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Hibridna in digitalna proizvodnja jeder: Pogled v prihodnost

Hybrid and digital core production: A look into the future

Povzetek

Prihodnost proizvodnje jeder bo hibridna, digitalna in učinkovitejša. V tem vizionarsko naravnanem članku je predstavljen pogled v prihodnost razvoja livarske industrije zaradi vse večjih zahtev po prilagodljivosti, kakovosti in trajnosti. Vključevanje digitalnih tehnologij in dodajnih postopkov, ki presega tradicionalno proizvodnjo, odpira nove razsežnosti v proizvodnji jeder.

Avtorja predstavljata hibridni model, pri katerem se proizvodnja jedra lahko izvaja v podjetju, aditivno s 3D-tiskanjem ali pa se v celoti odda v zunanje izvajanje – odvisno od geometrije jedra, velikosti serije in strateških zahtev. To prilagodljivo nastavitev podpirajo pametna uporaba podatkov, avtomatizacija in napredna simulacija procesov, ki omogočajo spremljanje v realnem času ter ciljno usmerjen nadzor stroškov in emisij.

Prehod z organskih na anorganska veziva je obravnavan kot odziv na strožje okoljske predpise, medtem ko nadzorni sistemi s podporo umetne inteligence in avtomatizirana logistika zmanjšujejo ročno delo in izboljšujejo zanesljivost postopkov. Popolnoma avtomatizirani sistemi so sposobni izdelati kompleksna jedra v najkrajšem cikličnem času, s tem pa je na voljo vpogled v potencial livarn naslednje generacije.

Ta članek ne ponuja le tehničnega pregleda, temveč tudi strateški pogled na to, kako se lahko obdelava jeder popolnoma preoblikuje z združitvijo znanja na področju izvedbe, digitalnih inovacij in prilagodljive avtomatizacije s ciljem izpolniti zahteve proizvodnje ulitkov v prihodnosti.

Ključne besede: hibridna proizvodnja jedra, digitalizacija v livarnah, 3D-tiskanje s peščenimi formami, avtomatizacija procesov v livarnah

Abstract

The future of core production will be hybrid, digital, and more efficient. This visionary article outlines a forward-looking perspective on how the foundry industry is evolving in response to increasing demands for flexibility, quality, and sustainability. Moving beyond traditional manufacturing, the integration of digital technologies and additive processes opens up new dimensions in core production.

The authors present a hybrid model where core production can be conducted in-house, additionally via 3D printing, or outsourced entirely — depending on the core geometry, lot size, and strategic requirements. This flexible setup is supported by smart data use, automation, and advanced process simulation, enabling real-time monitoring and targeted cost and emission control.

The transition from organic to inorganic binder systems is explored as a response to tightening environmental regulations, while AI-supported control systems and automated logistics reduce manual effort and improve process reliability. Fully automated systems are

shown to be capable of producing complex cores within the shortest cycling times, offering a glimpse into the potential of next-generation foundries.

This article offers not just a technical overview, but a strategic outlook on how core shops can reinvent themselves — blending craftsmanship, digital innovation, and scalable automation to meet the demands of tomorrow's casting production.

Keywords: hybrid core production, digitalization in foundries, 3D sand printing, process automation in foundries

1 Uvod

Proizvodnja peščenih jeder v livarski industriji se je skozi desetletja nenehno razvijala in doživela številne tehnološke preboje. Pot je bila dolga – od prve ročne uporabe sistemov na osnovi vodnega stekla [1] v preprostih lesenih jedrovnikih do mehaniziranih postopkov, kot je postopek croning s peskom, prevlečenim s smolo [2], [3]. Uvedba polnjenja jeder leta 1949 s Hansbergovim patentom [4] je pomenila mejnik, ki je revolucionarno spremenila industrijsko proizvodnjo. Danes so za industrijsko proizvodnjo jeder značilni najsodobnejši sistemi veziv, vključno s postopki vročega in hladnega strjevanja ter anorganskimi tehnologijami in avtomatizirani postopki. Kljub temu napredku pa je ročna proizvodnja še vedno nepogrešljiva pri nišnih aplikacijah, kot je litje velikih ulitkov ali maloserijska proizvodnja.

