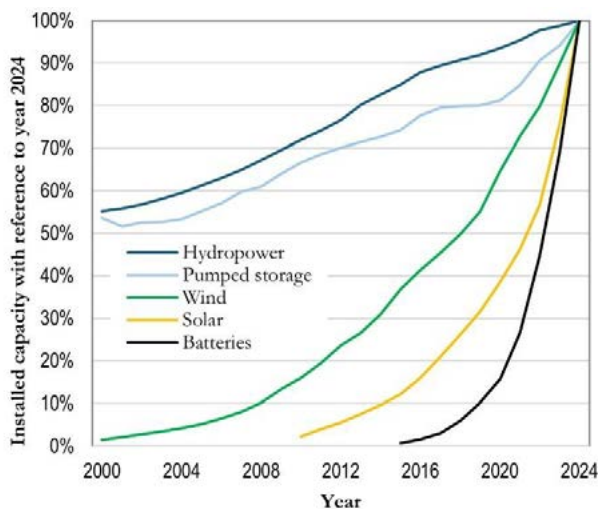


Figure 2: Increase in the capacity of the most used technologies for the exploitation of RES and storage of electricity in the last 25 years, in percentages compared to the year 2024. Cumulative installed power is considered, and for batteries, cumulative storage capacity. Data sources [7,8].

In the construction of hydropower plants and pumped storage hydropower plants, of the analysed materials used, steel (Fe) is most often used, and to some extent also Cu and Al. The gradual growth of these capacities, in addition to increased use in other industries, affects the growth in production of these metals. On the other hand, by comparing Figs. 1 and 2, it can be seen that the rapid growth in the installed capacity of solar and wind power plants and batteries coincides with the rapid growth in the mining and production of most critical materials. Li, Ni, Co and Graphite play a crucial role in battery manufacturing. REEs are essential for the permanent magnets used in wind turbines and electric vehicles. Al and Cu are extensively used in solar technologies and basically in all electricity-related technologies, including emerging RES technologies.

Which brings us to conclusion, that we are solving one problem (decarbonisation) by potentially creating others (depletion of abiotic resources, contaminating the biosphere). Modern technologies use metals from the Earth's crust, which must first be concentrated in order to harness RES. The extraction of different metals represents a different extent of interference with nature. Some examples: production of 1 ton of Fe requires extraction of approx. 1,6 ton of ore - 1:1,6; Cu - 1:125; Co - 1:1500; Li - 1:1900, the latter means contamination of 1900 tons of water and the surrounding ecosystem.

In developing new technologies for improving performance of RES utilisation and electricity storage, more and more critical and rare materials are used. With existing methodologies, it is difficult to assess whether the improvement of a decarbonization technology over its life cycle outweighs the extent of the irreparable damage it causes to nature. To some extent, the depletion of the Earth's crust can be reduced by recycling, which is never 100%, so waste will be generated in the form of concentrated metals that do not exist in nature. Finding a compromise will require a methodology capable of objectively assessing the environmental burden of technologies designed to reduce human impact.

Conclusions

A comparison of the production of critical [2] materials over the past 40 years with the most widely used technologies for renewable energy and electricity storage has shown that the rapid increase in capacity and performance of solar and wind power plants and batteries has led to a similarly rapid growth in mining, especially of rare metals. In the pursuit of increasingly efficient energy systems, rare metals, which are heavily dispersed in the Earth's crust, are increasingly used, which places (possible) disproportionate burden on nature during production. In the continuation of the work, we will focus on developing a methodology to objectively assess not only an individual indicator of an improved or new technology, but also the overall impact on nature throughout the life cycle.

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Eksperimentalno validiran numerični model za napovedovanje plinsko fokusiranih kapljevityh mikro-ploskev

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V delu predstavimo tri-razsežen, eksperimentalno validiran, numerični model za napovedovanje plinsko fokusiranih kapljevityh mikro-ploskev. Stisljiv tok plina v mikro-šobi pod kotom 45° simetrično nateka na kapljeviti curek in ga spremeni v kapljevito ploskev. Kapljevita ploskev je curek ploščate oblike, obdan s cilindričnim robom. Pri preučevani kombinaciji pretokov plina in kapljevine, opisani z Webrovim številom 51, Reynoldsovim številom plina 95 in kapljevine 330, kapljevita ploskev zazvame obliko verige. Numerični model, ki temelji na metodi končnih volumnov in volumna tekočine popiše nestacionaren, laminaren, stisljiv tok helija in nestiljiv, Newtonski tok vode. Za zmanjšanje računskega časa je uporabljeno adaptivno zgoščevanje mreže, ki popiše debeline kapljevityh ploskev pod 10 μm. Površina prvega člena tekoče verige je izračunana s 3 % natančnostjo, kar je znotraj 7 % merilne negotovosti eksperimentalnih podatkov.

Uvod

Kapljevite ploskve oz. ploščati curki se preučujejo že več kot stoletje [1-3]. V zadnjem času je bil napredek dosežen pri doseganju njihove debeline, manjše od mikrometra, z uporabo trkajočih se kapljevityh curkov [4-5], konvergentnih šob [6] in plinsko fokusiranih kapljevityh ploskev [7-8]. Zadnja metoda omogoča izdelavo curkov, katerih debelina je manjša od 100 nm. To je še posebej uporabno v eksperimentih serijske sinhrotronske kristalografije (SSX) [9] in serijske sekundne kristalografije (SFX) [10], kjer se z rentgenskimi laserji na proste elektrone (XFEL) določa molekulska sestava proteinov. Kapljevita ploskev v optično pot XFEL dostavlja kristale proteinov. Ob interakciji med XFEL in kristalom proteina na podlagi Braggovega uklona nastane signal, ki se ga zazna z detektorjem in nadaljnje pretvori v sliko molekulske sestave proteinov. Željeno je, da je kapljevita ploskev čim tanjša, saj se na ta način zmanjša šum ozadja signala, ki nastane ob interakciji XFEL in curka. S tem je analiza signala proteina, zaznanega z detektorjem, enostavnejša.

Karakterizacija mikro-curkov, ki dostavljajo vzorce proteinov do XFEL, se lahko določa z eksperimentalnimi meritvami [4-8] ali preko numeričnih simulacij [11-14]. Pokazano je bilo, da je računsko zahtevna numerična simulacija fokusiranih kapljevityh ploskev izvedljiva [14], vendar ni bila eksperimentalno validirana, kar zmanjšuje stopnjo zaupanja v njene rezultate.

V tem delu je predstavljen eksperimentalno validiran numerični model plinsko fokusiranih kapljevityh mikro-ploskev. Model,

analizira časovno odvisen, laminaren, dvofazni tok, kjer nastopata stisljiv tok helija in nestisljiv, Newtonski tok vode. Predstavljene so osnovne enačbe, na katerih model temelji in njegova eksperimentalna validacija.

Metode

Analiziran dvofazni tok helija in vode je opisan s stisljivimi Navier-Stokes enačbami, na podlagi metode končnih volumnov:

$$\partial \rho / \partial t + \nabla \cdot (\rho \mathbf{v}) = 0, \quad (1)$$

$$\partial (\rho \mathbf{v}) / \partial t + \nabla \cdot (\rho \mathbf{v} \mathbf{v}) = -\nabla P + \nabla \cdot \bar{\tau} + \sigma \kappa \nabla \alpha, \quad (2)$$

$$\partial (\rho e) / \partial t + \nabla \cdot (\rho e \mathbf{v}) = -\nabla \cdot (P \mathbf{v}) + \nabla \cdot (k \nabla T) + \nabla \cdot (\bar{\tau} \mathbf{v}), \quad (3)$$

kjer spremenljivke ρ , $\mathbf{v}$, P , $\bar{\tau}$, σ , κ , α , e , k in T predstavljajo gostoto, hitrost, tlak, strižni napetostni tenzor, površinsko napetost, ukrivljenost medfazne meje, delež faze, specifično notranjo energijo $e = c_p T - P/\rho + 1/2 |\mathbf{v}|^2$, toplotno prevodnost in temperaturo. Strižni napetostni tenzor in ukrivljenost sta izračunana sledeče:

$$\bar{\tau} = \mu [(\nabla \mathbf{v}) + (\nabla \mathbf{v})^T] - 2/3 \mu (\nabla \cdot \mathbf{v}) \mathbf{I}, \quad (4)$$

$$\kappa(\alpha) = -\nabla \cdot (\nabla \alpha / |\nabla \alpha|), \quad (5)$$

kjer μ predstavlja dinamično viskoznost, $\mathbf{I}$ pa enotsko matriko. Gostota plina je izračunana z modelom idealnega plina, viskoznost pa s Sutherlandovim modelom:

$$\rho_g = \frac{PM}{RT}, \quad (6)$$

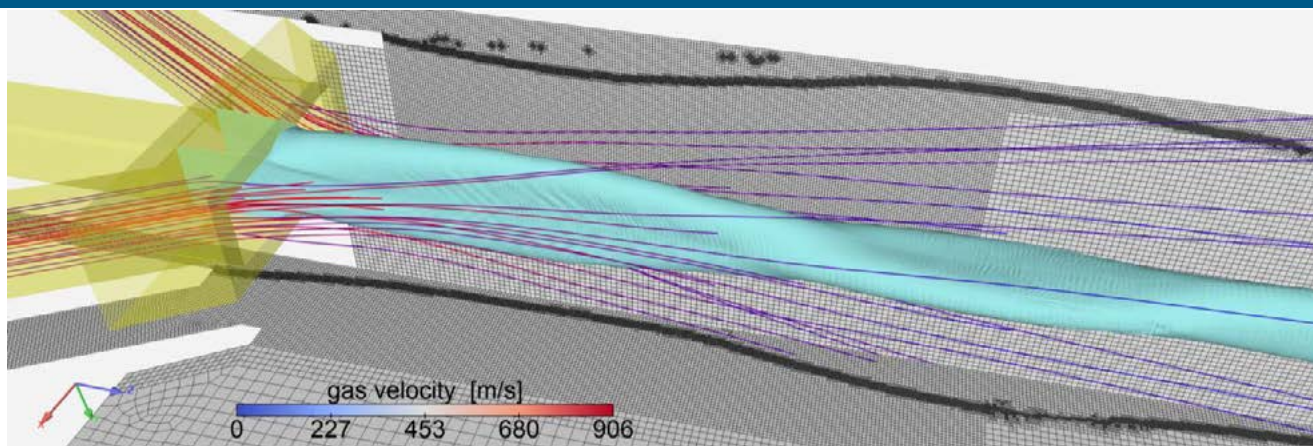
$$\mu_g = \frac{A_S \sqrt{T}}{1 + \frac{T}{T_S}}, \quad (7)$$

kjer sta M in R molska masa helija in splošna plinska konstanta. Za helij Sutherlandova temperatura znaša $T_S = 79$ K, Sutherlandova konstanta pa $A_S = 1,48 \cdot 10^{-6}$ kg m⁻¹ s⁻¹ K^{-1/2} [15]. Transport medfazne meje je popisan z metodo volumna tekočine, preko enačbe:

$$\partial (\rho \alpha_q) / \partial t + \nabla \cdot (\rho \mathbf{v} \alpha_q) = 0, \quad (8)$$

kjer α_q predstavlja delež sekundarne faze (vode). Vsota primarne (helij) α_p in sekundarne faze ustreza $\alpha_p + \alpha_q = 1$. Snovne lastnosti mešanice so izračunane preko volumsko uteženega povprečja $\vartheta(\alpha_q) = \alpha_q \vartheta_q + (1 - \alpha_q) \vartheta_p$, kjer ϑ_p in ϑ_q predstavljata snovno lastnost primarne in sekundarne faze.

Računska mreža in robni pogoji numerične simulacije so podobni kot v [16]. Dodatno smo uporabili adaptivno zgoščevanje mreže (AMR), ki na podlagi vrednosti globalnega maksimuma gradientov α določa kriterij za zgoščevanje ali redčenje medfazne meje. Ko lokalna vrednost gradienta α presega 0,06 vrednosti globalnega maksimuma, se celica zgosti,



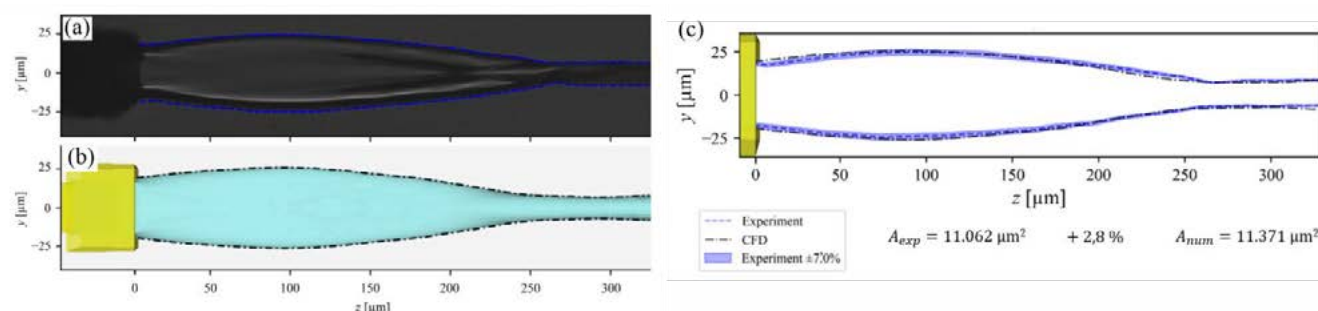
Slika 1: Numerični model plinsko fokusirane kapljevite mikro-ploskve z uporabo adaptivnega zgoščevanja mreže.

ko pa je manjša od 0,05, pa se razredči. Računska mreža na sliki 1 vsebuje dva nivoja AMR, kar privede do 1,8 milijona računskih celic. Čas izračuna simulacije na super računalniku (AMD EPYC 7402, 2,8 GHz, 96 jeder), da dobimo polno razvito kapljevito ploskev, znaša 5 dni.

Rezultati in diskusija

Slika 1 prikazuje tri-razsežno polnorazvito rešitev numerične simulacije plinsko fokusirane kapljevite mikro-ploskve za pretok helija 12,6 mg/min in pretok vode 600 $\mu\text{l/min}$, kar ustreza Webrovemu številu 51, Reynoldsovemu številu plina 95

Zahvale. Raziskavo so finančno podprli: Center for Free-Electron Laser Science (CFEL) v okviru projekta: *Innovative methods for imaging with the use of X-ray free-electron laser (XFEL) and synchrotron sources: simulation of gas-focused micro-jets*, in Javna agencija za znanstvenoraziskovalno in inovacijsko dejavnost Republike Slovenije (ARIS) v okviru programske skupine P2-0162 in projekta J2-4477 ter Programa za mlade raziskovalce. Delo je delno podprto tudi s strani Cluster of Excellence "CUI: Advanced Imaging of Matter" nemške raziskovalne fundacije (DFG), projekt EXC 2056 – ID 390715994.



Slika 2: Validacija numeričnega modela: eksperimentalna meritev (a), rezultat numerične simulacije (b) in primerjava rezultatov (c).

in kapljevine 330.

Na sliki 2(a) je prikazan posnetek eksperimentalnih meritev na sliki 2(b) pa rezultat numerične simulacije. Iz slik 2(a) in 2(b) smo izluščili medfazni meji in ju na sliki 2(c) prikazali eno preko druge. Okoli eksperimentalno dobljene medfazne meje je narisana tudi merilna negotovost, ki znaša 7 %. Primerjani medfazni meji se skoraj v popolnosti ujemata. Izračunana površina presega eksperimentalno izmerjeno za 2,8 %, kar je znotraj merilne negotovosti.

Zaključki

Predstavljeni numerični model, ki obravnava časovno odvisen, laminaren tok stisljivega idealnega plina in nestisljive Newtonske kapljevine, napove površino plinsko fokusirane kapljevite mikro-ploskve s 3 % natančnostjo. V prihodnje bodo simulacije razširjene na različne pretoke vode in helija, kar bo omogočilo boljše razumevanje dinamike kapljevityh ploskev, identifikacijo ključnih parametrov in njihovo optimizacijo za učinkovitejše delovanje mikro-šob.

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Numerično modeliranje in eksperimentalna validacija nanašanja sloja kapljavine na premikajoči se trak

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Proces nanašanja sloja kapljavine na premikajoči se trak je ključen v serijski kristalografiji, kjer znotraj sloja kapljavine znanstveniki natančno dostavljajo suspendirane proteine do mesta interakcije z rentgenskim žarkom. Z eksperimentalno validacijo smo ovrednotili dvo-razsežni numerični model nestisljivega, izotermnega, laminarnega dvofaznega toka nanašanja sloja, rešenega v programu ANSYS Fluent. Simulacijo in eksperiment smo izvedli pri stabilnem nanašanju binarne mešanice 90 % vode in 10 % etanola (po masnem deležu), pri volumskem pretoku $100 \mu\text{l min}^{-1}$, hitrosti traka $2,0 \text{ mm s}^{-1}$, oddaljenosti šobe od traka $0,6 \text{ mm}$ in nagnjenosti šobe 45° . Eksperiment smo zajeli z monokromatsko kamero in s Python programom primerjali pridobljene vrednosti debeline sloja kapljavine ter položaje stičnih linij z numerično simulacijo. Rezultati so pokazali večja odstopanja debeline in položaja gorvodne dinamične stične linije, medtem ko je bil popis lokacije statičnih linij uspešen. Raziskava je bila izvedena za nabor procesnih, reoloških in geometrijskih parametrov ter predstavlja izhodišče za nadaljnje študije.

Uvod

Proces nanašanja sloja kapljavine na realno heterogeno površino je kompleksen dinamičen proces, ki ga lahko opišemo z analizo časovno spreminjajočih geometrijskih parametrov nastalega sloja. Takšna analiza je ključna, ko robni učinki močno vplivajo na dinamiko kapljavine, kot na primer pri elektrodah litij-ionskih baterij [1,2] in v serijski kristalografiji [3] na dinamiko proteinov suspendiranih v sloju kapljavine, kjer dinamika nanašanja sloja kapljavine vpliva na učinkovitost transporta proteinov.

Metodologija raziskave

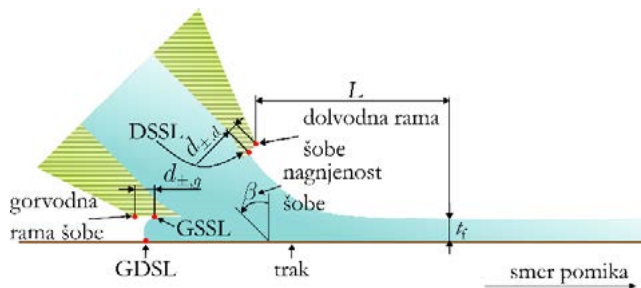
Raziskavo smo naredili pri stabilnem nanašanju binarne mešanice 90 % vode in 10 % etanola (po masnem deležu) pri volumskem pretoku $100 \mu\text{l min}^{-1}$, hitrosti traka $2,0 \text{ mm s}^{-1}$, oddaljenosti šobe od traka $0,6 \text{ mm}$ in nagnjenosti šobe 45° . Primerjali smo debelino sloja kapljavine t_f , izmerjeno na razdalji $L = 7,5 \text{ mm}$ od dolvodne rame šobe in položaja treh stičnih linij: x-komponento gorvodne dinamične stične linije (GDSSL) in razdalji med gorvodno ter dolvodno statično stično linijo (GSSL, DSSL) in pripadajočima ramama šobe. Položaj GDSSL smo izračunali relativno na položaj gorvodne rame šobe - negativen predznak vrednosti predstavlja pomik v gorvodno smer, pozitiven predznak pa v dolvodno smer. Razdalji med

statičnima stičnima linijama in ramama šobe smo označili z oznakama $d_{\pm,g}$ in $d_{\pm,d}$, ter ju izračunali po enačbah:

$$d_{\pm,g} = \sqrt{(x - x_0)^2 + (y - y_0)^2} \text{ sig}(x - x_0), \quad (1)$$

$$d_{\pm,d} = \sqrt{(x - x_0)^2 + (y - y_0)^2} \text{ sig}(y - y_0), \quad (2)$$

kjer indeks 'g' predstavlja gorvodno in indeks 'd' dolvodno smer. Merjene geometrijske spremenljivke in terminologija so prikazane na sliki 1.



Slika 1: Merjene geometrijske spremenljivke in terminologija.