Proizvodnja peščenega jedra je osnova številnih livarskih aplikacij. To je bistvenega pomena za kompleksne geometrije in zelo natančne komponente za panoge, kot so avtomobilska, strojna, letalska in vesoljska industrija. V preteklosti je mehanizirana proizvodnja peščenih jeder poleg stroškovne učinkovitosti zagotavljala tudi zanesljivost, ki je ročni postopki niso mogli doseči. Vendar je za soočanje z današnjimi izzivi, kot so trajnost, ohranjanje virov in stroškovni pritisk, potrebna sprememba paradigme: kombinacija tradicionalnih tehnik z najsodobnejšo tehnologijo.

1 Introduction

The production of sand cores in the foundry industry has developed continuously over the decades and experienced numerous technological breakthroughs. It was a long way from the early manual use of water glass-based systems [1] in simple wooden core boxes to mechanized processes such as the Croning process with resin-coated sand [2], [3]. The introduction of core shooting in 1949 with Hansberg's patent [4] marked a milestone that revolutionized industrial production. Today, state-of-the-art binder systems - including hot and cold curing processes as well as inorganic technologies - and automated processes characterize industrial core production. However, despite these advances, manual production remains indispensable in niche applications such as large-scale casting or small-batch production.

Sand core production forms the backbone of many foundry applications. It is essential for complex geometries and high-precision components that are in demand in industries such as automotive, mechanical engineering, and aerospace. Historically, the mechanized production of sand cores offered not only cost efficiency but also a reliability that manual processes could not match. However, in order to meet today's challenges, such as sustainability, resource conservation, and cost pressure, a paradigm shift is needed: the combination

2 Kaj pomenita hibridizacija in digitalizacija jedrarne prihodnosti?

Hibridna proizvodnja omogoča livarnam prilagodljivost pri izpolnjevanju zahtev spreminjajočega se trga. Cilj je proizvajati visokokakovostne izdelke ob hkratnem ohranjanju virov in zmanjševanju stroškov na enoto. S tem pristopom se podjetja na podlagi svojega posebnega portfelja izdelkov odločijo, katera jedra je treba izdelati s tradicionalnimi metodami, katera z dodajnimi postopki in katera kot storitev pridobiti od zunanjih ponudnikov (»jedro kot storitev«).

Za utemeljitev teh odločitev so bistvene zanesljive podlage za izračun. Digitalni sistemi, ki so popolnoma vključeni v obstoječe sisteme, omogočajo hitro določanje natančnih podatkov. Rešitve, kot je programska oprema Laempe Digital Cockpit, združujejo obratovalne podatke, jih analizirajo in vizualno prikazujejo v realnem času. Tako lahko podjetja ne le spremljajo učinkovitost celotnega obrata (»OEE«), temveč tudi zgodaj prepoznajo možnosti za optimizacijo. Spremljanje v realnem času omogoča takojšnje posredovanje, zlasti v primeru napak, kar je očitna izboljšava v primerjavi s tradicionalno analizo ob koncu cikla.

Digitalizacija ne prinaša le operativnih prednosti, temveč tudi strateške priložnosti. S sistematičnim beleženjem empiričnih vrednosti lahko podjetja dolgoročno optimizirajo in ustvarijo bazo znanja, ki presega znanje posameznih zaposlenih. To ne zagotavlja le kontinuitete, temveč tudi spodbuja inovacije in večjo učinkovitost.

of traditional techniques with state-of-the-art technology.