Problem smo obravnavali kot nestisljiv, izotermen in laminaren dvofazni tok. Ohranitveni enačbi za maso in gibalno količino sta:

$$\nabla \cdot \mathbf{v} = 0, \quad (3)$$

$$\frac{\partial(\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v} \mathbf{v}) = -\nabla P + \mu \nabla^2 \mathbf{v} + \rho \mathbf{g} + \sigma \kappa \nabla \alpha, \quad (4)$$

kjer t , ρ , $\mathbf{v}$, P , μ , $\mathbf{g}$, σ , κ in α predstavljajo čas, gostoto, vektor hitrosti, tlak, viskoznost, vektor gravitacijskega pospeška, koeficient površinske napetosti, ukrivljenost in delež faze. Volumski prispevek zaradi površinske napetosti je bil izračunan z modelom kontinuumske površinske sile (ang. *Continuum Surface Force, CSF*) [4]. Medfazno mejo med kapljavino in plinom smo zajeli z metodo volumna tekočine (ang. *Volume of Fluid, VOF*), pri čemer je bila advekcija deleža faze izračunana eksplicitno z enačbo:

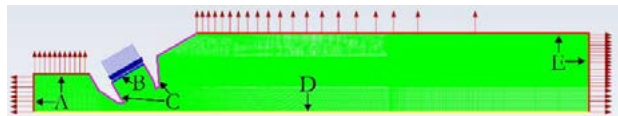
$$\frac{\partial \alpha}{\partial t} + \mathbf{v} \cdot \nabla \alpha = 0, \quad (5)$$

kjer je delež faze enak 1 za kapljavino in 0 za plin. Snovne lastnosti faz so izračunane z enačbo:

$$\vartheta(\alpha) = \alpha \vartheta_k + (1 - \alpha) \vartheta_p, \quad (6)$$

kjer ϑ_k in ϑ_p predstavljata snovne lastnosti kapljavine in plina. Za sklopitev tlačnega in hitrostnega polja smo uporabili algoritem *Coupled*. Delež faze je bil izračunan z eksplicitno metodo VOF z geo-rekonstrukcijsko shemo., za natančnejši popis medfazne meje pa je bilo uporabljeno adaptivno zgoščevanje mreže. Robni pogoji, prikazani na sliki 2, so vključevali tlačni izstop na robovih fluidne domene (A, E), nepremikajočo se steno (C) za šobo, laminarni hitrostni profil v okrogli cevi (B) in premikajočo se steno (D). Z goniometrom smo izmerili stični kot $54,1^\circ$ na šobi in $71,4^\circ$ na traku, kar smo

uporabili kot vhodni podatek v programu ANSYS Fluent. Na premikajoči se steni je bil nastavljen Navierjev zdrs [5] in dinamični stični kot, izračunan po Kistlerjevi metodi [6] za napredujoči dinamični stični kot in metodo za umikajoči dinamični stični kot [7,8].

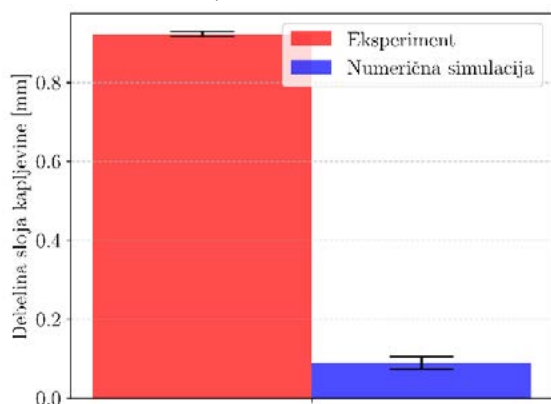


Slika 2: Robni pogoji. A: tlačni izstop, B: laminarni hitrostni profil, C: nepremikajoča se stena, D: premikajoča se stena, E: tlačni izstop.

Navierjev zdrs in dinamični stični kot sta bila implementirana preko uporabniško definirane funkcije (ang. *User Defined Function, UDF*) [9]. Nastavljena dolžina zdrsa je bila 10^{-6} m. Pri numerični simulaciji smo za primerjavo z eksperimentom analizirali vrednosti le kvazi-stacionarno razvito rešitev. Za dosego tega stanja je bilo potrebno izračunati približno 0,3 sekunde fizičnega časa, izhajajoč iz že razvite rešitve s podobnimi procesnimi in istimi geometrijskimi ter reološkimi parametri. Eksperiment smo zajemali s stranskega pogleda z monokromatsko kamero PixeLink PL-755MU-T, nameščeno na optičnem mikroskopu. Vsak posnetek je vseboval 79 slik, pridobili pa smo tri videoposnetke, iz katerih smo izračunali povprečne vrednosti in standardne odklone. Analizo smo izvedli v okolju Python z lastno razvito programsko opremo, ki temelji na računalniškem vidu in omogoča objektivno ter natančno določanje geometrijskih parametrov sloja kapljavine.

Rezultati in diskusija

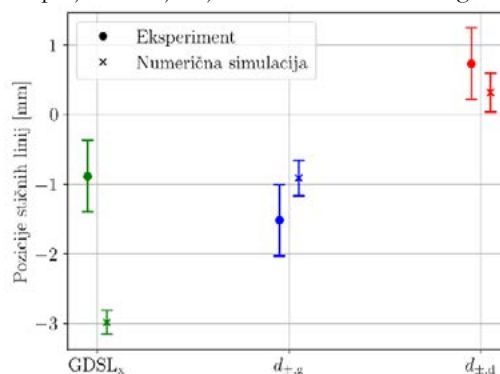
Primerjava debeline sloja kapljavine med eksperimentom in numerično simulacijo, prikazana na sliki 3 (povprečno vrednost predstavlja stolpec, en standardni odklon pa črtica napake), kaže izrazito odstopanje: povprečna debelina sloja je bila pri eksperimentu 0,92 mm, medtem ko je numerična simulacija napovedala debelino le 0,09 mm.



Slika 3: Primerjava debeline sloja kapljavine med eksperimenti in numerično simulacijo.

Primerjava položaja stičnih linij je prikazana na sliki 4, kjer simbol krog predstavlja eksperiment, križ pa numerično simulacijo. Položaj GDSL je pri eksperimentu pomaknjena bolj dolvodno kot v simulaciji, kar nakazuje nepravilno zajetje dinamike GDSL. Položaja statičnih stičnih linij $d_{\pm g}$ in $d_{\pm d}$ pri simulaciji sta znotraj razpona eksperimentalnih vrednosti, kar potrjuje pravilnost njihovega izračuna. Zaradi odstopanj pri

debelini sloja in položaju GDSL sta napačna tudi gorvodna in dolvodna ukrivljenost meniskusa, kar pomembno vpliva na hitrostno polje znotraj sloja in stabilnost nanešenega sloja.



Slika 4: Primerjava položaja stičnih linij med eksperimenti in numerično simulacijo.

Zaključki

Primerjava numerične simulacije z eksperimentom je pokazala velika odstopanja pri debelini sloja kapljavine in položaju gorvodne dinamične stične linije, medtem ko sta položaja statičnih stičnih linij uspešno zajeta. Za boljše ujemanje med numeričnim modelom in eksperimentom je potrebna prilagoditev robnih pogojev, predvsem modelov in vstopnih podatkov za izračun zdrsa in dinamičnega stičnega kota, s čimer bi bolje popisali vpliv realne površinske hrapavosti. Nadalje moramo kvantificirati vpliv zmotnih tokov (ang. *spurious currents*), značilnih za probleme z majhnimi kapilarnimi števili. Prehod na tro-razsežni numerični model bo dodatno izboljšal natančnost, saj dvo-razsežni model ne zajame v celoti robnih učinkov prisotnih pri slojih kapljavine z majhnim razmerjem med debelino in širino.

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Stisljiv plinsko-fokusiran curek mešanice vode in etanola v šobah z dvojnimi fokusiranjem

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V serijski femtosekundni kristalografiji se kapljeviti curki uporabljajo za dovajanje mikrometrskih kristalov v pot rentgenskega žarka. V tej študiji šobo z dvojnimi fokusiranjem, ki je namenjena tvorbi takšnih curkov, modeliramo numerično. Šoba proizvede kapljeviti curek, ki ga obdaja sekundarna kapljevina, obe pa sta fokusirani s sotočkom stisljivega plina. Kot primarni in sekundarni tekočini sta uporabljeni voda in etanol, medtem ko helij deluje kot fokusirni plin. Prejšnje predpostavke o nemešanju oziroma predhodno pomešanih tekočinah na vstopih šobe so nadgrajene z uporabo mešalnega modela ter z upoštevanjem stisljivosti plina. Tak pristop združuje enačbe o ohranitvi mase, gibalne količine, energije in koncentracije v dvofaznem, dvo-komponentnem sistemu, pri čemer Jouyban–Acree model opisuje nelinearne učinke mešanja na lastnosti tekočine. Rešitev, osnovana na okolju OpenFOAM, razširjenem za obravnavo binarnega mešanja ter stisljivega toka plina, napoveduje stabilnost curka, njegov premer, dolžino in hitrost pri različnih koncentracijah etanola na sekundarnem vstopu. Rezultati kažejo vpliv koncentracije etanola na obliko curka. Razviti model ponuja napovedno orodje za optimizacijo šob z dvojnimi fokusiranjem.

Uvod

Kapljevite strukture mikrometrskih dimenzij, kot so curki, kapljice in ploščati curki, imajo ključno vlogo v serijski femtosekundni kristalografiji (SFX) [1]. Takšne kapljevite strukture se uporabljajo za prenos kristaliziranih vzorcev v eksperimentih SFX, kjer rentgenski žarki iz rentgenskih laserjev na proste elektrone interagirajo z mikro-kristali in omogočajo pridobivanje difrakcijskih podatkov na atomski ravni. Ker se vsak kristal med interakcijo z laserjem uniči, morajo curki neprekinjeno dovajati sveže vzorce, pri tem pa ostati dovolj tanki, da se zmanjša poraba vzorca in sipanje ozadja. Dolgi in stabilni curki so prav tako zaželeni, saj omogočajo interakcijo z laserjem dovolj stran od šobe, kar preprečuje njene poškodbe in zagotavljajo stabilno poravnavo med meritvami.

Šobe z dvojnimi fokusiranjem (DFFN) [2] združujejo fokusiranje primarne kapljevine s sekundarno kapljevino in s stisljivim plinom. Na ta način tvorijo stabilne, tanke in hitre kapljevite curke pri minimalnih pretokih vzorca. Prednosti DFFN v primerjavi s konvencionalnimi tehnikami zahtevajo podrobno preučitev njihovega delovanja. Eksperimentalne študije so bile doslej omejene predvsem na osnovne kvalitativne podatke o curkih, medtem ko so numerične raziskave predvidevale bodisi nemešanje med primarno in sekundarno

kapljevino bodisi že predhodno zmešane kapljevine na vstopu šobe [2,3]. V nedavni numerični študiji [4] je bila izvedena poglobljena analiza dinamike mešanja tekočin na osnovi mešalnega Jouyban–Acree modela [5,6], vendar z uporabo predpostavke nestisljivega plina. Namen te študije je razširiti delo [4] z vključitvijo stisljivosti učinkov fokusirnega plina.

Metode

Zaradi cilindrične simetrije geometrije šobe je uporaba osno simetrične numerične predpostavke zadostna [7-11]. Računsko območje in njegova prostorska diskretizacija sta prikazana na sliki 1(a). Numerični model vključuje Newtonski, laminaren, stisljiv, dvofazni plinsko-kapljeviti sistem, pri čemer kapljevito fazo predstavlja binarni sistem voda–etanol. Vodilne enačbe so podane kot:

$$\partial \rho / \partial t + \nabla \cdot (\rho \mathbf{v}) = 0 \quad (1)$$

$$\partial (\rho \mathbf{v}) / \partial t + \nabla \cdot (\rho \mathbf{v} \mathbf{v}) = -\nabla p + \nabla \cdot \bar{\tau} + \mathbf{f}_\sigma \quad (2)$$

$$\partial (\rho e) / \partial t + \nabla \cdot (\rho \mathbf{v} e) = -\nabla \cdot (p \mathbf{v}) + \nabla \cdot (\bar{\tau} \mathbf{v}) - \nabla \cdot \mathbf{q} \quad (3)$$

$$\partial (\rho Y_e) / \partial t + \nabla \cdot (\rho \mathbf{v} Y_e) = \nabla \cdot (D \nabla Y_e) \quad (4)$$

kjer, $\mathbf{v}$, p , ρ , μ predstavljajo hitrost, tlak, gostoto in viskoznost. Strižni napetostni tenzor je popisan z $\bar{\tau} = \mu [(\nabla \mathbf{v}) + (\nabla \mathbf{v})^T] - 2/3 \mu (\nabla \cdot \mathbf{v}) \mathbf{I}$, specifična totalna

energija pa z $e = c_v T + 0,5 |\mathbf{v}|^2$. Koncentracija etanola je Y_e , koncentracija vode pa $Y_w = (1 - Y_e)$. D je difuzijski koeficient med etanolom in vodo, $\mathbf{f}_\sigma$ pa sila površinske napetosti. Metoda volumna tekočine (VOF) je uporabljena za sledenje medfazne meje med plinom in kapljevino. VOF uporablja delež faze α (0: plin, 1: kapljevina), ki nastopa v advekcijki enačbi:

$$\partial \alpha / \partial t + \mathbf{v} \cdot \nabla \alpha = 0. \quad (5)$$

Sila površinske napetosti je izračunana z uporabo kontinuumskega modela površinske sile [12] kot $\mathbf{f}_\sigma = \sigma \kappa \Delta \alpha$, kjer je σ površinska napetost, κ pa ukrivljenost površine. Gostota, viskoznost in površinska napetost med vodo in etanolom so izračunane z Jouyban–Acree modelom:

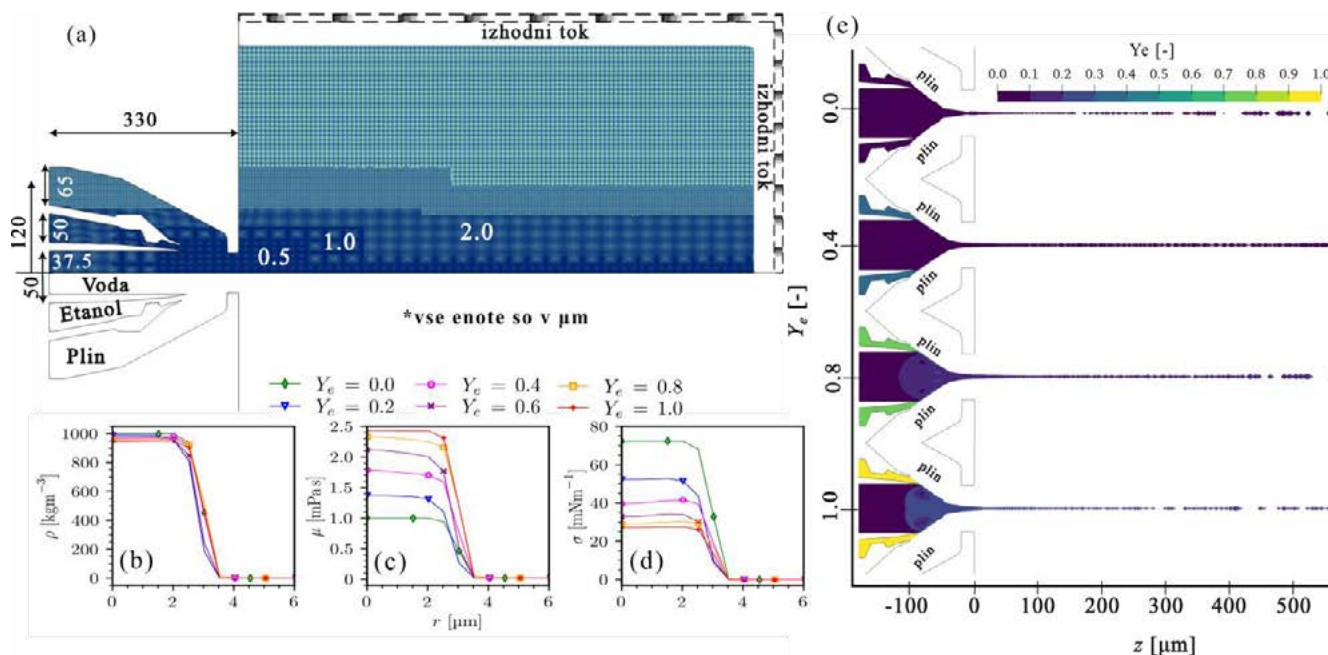
$$\ln(\theta_l) = Y_w \cdot \ln(\theta_w) + Y_e \cdot \ln(\theta_e) - a(Y_w \cdot Y_e)/T - b(Y_w \cdot Y_e)(Y_w - Y_e)/T + c(Y_w \cdot Y_e)(Y_w - Y_e)^2/T, \quad (6)$$

kjer θ_l predstavlja ali gostoto, viskoznost ali površinsko napetost kapljevine. Koeficienti, ki nastopajo v Jouyban–Acree modelu (a, b, in c) so povzeti po [5]. Lastnosti vode in etanola pri standardnih pogojih (293 K in 101 325 Pa) so $\rho_w = 998 \text{ kgm}^{-3}$, $\mu_w = 0,001 \text{ Pa s}$ in $\sigma_w = 0,072 \text{ Nm}^{-1}$, ter

$\rho_e = 791 \text{ kgm}^{-3}$, $\mu_e = 0,00114 \text{ Pa s}$ in $\sigma_e = 0,0224 \text{ Nm}^{-1}$. Lastnosti helija so $\rho_g = 0,164 \text{ kgm}^{-3}$ in $\mu_g = 1,96 \times 10^{-5} \text{ Pa s}$.

Metoda končnih volumnov (FVM) in metoda volumna tekočine (VOF) v programskem okolju OpenFOAM je razširjena tako, da vključuje temperaturno odvisen model mešanice.

na vstopu sekundarne kapilare kažejo na prehod iz kapilarnega v viskozno-dominantni režim. Dolžina curka se povečuje do deleža etanola približno 0,5, nato pa se z naraščajočo viskoznostjo ponovno zmanjšuje. Krajevne in časovne spremembe materialnih lastnosti mešanice močno vplivajo na delovanje curka. Nadaljnji razvoj modela bo usmerjen v vključitev kemijske kinetike mešanja med vodo in etanolom.



Slika 1. (a) Shematski prikaz diskretiziranega računskega območja, (b) gostota, (c) viskoznost in (d) površinska napetost na izstopu iz šobe vzdolž radialne smeri, (e) koncentracijsko polje mešanice voda-etanol za različne koncentracije etanola na vstopu sekundarne kapilare.

Rezultati in diskusija

Numerične simulacije so bile izvedene pri konstantnih pretokih primarne in sekundarne kapljevine $10 \mu\text{l}/\text{min}$, ter s pretokom plina $10 \text{ mg}/\text{min}$. Izhod iz šobe je bil modeliran kot vakuum s tlakom 150 Pa . Na začetku je bil skozi obe kapilari, ki dovajata vodo (primarna) in etanol (sekundarna), vzpostavljen tok vode ($Y_e = 0$). Nastali curek je bil najmanjši, kot je prikazano na sliki 1(e). V nadaljevanju je bila koncentracija etanola v sekundarni kapilari postopno povečana z $Y_e = 0$ na $Y_e = 1$. Z naraščajočo koncentracijo etanola se viskoznost mešanice poveča, medtem ko se površinska napetost zmanjša, kar povzroči različne vplive na stabilnost curka. Pri zmernih deležih etanola zmanjšanje površinske napetosti oslabi kapilarne sile, kar omogoča večje raztezanje curka in s tem daljše curke. Pri višjih deležih etanola pa povečana viskoznost okrepi viskozno disipacijo, ki duši medfazne perturbacije in omejuje pospeševanje v osni smeri. Ob konstantnem plinskem fokusiranju ta povečana viskozna upornost povzroči zmanjšano raztezanje curka in postopno krajšanje njegove dolžine.

Zaključki

Curki DFF so bili analizirani s pomočjo numeričnega modela DFFN, kjer binarna mešanica voda-etanol deluje kot kapljevita faza, ki jo fokusira visoko-hitrostni sotočni stisljiv plin. Razviti numerični model je bil rešen v okolju OpenFOAM z uporabo metode končnih volumnov (FVM) in metode volumna tekočine (VOF). Spremembe koncentracije etanola od 0 do 1

Izboljšani model bo omogočil napovedno zasnovo in optimizacijo šob z dvojnimi fokusiranjem.