2 What does hybridization and digitalization mean in the core shop of the future?

Hybrid production gives foundries the flexibility they need to adapt to the requirements of a changing market. The aim is to produce high-quality products while conserving resources and minimizing unit costs. With this approach, companies decide, based on their specific product portfolio, which cores should be produced using traditional methods, which should be manufactured using additive processes and which should be sourced from external providers as a service (“core as a service”).

Reliable calculation bases are essential for these decisions to be well-founded. Digital systems that are seamlessly integrated into existing systems allow precise data to be determined quickly. Solutions such as the Laempe Digital Cockpit bundle operate on data, analyze it, and display it visually in real time. In this way, companies can not only monitor the effectiveness of their entire plant (“OEE”), but also identify optimization potential at an early stage. Real-time monitoring enables immediate intervention, particularly in the event of faults, which is a clear improvement over traditional analysis at the end of a shift cycle.

Digitalization not only brings operational advantages but also strategic opportunities. By systematically recording empirical values, companies can optimize in the long term and create a knowledge base that goes beyond individual employees. This not only ensures continuity but also promotes innovation and increased efficiency.

2.1 Sodobni nadzorni sistemi: učinkovitost s procesi, ki temeljijo na podatkih

Prihodnost proizvodnje jeder bodo odločilno zaznamovali nadzorni sistemi, ki temeljijo na podatkih. Te tehnologije omogočajo optimalno uporabo sistemov in natančno načrtovanje proizvodnih procesov s pomočjo umetne inteligence. Scenariji in simulacije, podprte z umetno inteligenco, omogočajo boljše razumevanje tehničnih procesov in prilagajanje parametrov v realnem času. To omogoča nenehno izboljševanje proizvodnih procesov in njihovo usmerjenost k največji stopnji učinkovitosti.

Simulacije in inteligentne nadzorne rešitve pomagajo pri ekonomični izvedbi zapletenih geometrij, saj vnaprej prepoznajo morebitne izzive. Osebno strokovno znanje in empirične vrednote so vključene v digitalne sisteme, kar je podlaga za nenehno optimizacijo. Zaradi vse večjih zahtev po raznolikosti izdelkov in učinkoviti rabi virov se livarne soočajo z nalogo dejavnega oblikovanja te spremembe. Hibridna in digitalna proizvodnja jedra pomaga določiti idealno obratovalno točko, da se doseže največja učinkovitost ob najmanjših stroških. Da bi to dosegli, ne potrebujemo le sodobnih tehnologij, temveč tudi usposobljeno osebje in obsežno znanje o procesih, ki se prenaša v digitalne rešitve.

2.2 Proizvodnja jeder s streljanjem jeder

Prvi korak pri načrtovanju je določitev najboljše možne strojne in sistemske tehnologije za vsako vrsto jedra, pri čemer je treba upoštevati specifične, vendar prilagodljive rešitve za avtomatizacijo. Najbolje bi bilo, če bi vključili obstoječe sisteme in tako izkoristili sinergije.

Osrednji pristop je zgodnja integracija vseh proizvodnih korakov – od proizvodnje

2.1 Modern control systems: efficiency through data-driven processes

The future of core production will be decisively shaped using data-driven control systems. These technologies make it possible to optimally utilize systems and precisely plan production processes with the help of artificial intelligence (AI). AI-supported scenarios and simulations offer a better understanding of technical processes and allow parameters to be adjusted in real time. This allows manufacturing processes to be continuously improved and geared towards maximum efficiency.

Simulations and intelligent control solutions help to realize complex geometries economically by identifying potential challenges in advance. Personal expertise and empirical values are integrated into digital systems, creating the basis for continuous optimization. In view of the increasing demands for product diversity and resource efficiency, foundries are faced with the task of actively shaping this change. Hybrid and digital core production helps to identify the ideal operating point in order to achieve maximum efficiency at minimum cost. To achieve this, not only are modern technologies required, but also trained personnel and comprehensive process knowledge that is transferred to digital solutions.