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Numerični model tokovnega fokusiranja v električnem polju s stisljivim tokom

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Tokovno fokusiranje je široko uporabljena metoda za tvorbo kapljevityh mikro-curkov in kapljic na širokem spektru aplikacij, od strukturne biologije do nanotehnologije. Nedavne eksperimentalne in numerične raziskave so pokazale, da lahko z uporabo električnega polja dodatno izboljšamo stabilnost in fokusiranje curka, kar je znano kot elektro-tokovno-fokusiranje. Pri tem lahko kapljevito fazo obravnavamo nestisljivo, fokusirni plin pa znatno ekspandira, kar mehansko in toplotno vpliva na dinamiko curka. V tem delu je predstavljen stisljiv večfazni model, ki združuje dvofazne Navier-Stokesove enačbe z elektrostatičnimi silami, izpeljanimi iz Maxwellovega tenzorja napetosti. Stisljivost plina je eksplicitno upoštevana, kar omogoča izračun ohlajanja zaradi ekspanzije. Vključen je tudi vpliv segrevanja zaradi Joulovega učinka. Gostota, viskoznost in površinska napetost tekočine so obravnavane kot temperaturno odvisne. Model je uporabljen za geometrije, značilne za plinsko-dinamične virtualne šobe. Analiziran je vpliv ekspanzije plina na podhlajevanje kapljevitega curka ter posledično na njegovo vedenje pod skupnim vplivom viskoznih, kapilarnih in elektrostatičnih napetosti.

Uvod

Naprave za tokovno fokusiranje [1–2] se pogosto uporabljajo za tvorbo stabilnih mikro- in nano- curkov v aplikacijah, kot so brizgalno tiskanje, dostava zdravil, elektroprayi in injiciranje vzorcev rentgenske laserje na proste elektrone [3]. Uporaba zunanjega električnega polja [4,5] omogoča dodatno kontrolo, saj poveča stabilnost in nastavljivost curka ter vpliva na njegovo razpadanje in tvorbo kapljic.

Predhodne teoretične in eksperimentalne raziskave [4,6–8] so vzpostavile temelj razumevanja električno gnanih sistemov mikronskih curkov in kapljic. Kljub napredku numeričnih modelov za nestisljive dvofazne elektrohodinamske (EHD) sisteme ostajajo vplivi stisljivosti in temperaturne odvisnosti curkov neraziskani.

V tem delu je predstavljen stisljiv dvofazni EHD model za opis tokovno fokusiranih mikrocurkov pod vplivom električnega polja. Model vključuje temperaturno odvisno viskoznost, gostoto in površinsko napetost ter omogoča bolj realističen opis mikronskih tokov. Predstavljene so osnovne enačbe, numerična izvedba in preliminarne rezultati.

Metode

Sistem je opisan s stisljivimi Navier–Stokesovimi enačbami,

$$\partial_t \rho + \nabla \cdot (\rho \mathbf{v}) = 0, \quad (1)$$

$$\partial_t (\rho \mathbf{v}) + \nabla \cdot (\rho \mathbf{v} \mathbf{v}) = -\nabla p + \mathbf{f}_\mu + \mathbf{f}_E + \mathbf{f}_\sigma, \quad (2)$$

$$\partial_t (\rho e) + \nabla \cdot (\rho e \mathbf{v}) = -p \nabla \cdot \mathbf{v} + \dot{q}_\mu + \dot{q}_k + \dot{q}_J, \quad (3)$$

ki so sklopljene z elektrostatičnimi enačbami

$$\nabla \cdot (\epsilon \mathbf{E}) = \rho_E, \quad (4)$$

$$\partial_t \rho_E + \nabla \cdot (\rho_E \mathbf{v}) = -\nabla \cdot (K \mathbf{E}). \quad (5)$$

Parcialni odvod po času je označen z ∂_t . Spremenljivke $\rho, \mathbf{v}, p, e, \epsilon, \mathbf{E}, \rho_E, K$ predstavljajo gostoto, hitrost, tlak, specifično notranjo energijo, električno permitivnost, električno polje, gostoto električnega naboja in električno prevodnost. Izvorni členi v momentni enačbi so

$$\mathbf{f}_\mu = \nabla \cdot (\mu[(\nabla \mathbf{v}) + (\nabla \mathbf{v})^T] - 2/3 \mu(\nabla \cdot \mathbf{v})\mathbf{I}), \quad (6)$$

$$\mathbf{f}_E = \nabla \cdot (\epsilon \mathbf{E} \mathbf{E} - 1/2 \epsilon |\mathbf{E}|^2 \mathbf{I}), \quad (7)$$

$$\mathbf{f}_\sigma = \sigma \kappa \nabla \alpha, \quad (8)$$

kjer μ, σ, κ predstavljajo viskoznost, površinsko napetost in ukrivljenost medfazne meje $\kappa = -\nabla \cdot (\nabla \alpha / |\nabla \alpha|)$. Parameter α predstavlja volumski delež v metodi volumna tekočine (ang. *volume of fluid* – VOF). Fazna funkcija je omejena med 0 in 1, pri čemer vrednost 0 predstavlja plinsko fazo, vrednost 1 pa tekočinsko fazo. Transport medfazne meje brez fazne spremembe je opisan z enačbo

$$\partial_t (\rho \alpha) + \nabla \cdot (\rho \mathbf{v} \alpha) = 0. \quad (9)$$

Izvorni členi v energijski enačbi so

$$\dot{q}_\mu = (\mu[(\nabla \mathbf{v}) + (\nabla \mathbf{v})^T] - 2/3 \mu(\nabla \cdot \mathbf{v})\mathbf{I}) : \nabla \mathbf{v}, \quad (10)$$

$$\dot{q}_k = -\nabla \cdot \mathbf{q}, \quad (11)$$

$$\dot{q}_J = K |\mathbf{E}|^2, \quad (12)$$

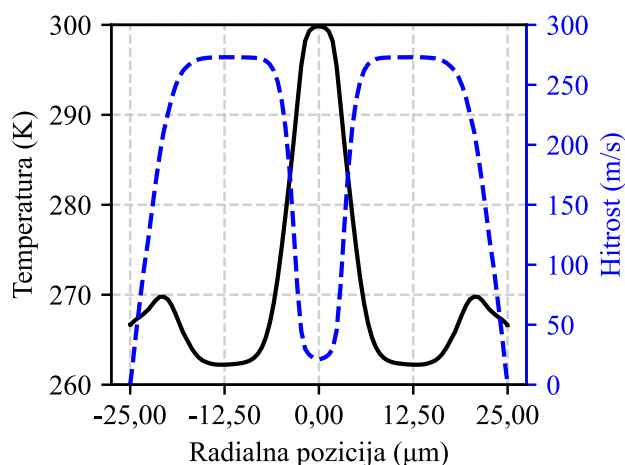
kjer $\mathbf{q} = -k \nabla T$ predstavlja Fourierjev toplotni tok s temperaturo T in toplotno prevodnostjo k .

Snovne lastnosti so čez medfazno mejo med kapljevino in plinom interpolirane z uporabo uteženega aritmetičnega povprečja (WAM), medtem ko so električne lastnosti interpolirane z uporabo geometričnega povprečja (GM) [9].

$$\Psi(\alpha) = \begin{cases} \Psi_1 \alpha + \Psi_2 (1 - \alpha) & : \Psi = \rho, \mu, k \\ \Psi_1^\alpha \Psi_2^{1-\alpha} & : \Psi = K, \epsilon \end{cases} \quad (13)$$

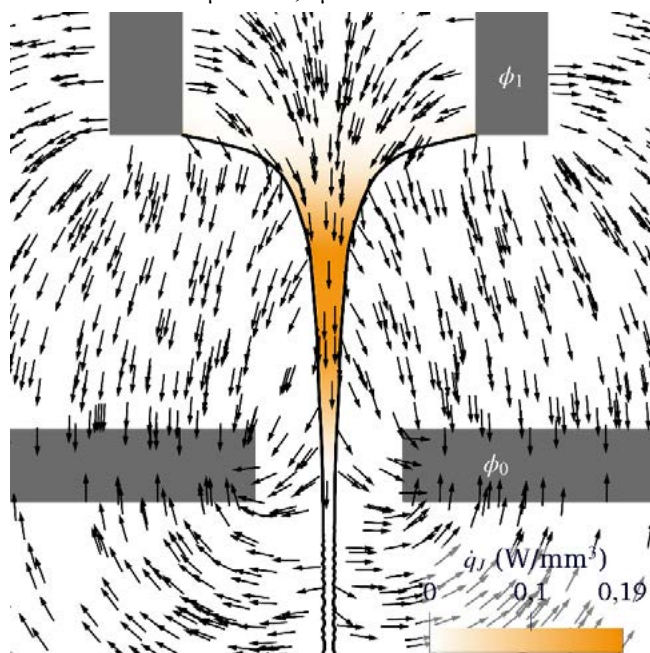
Indeksa 1 in 2 označujeta kapljevito in plinsko fazo. Za zajem učinkov ekspanzije plina in Joulovega segrevanja sta viskoznost in površinska napetost modelirani kot temperaturno odvisni lastnosti. Viskoznost plina je določena po Sutherlandovem zakonu $\mu_g(T) = A_s \sqrt{T} / (1 + T_s/T)$, medtem ko sta viskoznost tekočine in površinska napetost podani z

aproximacijsko krivuljo tabeliranih podatkov, $\mu_l(T) = C_0 - C_1T + C_2T^2$, in $\sigma(T) = D_0 - D_1T$. Parametri A_S , T_S , C_0 , C_1 , C_2 , D_0 , D_1 so konstante modelov in so dostopni v podatkovni bazi NIST [10].



Slika 1: Temperaturni in hitrostni profil v radialni smeri na izstopu iz elektrode ϕ_0 .

V simulaciji je bila uporabljena podobna geometrija kot v [9], kjer iz kapilare pod el. potencialom (napetost $\phi_1 = 1$ kV) premera $100 \mu\text{m}$ izhaja kapljeviti curek (pretok $20 \mu\text{l/min}$), ki nato potuje skozi $50 \mu\text{m}$ odprtino v dolvodni elektrodi (napetost $\phi_0 = 0$ V). Preko dolvodne elektrode vzpostavimo tudi tlačni gradient ($\Delta p = 60$ kPa), ki povzroči pretok plina. Uporabljeni tekočini sta heksan ($\rho = 685$ kg/m³, $\mu = 0,019$ mPas, $\epsilon_r = 1$, $K = 0,1$ fS/m) in zrak ($\rho = 1,2$ kg/m³, $\mu = 0,38$ mPas, $\epsilon_r = 1,93$, $K = 1,56$ $\mu\text{S/m}$). Začetna temperatura obeh tekočin je 300 K. Računska domena je bila strukturirana s heksaedrsko mrežo s štirimi stopnjami postopnega zgoščevanja velikosti celic od $8 \mu\text{m}$ do $0,5 \mu\text{m}$.



Slika 2: Vizualizacija Joulovega toplotnega toka $\dot{q}_J$ in silnic električnega polja E . Kapilara in dolvodna elektroda sta označeni s pripadajočima napetostima ϕ_1 in ϕ_0 .

Rezultati in diskusija

Pri danih pogojih se formira stabilen mikronski curek s premerom $4 \mu\text{m}$. Temperatura curka se v dolvodni smeri zniža za največ okoli 10 K, pri čemer temperatura plina pade za več kot 35 K. Hitrost plina po končani ekspanziji doseže maksimalno hitrost 280 m/s, medtem ko curek med pospešuje vse do 30 m/s. Na Sliki 1 sta prikazana profila temperature in hitrosti v radialni smeri na izstopu iz elektrode ϕ_0 .

Joulov toplotni tok je največji v območju med kapilaro in elektrodo ter znaša približno 10^{-1} W/mm³. Na Sliki 2 je prikazan skupaj s silnicami električnega polja. Silnice zaradi preglednosti niso skalirane, največja jakost električnega polja je 18 MV/m in se nahaja med kapilaro in elektrodo. V dolvodni smeri od elektrode je električno polje zanemarljivo majhno in je posledica električnega naboja zbranega na medfazni meji. Največja gostota električnega naboja se nahaja na medfazni meji, v neposredni bližini kapilare, in znaša 57 C/m³. Vzdržljivost curka del naboja preko konvekcije preide v plinasto fazo in se razelektri na elektrodi oz. zapusti računsko domeno.

Zaključki

Razvili smo stisljiv EHD numerični reševalnik za večfazne tokove in ga uporabili na konfiguraciji tokovnega fokusiranja curkov v električnem polju, pri čemer je bil kot fokusirana kapljevina uporabljen heptan, kot fokusirni plin pa zrak. Pri visokih hitrostih plinaste faze izrazito podhlajevanje plina zahteva vključitev temperaturno odvisnih lastnosti. Kapljevita faza doživi ohladitev za približno 10 K, pri čemer je učinek najizrazitejši v bližini medfazne meje. Čeprav Joulovo segrevanje deluje v nasprotni smeri, je njegov prispevek pri tekočinah z nizko električno prevodnostjo zanemarljiv in ne vpliva bistveno na temperaturno polje.

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Drone-based motion capture in alpine skiing — a pilot study

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Markerless drone-based motion capture (MoCap) supported by computer vision has great potential for kinematic measurements in sport. In the present study, a drone-based MoCap system equipped with a stereo camera and a Real Time Kinematics (RTK) Global Navigation Satellite System (GNSS) was developed and tested for alpine skiing kinematic measurements. The global position of a skier's helmet was compared with a reference RTK GNSS carried by the skier. The current prototype system is not yet accurate enough to meet the requirements of most biomechanical analyses, therefore possible improvements are proposed for future studies.

Introduction

The development of computer vision supported by deep learning techniques has greatly increased the applicability of markerless motion capture (MoCap) systems [1]. To overcome the limitation of the capture volume that fixed MoCap systems suffer from, MoCap systems can be mounted on unmanned aerial vehicles (UAVs) or drones, enabling MoCap over extended areas in natural outdoor environments. Such drone-based MoCap systems are particularly useful for kinematic measurements of sports activities, where subjects move across considerable distances, and where easy-to-use and time-efficient measurements in real-life conditions are desired. Another advantage of such systems is that subjects do not need to be equipped with sensors, which could interfere with their natural movement, thus enabling measurements of the highest ecological validity.¹

Video-based tracking, using a single camera attached to a drone has been used for the analysis of game and racket sports [2]. Jacobsson et al. [3] proposed an autonomously flying drone system equipped with a LiDAR depth camera, a LiDAR-based altitude sensor, and a GNSS, which would enable real-time sports performance analysis of athletes based on artificial intelligence markerless MoCap software. In alpine skiing, drone-assisted MoCap has already been used, but only in combination with terrestrial cameras [4, 5].

The aims of the present study were (1) to set up a drone-based MoCap system for markerless kinematic measurements in alpine skiing, (2) to test its applicability and evaluate its accuracy, and (3) to provide advice for future improvements.

Materials and methods

The global position of the helmet (specifically, the antenna mounted on the helmet) of a certified alpine ski instructor was measured using two independent systems: (1) a markerless

drone-based MoCap system (prototype) and (2) a Real Time Kinematics (RTK) Global Navigation Satellite System (GNSS, reference system) carried by the skier (Figure 1). The skier was informed about the study procedure before the measurements and gave written consent for participation. He was also informed about the risks concerning the UAVs. The study was conducted in accordance with the Helsinki Declaration and was approved by the Ethics Committee of the Faculty of Kinesiology at the University of Zagreb, Croatia.



Figure 1: Skiing kinematic measurements with two independent systems.

1. Markerless drone-based MoCap system (figures 1 and 2a). The global position of this system was measured with a RTK GNSS (Here 4, CubePilot Global Pty Ltd., Victoria, Australia), while the position of the skier relative to the UAV was measured with a stereo camera (ZED 2i, Stereolabs Inc., San Francisco, CA). To capture the video streams and inertial motion unit (IMU) data from the stereo camera, the camera was coupled to a small onboard computer (Jetson Nano, NVIDIA Corporation, Santa Clara, CA).

The UAV was manually operated by an experienced and licensed operator. To ensure safety, the drone flew at a distance of 10 to 30 meters behind the skier. Terrain following was enhanced using a LiDAR (TF02-Pro UART, Benewake Co., Ltd., Beijing, China), so the operator did not have to account for the slope. All permissions for UAV operation were obtained. The sampling frequency of the stereo camera was approximately 30 Hz.

2. A reference RTK GNSS was used to measure the global position of the skier's helmet (figures 1 and 2b). The system consisted of a multiband GNSS antenna (ANN-MB-00, u-blox

¹Ecological validity is a measure of how test performance predicts behaviors in real-world settings. In sport science this is an essential criterion for applicability of the experimental results in real-world conditions.

AG, Thalwil, Switzerland) mounted on the skier's helmet, connected to a high-precision GNSS receiver (simpleRTK3B Pro, based on the mosaic-X5 module, Septentrio NV, Leuven, Belgium).

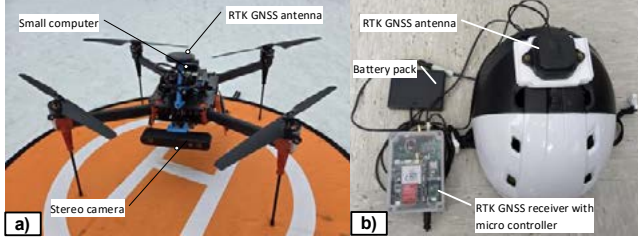


Figure 2: a) The drone-based MoCap system and b) the reference system.

The receiver was interfaced with a microcontroller (Teensy 4.1, PJRC, Sherwood, OR) responsible for logging GPS and GLONASS signals using both L1 and L2 frequency bands. The entire setup, including rechargeable batteries, weighed 400 g and was carried in a waist pouch by the skier.

For accurate positioning, both RTK GNSS units (the reference system and the UAV prototype) were connected to a nearby Continuously Operating Reference Station (CORS). Their accuracy depended on the RTK position solution. The fixed solution provides absolute sub-decimetres position accuracy, while the float solution can be as repeatable as the fixed solution or deviate by up to five metres [6].

Data processing. The global position of the skier was obtained from the drone-based MoCap system data by synchronising and combining the RTK GNSS and stereo camera data. A software development kit (Stereolabs Inc., San Francisco, CA), integrated into in-house software, was used for recognition and determination of the relative 3D skeleton position of the skier (Figure 4).

The measured data from both systems were interpolated to the same number n of data points and filtered with a low-pass Butterworth filter with a normalized cutoff frequency of 1.0. The agreement between the trajectories was quantified using the mean absolute error (MAE) over all data points:

$$\text{MAE} = \frac{1}{n} \sum_{i=1}^n |d_i - \hat{d}_i| \quad (1)$$

where d_i denotes the reference distance of the i -th data point and $\hat{d}_i$ the evaluated distance of the i -th data point. All calculations were performed in MATLAB (MathWorks, Natick, MA).

Results

The accuracy of the drone-based MoCap system was estimated by comparing the trajectory of the skier's helmet obtained with both systems over two sequential ski turns (Figure 3). Since the RTK GNSS of the drone-based MoCap system had a float position solution, its accuracy was poor, with a MAE of 0.744 m.

Discussion

The drone-based MoCap system is currently not accurate enough for most biomechanical analyses of alpine skiing. The

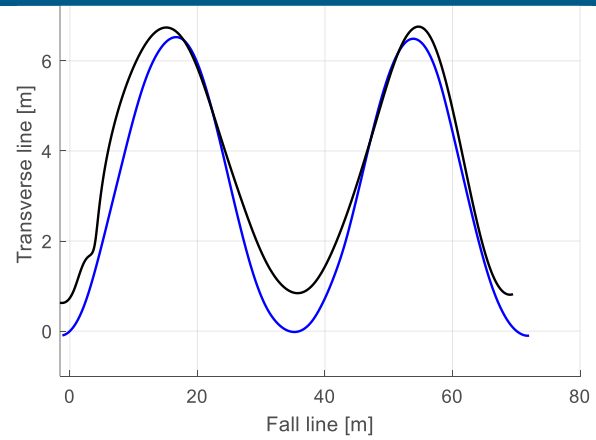


Figure 3: The trajectories of the skier's helmet measured with the reference system (blue line) and the UAV prototype (black line) over two random ski turns. The trajectories are shown as projections on the plane defined by the fall line and its transverse line.

limitations of the measurements and the prototype itself, along with suggestions for improvement, are as follows:

1. The UAV was manually driven, making it difficult to maintain a minimal distance to the skier for optimal camera performance, while also ensuring a sufficient safety distance to prevent possible drone collisions. Automatic flight with low reaction time is recommended.
2. The skier presented only a small portion of the camera's field of view, which reduced the position accuracy of the camera. It is suggested to use a stereo camera with a field of view adapted to the predicted distance to the skier.
3. There were problems with the prototype's RTK position solution. For higher accuracy, a more stable and reliable connection to the CORS is suggested with more visible satellites, or usage of an own RTK base station.