2.2 Core production by core shooting

The first step in planning is to identify the best possible machine and system technology for each core type, taking into account specific but flexible automation solutions. Ideally, this is done by incorporating existing systems in order to exploit synergies.

A central approach is the early integration of all production steps - from core production, removal, and post-treatment (such as deburring, finishing, drying, or assembly) to storage logistics jedra, odstranjevanja in naknadne obdelave (kot so glajenje, končna obdelava, sušenje ali montaža) do logistike skladiščenja in vgradnje jedra v matrice ali orodja. Pri načrtovanju jedrovnikov je treba upoštevati vse procesne zahteve: Katera usmeritev jedra je optimalna za postopek streljanja? Ali lahko (robotsko) prijemalo varno obvlada to usmeritev – med odstranjevanjem, predelavo, skladiščenjem ali nastavljanjem jedra? Drugi vidik je standardizacija konceptov prijemal in shranjevanja za različne vrste jeder. Ali je mogoče avtomatizacijo ekonomično uvesti tudi za majhne serije, ne da bi za vsako različico potrebovali popolnoma novo nastavitev orodja?

Analizirati je treba tudi pretok materiala med obratom za obdelavo jeder in livarno. Katere rešitve ločevanja med procesnimi koraki so smiselne, da se v primeru delne odpovedi ohranijo preostali procesi in preprečijo prekinitve v celotni procesni verigi? Proučiti je treba tudi možnost izdelave velikih, ročno izdelanih jeder za ročno oblikovane dele s streljanjem jeder. To bi lahko pospešilo proizvodnjo in zmanjšalo število potrebnega osebja. Če so ti vidiki dosledno upoštevani, sodobna strojna tehnologija podpira učinkovito delovanje. Vedno večja avtomatizacija in prilagodljivost strojev za streljanje jeder revolucionarno spreminjata proizvodnjo, tudi za majhne in srednje velike serije. Skrbno načrtovanje, ki vključuje vse faze izdelave, skladiščenja, logistike in vstavljanja jedra, zagotavlja večjo učinkovitost in nižje stroške ter omogoča, da je proizvodnja jeder pripravljena na prihodnje izzive.

2.3 Proizvodnja jedra s 3D-tiskanjem

Uporaba tehnologij 3D-tiskanja v proizvodnji jeder [5] prinaša številne prednosti. Posamezni sistemi omogočajo izdelavo majhnih in srednje velikih serij brez

and the core-setting into dies or molds. All process requirements must be taken into account when designing the core boxes: Which orientation of the cores is optimal for the shooting process? Can this orientation be safely handled by a (robot) gripper - whether during removal, reworking, storage, or core-setting? Another consideration is the standardization of gripper and storage concepts for different core types. Can automation also be implemented economically for small series without the need for a completely new tool setup for each variant?

The material flow between the core shop and foundry also needs to be analyzed. Which decoupling solutions between the process steps make sense to maintain the remaining processes in the event of a partial failure and avoid interruptions to the entire process chain? The possibility of producing large, manually manufactured cores for hand-molded parts by core shooting should also be examined. This could speed up production and reduce the number of personnel required. If these aspects are consistently taken into account, modern machine technology supports efficient operation. The increasing automation and flexibility of core shooters are revolutionizing production, even for small and medium-sized series. Careful planning, which includes all steps of core making, storage, logistics, and core insertion processes, ensures increased efficiency and reduced costs - and makes core production fit for future challenges.

2.3 Core production by 3D printing

The use of 3D printing technologies in core production [5] opens up numerous advantages. Individual systems make it possible to produce small and medium batch sizes without the use of expensive uporabe dragih orodij. Ker se tiskanje izvaja neposredno iz digitalnih 3D-podatkov, je mogoče spremembe različic izvesti hitro. Odpravljeni so stroški, povezani s konvencionalno proizvodnjo jeder za izdelavo in prilagajanje orodja, ter stroški skladiščenja in vzdrževanja orodja.