In future studies, also measurement of skier full-body kinematics is planned with the usage of skeleton tracking algorithms as shown in Figure 4. Deep learning techniques enable to reconstruct 3D locations of specific points also if these are not permanently visible on the camera.



Figure 4: Sequence of frames with skeleton tracking. Skeleton tracking has potential for future drone assisted MoCap measurements.

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Thermodynamic and thermoeconomic analysis of continuous casting of steel from the perspective of waste heat recovery

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Continuous casting of steel is an energy-intensive process with significant exergy losses. To address these losses, a thermodynamic and thermoeconomic analysis was performed. Using a numerical simulation model of continuous casting of steel billets, the distribution of strand surface temperature and heat flux were calculated and used to determine the lost exergy flux. The costs associated with these exergy losses were then computed, and the economic potential of waste heat recovery was evaluated using a Curzon–Ahlborn heat engine operating at a maximum power. The resulting cost fluxes are presented graphically.

Introduction

The steel industry is among the most energy-intensive sectors of the economy and represents a significant source of global CO₂ emissions. The economic performance of secondary steel production in small steel plants, typical in the Republic of Slovenia, is largely determined by the prices of raw materials and energy carriers. Steel production in an electric arc furnace (EAF) requires substantial amounts of electrical and chemical exergy, which is typically almost entirely lost during the continuous casting process due to technological constraints imposed by the quality requirements of steel semi-products, the plant's productivity, and the operational safety of all machinery and equipment. Consequently, the cast semi-products must be reheated in reheating furnaces to reach the rolling temperature. These exergy losses impose substantial economic and environmental burdens on steel plants. In this paper, the economic potential of waste heat from the continuous casting of steel billets is evaluated and presented graphically.

Methods

The control volume encompasses a 180 mm × 180 mm billet, extending from the meniscus in the mould up to a length of 25 m. It is modelled using the multiscale Lagrangian travelling slice model, as shown in Figure 1 [1,2].

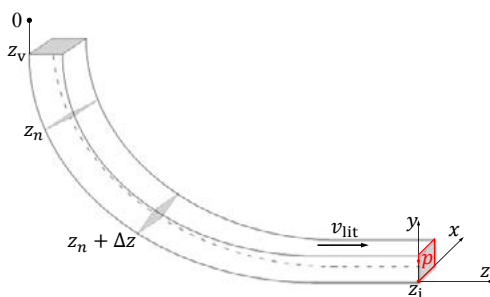


Figure 1: Schematic of the multiscale travelling slice model for continuous casting of steel billets [1,2].

The model is used to numerically compute the distributions of the strand surface temperature and surface heat flux. Multiphase phenomena are modelled using the mixture formulation of Bennon et al. [3]. Steel material properties are obtained from the JMatPro [4] software. The governing energy transport equation (1) for the travelling slice accounts for diffusion in the perpendicular direction of the casting and advection, with neglected diffusion, in the direction of the casting

$$\frac{\partial(\rho h)}{\partial t} = \nabla \cdot (\lambda \nabla T), \quad (1)$$

where h is the mixture mass-specific enthalpy, T is the temperature, t is time, λ is the mixture thermal conductivity, and ρ is the mixture density.

Macrosegregation is modelled using the governing species transport equation of the mixture formulation (2), which accounts for species diffusion, where an enhanced solute diffusion coefficient models the convection

$$\frac{\partial(\rho C)}{\partial t} = \nabla \cdot (\rho f_{m,l} D_1 \nabla C_1), \quad (2)$$

where C is the mixture mass fraction, C_1 is the mass fraction in the liquid phase, D_1 is the solute diffusion coefficient in the liquid phase, and $f_{m,l}$ is the liquid phase mass fraction.

To simplify the description of fluxes and distributions on the strand's lateral surface, the surface is unfolded, and a new coordinate p is introduced along the perimeter of the travelling slice, as shown in red in Figure 1. The origin of the p -coordinate coincides with the origins of the x - and y -coordinates.

Equation (3) represents the distribution of the exergy flux transferred by heat

$$\dot{\Phi}_Q''(p, z) = \left(1 - \frac{T_0}{T(p, z)}\right) \dot{Q}''(p, z), \quad (3)$$

where p is the coordinate along the strand perimeter, Q is the heat, T is the surface temperature, T_0 is the ambient temperature, z is the coordinate along the strand length, and Φ_Q is the exergy transferred by heat. " marks the surface-specific quantity, and dot on the quantity the time derivative.

Equation (4) is used to calculate the distribution of the cost flux of the exergy transferred by heat

$$\dot{B}_{\Phi, Q}''(p, z) = \beta_{\Phi} \dot{\Phi}_Q''(p, z), \quad (4)$$

where $B_{\Phi, Q}$ is the cost of the exergy transferred by heat, and β_{Φ} is the cost per unit of exergy. The cost per unit of exergy is based on a previous thermoeconomic analysis of a 65-ton electric arc furnace and a 65-ton ladle furnace, amounting to €0.37 kWh⁻¹ [5]. The thermoeconomic analysis considered the costs of energy carriers in Slovenia as of June 5, 2025 [6].

Equation (5) represents the distribution of the maximum power produced by the endoreversible Curzon–Ahlborn heat engine [7,8]

$$W''_{Q,CA}(p, z) = \left(1 - \sqrt{\frac{T_0}{T(p, z)}}\right) \dot{Q}''(p, z), \quad (5)$$

where T is the surface temperature and $W_{Q,CA}$ is the work produced by the endoreversible Curzon–Ahlborn heat engine, representing the finite-time exergy transferred by heat.

Equation (6) is used to calculate the distribution of the cost flux of the electricity produced by the Curzon–Ahlborn heat engine

$$\dot{B}''_{el,CA}(p, z) = \beta_{el} W''_{Q,CA}(p, z), \quad (6)$$

where $B_{el,CA}$ is the cost of the electricity produced by the endoreversible Curzon–Ahlborn heat engine and β_{el} is the cost per unit of electricity in Slovenia, which amounted to €0.18 kWh⁻¹ on June 5, 2025 [6]. In this idealised example, losses during the conversion of mechanical power into electricity were considered negligible.

Equation (7) expresses the integral transfer rate of a general quantity flux

$$\dot{X} = \iint \dot{X}''(p, z) dA, \quad (7)$$

where A is the area and X is a general quantity.

Results and discussion

The results include graphical representations of the calculated fields, highlighting regions of the largest irreversibility for steel 46MnVS5 cast at a temperature of 1515°C and a casting speed of 1.62 m min⁻¹ [9]. Figure 2 shows the cost flux of exergy transferred by heat on the four lateral surfaces of the strand.

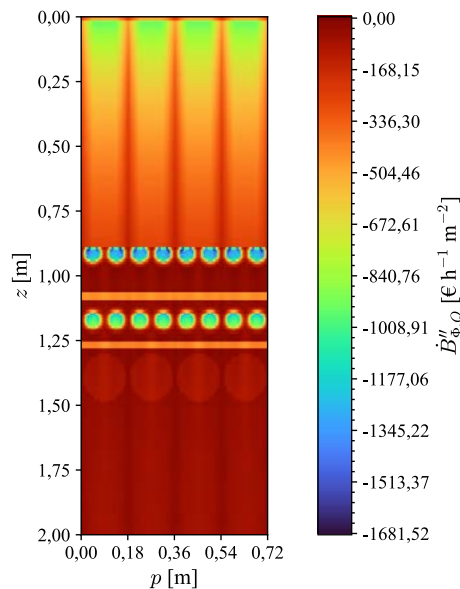


Figure 2: Exergy cost flux on the four lateral surfaces of the strand within the first 2 m from the meniscus in the mould.

Figure 3 shows the cost flux of finite-time exergy transferred by heat on the strand's lateral surface, representing the recoverable portion of the cost flux shown in Figure 2. The difference between these fluxes corresponds to the unavoidable cost of casting.

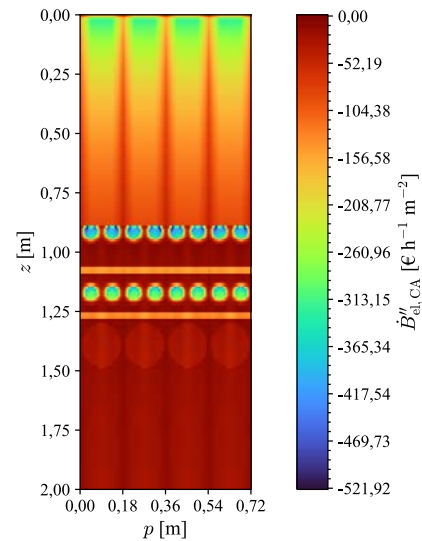


Figure 3: Finite-time exergy cost flux on the four lateral surfaces of the strand within the first 2 m from the meniscus in the mould.

The integral transfer rates of the fluxes are presented in Table 1. The values correspond to the size of the control volume used in the analysis. For a multi-strand caster, the numbers scale proportionally.

Table 1: Integral transfer rates for steel 46MnVS5.

Quantity	Symbol	Value
Total heat transfer rate	$\dot{Q}$	−3.852 MW
Total rate of exergy transferred by heat	$\dot{\phi}_Q$	−2.968 MW
Total rate of exergy cost	$\dot{B}_{\phi,Q}$	−€1098 h ⁻¹
Total rate of finite-time exergy	$\dot{W}_{Q,CA}$	−2.011 MW
Total rate of finite-time exergy cost	$\dot{B}_{el,CA}$	−€362 h ⁻¹

Conclusions

A numerical thermodynamic and thermoeconomic assessment of exergy losses during the continuous casting of steel billets was conducted. The results indicate that a substantial fraction of the supplied exergy is irreversibly destroyed during the operation, representing a significant economic loss. Using finite-time thermodynamics, the recoverable portion of this exergy was quantified and its economic value estimated. These findings demonstrate that waste heat recovery from continuous casting can offer significant economic benefits for steel plants with high energy costs.