Medtem ko se je 3D-tiskanje s peščenimi kalupi včasih uporabljalo predvsem za posamezne kose in majhne serije – zaradi razmeroma dolgega časa postopka in velikega ročnega napora pri razpakiranju – se je tehnologija zdaj močno razvila. Najsodobnejši tiskalniki visoke hitrosti s popolnoma avtomatiziranimi sistemi razpakiranja in čiščenja zdaj omogočajo učinkovito proizvodnjo jeder, pripravljenih za litje. Izjemen primer tega je linija za 3D-tiskanje družbe Laempe, ki se uspešno uporablja v livarni lahkih kovin BMW v Landshutu. Sistem sestavlja šest tiskalnikov, dve mikrovalovni postaji za strjevanje, samodejna priprava in vračanje materiala za orodja ter popolnoma samodejno čiščenje jedra in končna 3D-meritev jedra. Ta celovita rešitev omogoča proizvodnjo od začetka do konca brez ročnih posegov. To je pomemben pogoj za reševanje izzivov, s katerimi se soočajo livarne: Z razvojem novih tehnologij za vozila se zahteve po ulitih delih in njihovi geometriji nenehno povečujejo. Novi šestvaljni motor skupine BMW Group na primer zahteva natančna jedra ulitkov zaradi optimiziranih hladilnih kanalov, česar ni mogoče doseči s tradicionalnimi postopki. To med drugim velja za kombinirana jedra, ki izdelajo hladilne kanale, katerih kompleksne strukture omogočajo boljše hlajenje ter prispevajo k povečanju učinkovitosti in zmanjšanju emisij motorja. Štiri taka šestvaljna kombinirana jedra za izdelavo hladilnih kanalov za novo generacijo motorjev je mogoče izdelati v 20 minutah s tiskalnikom na sistemu Laempe.

tools. As printing is carried out directly from the digital 3D data, variant changes can be implemented quickly. The costs associated with conventional core production for tool production and adaptation, as well as the costs for tool storage and maintenance, are eliminated.

Slika 1. Stroj za izdelavo jeder: Učinkovit in prilagodljiv: Sodobni stroji za izdelavo jeder ostajajo osrednji steber hibridne proizvodnje jeder
(vse slike: © Laempe Mössner Sinto GmbH)

Figure 1. Core shooting machine :Efficient and flexible: Modern core shooting machines remain a central pillar of hybrid core production.
(all Pictures: © Laempe Mössner Sinto GmbH)

While 3D sand printing used to be used primarily for individual pieces and small batches - due to comparatively long process times and the high manual effort involved in unpacking, - the technology has now developed significantly. State-of-the-art high-speed printers with fully automated

Zaradi tega napredka lahko 3D-tiskanje s peščenimi formami ne le zmanjša stroške in čas, potreben za izdelavo orodij za posamezne kose in majhne serije, temveč lahko izvede tudi kompleksne strukture za velike serije, ki ne bi bile izvedljive s konvencionalnimi postopki, ki temeljijo na orodjih.

Slika 2. Sistem za 3D-tiskanje: Natančnost brez orodij: Linija Laempe za 3D-tiskanje omogoča hitro izdelavo jeder za zahtevne geometrije – popolnoma avtomatizirano in pripravljeno za ulivanje.

Figure 2. 3D printing system: Precision without tooling: The Laempe 3D printing line enables high-speed core production for demanding geometries – fully automated and ready-to-cast.