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Real-Time Detection of Casting Inclusions and Tool Breakage via Turret Vibration Monitoring

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^bIskra ISD d.o.o., Savska Loka 4, 4000 Kranj

Laboratory LADISK has in collaboration with Iskra ISD, developed a vibration-based system for detecting inclusions in cast parts and tool breakage during turning operations. The problem arises when a CNC machine continues machining after a cutting-edge fracture, producing a large number of defective parts before the issue is noticed. Tool breakage usually occurs suddenly due to inclusions rather than wear, and inclusions themselves can also cause unacceptable surface defects. Continuous inspection of all parts would be too costly; therefore, our system continuously measures vibrations on the tool turret. A dedicated device records acceleration data and communicates with the Fanuc controller, which signals when machining occurs. The system then decides whether machining can continue or if operator intervention is required. Data from multiple devices are collected via MQTT to a central monitoring system, providing real-time visualization and scalability across several machines.

Introduction

During the machining of cast components, material inclusions can cause sudden tool breakage or surface defects that render parts unacceptable (Figure 1). In high-volume production, CNC lathes often operate continuously, so such failures may remain unnoticed for extended periods, producing large numbers of defective parts. Traditional quality control methods, such as end-of-line surface roughness measurements or vision-based inspections, are costly, and often require significant modification of existing manufacturing processes [1].

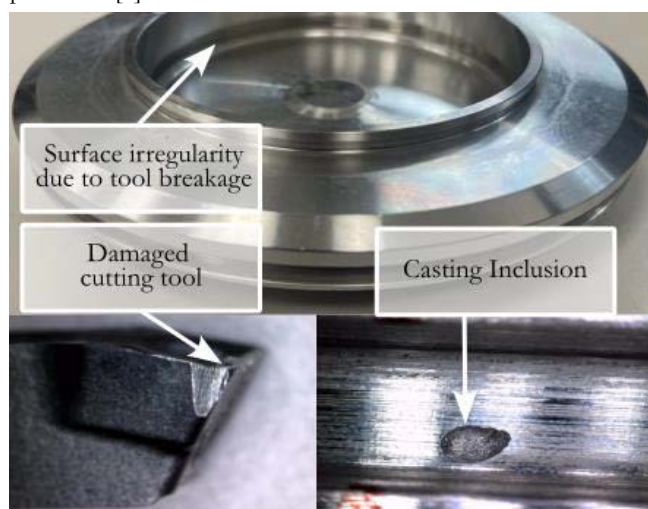


Figure 1: Examples of machining defects on workpiece and cutting tool.

To address these challenges, a real-time, non-invasive monitoring system was developed to detect material inclusions and tool breakage through vibration analysis directly on the tool turret. The system, implemented in collaboration with Iskra ISD on production CNC machines, communicates with the machine via simple electrical signals, allowing automatic intervention when abnormal conditions are detected. This approach prevents the production of defective parts and reduces downtime, improving process reliability and efficiency.

Methodology

A vibration measurement setup was designed to monitor the tool turrets during machining. The goal was to capture the dynamic response as close as possible to the cutting tools to maximize the signal-to-noise ratio. However, because the tools are mounted on a rotating turret head, the accelerometer could not be placed directly on the tool holder due to cable routing limitations. Instead, it was mounted on the stationary turret housing, outside the machining area. This ensured stable attachment and protection from coolant, chips, and other environmental influences while allowing uninterrupted machine operation.

Acceleration signals were continuously sampled and analyzed for amplitude variations. Figure 2 shows vibration data recorded during machining of a single workpiece, where one cutting tool was damaged. A clear increase in vibration amplitude is observed when the damaged tool was active (grey area), while other tools produced nearly identical signals with good repeatability.

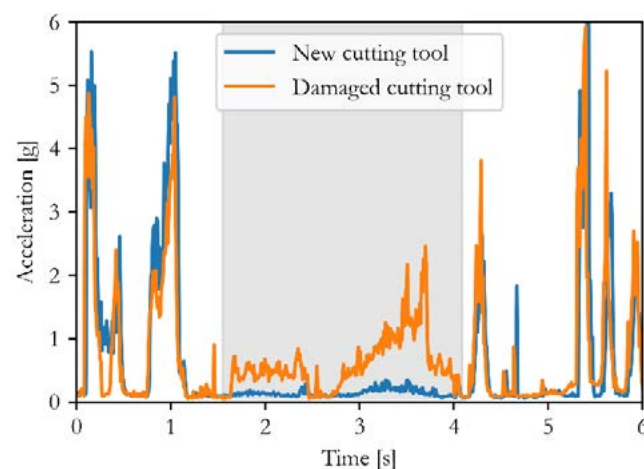


Figure 2: Comparison of acceleration amplitude between new and damaged cutting tool.

Because relatively high vibration amplitudes can also occur during normal cutting, the system architecture was designed to reliably identify which tool was active at any given time, as illustrated in Figure 3. The acquisition device was integrated

with the Fanuc controller, which provides a digital trigger signal whenever the monitored tool is engaged in cutting. This synchronization enables the acquisition system to isolate and analyze only the relevant vibration segments, thereby preventing false detections caused by other tools or normal process variations.

Based on the analysis of the acquired signal, the device evaluates whether the measured vibration amplitude remains within the predefined acceptable range. The corresponding feedback is then transmitted to the Fanuc controller, which either continues machining under normal conditions or stops the process and requests operator intervention when an abnormal condition is detected.

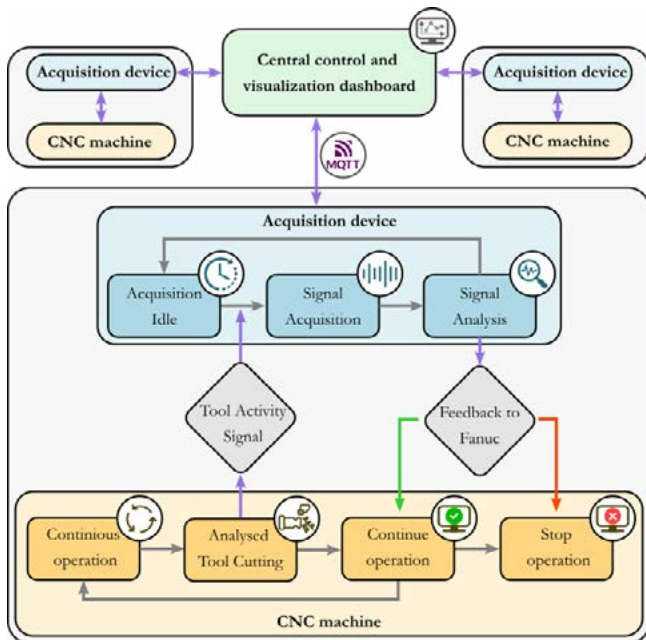


Figure 3: Schematic representation of acquisition, decision making and information workflow.

The decision-making process is based on evaluating the maximum vibration amplitude recorded during each cutting cycle. After acquisition, the signal is analyzed to extract the peak amplitude within the active cutting period. If this maximum value falls within the predefined acceptable range, the operation is classified as OK, indicating normal cutting conditions. When the measured amplitude exceeds the upper threshold, it typically signifies a damaged cutting edge or the occurrence of an inclusion impact in the casting. Conversely, amplitudes significantly below the lower threshold suggest that the cutting insert has fractured completely, resulting in a loss of contact and ineffective machining. This simple yet robust threshold-based approach enables real-time classification of machining conditions and provides a reliable trigger for automated machine intervention.

Results and discussion

A prototype acquisition device, shown on Figure 4, was developed using a Raspberry Pi single-board computer with an MCC DAQ 172 module for high-frequency data acquisition. Because the Fanuc controller operates at 24 V DC logic, a signal conditioning interface was designed to safely convert signals to 3.3 V DC for bidirectional communication. Acceleration was measured with an industrial IEPE

accelerometer (500 g range) to accommodate the high vibration amplitudes that occur during tool failure. The sampling frequency was set to 51.2 kHz, enabling the detection of even small dynamic changes during cutting.



Figure 2: Assembly of acquisition device.

The device can operate fully autonomously with predefined vibration thresholds. For extended functionality, all acquisition units communicate with a central monitoring dashboard via the MQTT protocol. Each device acts as an MQTT client, sending live vibration data, tool status, and decision results to a central broker. The central system stores all data for analysis, visualization, and performance tracking of individual machines.

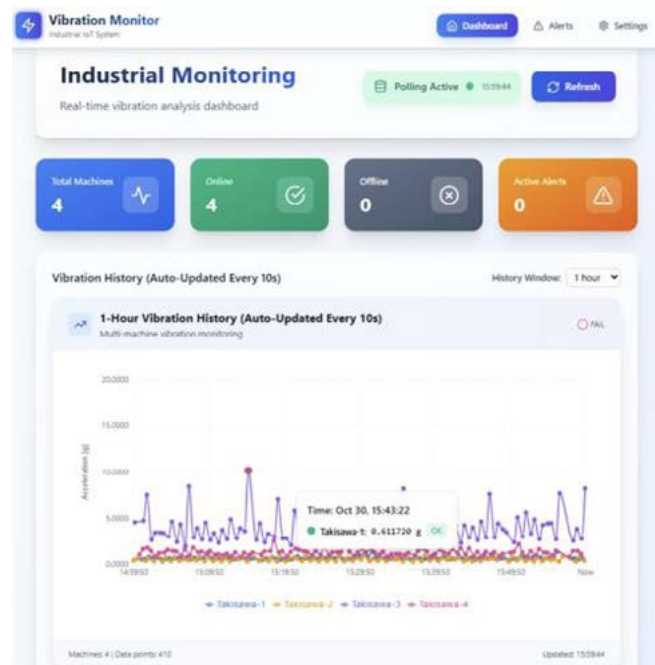


Figure 4: Screenshot of central monitoring dashboard.

Conclusions

The developed system enables accurate, real-time detection of cutting insert breakage and material inclusions during CNC turning. By integrating vibration monitoring with the Fanuc control system, defective parts can be identified immediately, reducing scrap and unplanned downtime. The MQTT-based architecture allows scalable remote monitoring and centralized data analysis for long-term performance tracking and predictive maintenance.

[1] Jang, Dong Young, et al. *International Journal of Machine Tools and Manufacture* 36(4) (1996): 453-464.

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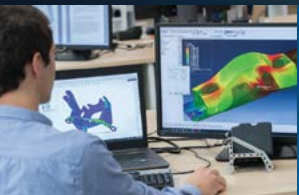
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