2.4 Pridobivanje jeder pri zunanjih ponudnikih

V številnih livarnah velja izdelava jeder za zamuden in stroškovno intenziven postopek, ki pogosto ni v ospredju tehnološkega razvoja ali človeških virov. Odločitev, da se jedra in orodja pridobijo od specializiranih dobaviteljev, je privlačna alternativa. To livarnam omogoča, da svoje vire usmerijo v ključne kompetence in hkrati povečajo svojo produktivnost.

unpacking and cleaning systems now enable the efficient production of ready-to-cast cores. An outstanding example of this is the 3D printing line from Laempe, which is successfully used in the BMW light metal foundry in Landshut. The system consists of six printers, two microwave stations for curing, automatic mold material preparation and return, as well as fully automatic core cleaning and final 3D measurement of the core. This complete solution enables end-to-end production without manual intervention. An important prerequisite for the challenges facing foundries: With the development of new vehicle technologies, the demands on cast parts and their geometries are constantly increasing. The BMW Group's new six-cylinder engine, for example, requires precise casting cores due to optimized cooling channels, which cannot be achieved with traditional processes. This applies, among other things, to the water jacket combination cores, whose complex structures enable improved cooling and contribute to increasing the efficiency and reducing the emissions of the engine. Four six-cylinder water jacket combination cores for the new generation of engines can be produced within 20 minutes using a printer on the Laempe system.

Thanks to these advances, the 3D sand printing process can not only reduce the costs and time required for tool production for individual pieces and small series, but can also realize complex structures for large series that would not be feasible with conventional tool-based processes.

2.4 External procurement of cores

In many foundries, core making is seen as a laborious and cost-intensive area that is often not the focus of technological development or human resources. The decision to source cores and moulds from specialized suppliers offers an attractive

Slika 3, Sistem za 3D-tiskanje: Natančnost brez orodij: Linija Laempe za 3D-tiskanje omogoča hitro izdelavo jeder za zahtevne geometrije – popolnoma avtomatizirano in pripravljeno za ulivanje.

Slika 3. AR-očala pri servisiranju: Podpora v realnem času: Laempe-AR omogoča serviserjem virtualno sodelovanje s strankami za hitro odpravljanje težav in zmanjšanje izpadov.

Specializirani ponudniki storitev, katerih glavna dejavnost je proizvodnja jeder, ne ponujajo le možnosti pokrivanja proizvodnih konic ali dobave zapletenih jeder, ki jih ni mogoče izdelati z lastnimi stroji. Njihovo strokovno znanje in izkušnje na področju proizvodnje jeder jim omogočajo uporabo najsodobnejših tehnologij, kar zagotavlja visoko raven učinkovitosti in kakovosti.

Primer takšnega dobavitelja je INACORE GmbH, skupno podjetje družb Laempe Mössner Sinto GmbH in R. Scheuchl GmbH. Podjetje se osredotoča zlasti na proizvodnjo anorganskih jeder in poleg tehnološko naprednih rešitev zagotavlja tudi dragocene poslovne prednosti z optimiziranimi procesi in uporabo podatkov.

alternative. This allows foundries to focus their resources on core competencies while increasing their productivity.

Specialized service providers, whose main business is core production, not only offer the possibility of absorbing production peaks or supplying sophisticated cores that could not be produced with their own machinery. Their expertise in core production allows them to use state-of-the-art technologies, resulting in a high level of efficiency and quality.

One example of such a supplier is INACORE GmbH, a joint venture between Laempe Mössner Sinto GmbH and R. Scheuchl GmbH. The company focuses in particular on inorganic core production, delivering not only technologically advanced solutions, but also valuable commercial benefits through optimized processes and data usage.

2.5 Analysis of core costs and CO_2 footprint

Many foundries have limited insight into accurate unit costs, including costs along the entire value chain. Modern calculation programs with high technical standards provide clarity here. Based on component geometry and planned quantities, they make it possible to calculate precisely how much a core will cost and how high the expected CO_2 emissions will be. Tools such as the TSET calculation program provide reliable data on costs and the ecological balance sheet.

Costs are calculated either based on standard values or by making specific adjustments to the respective production plant. Plant-specific data, such as that collected by the “Laempe Digital Cockpit” (LDC), can be incorporated into the analysis. This system collects information from the core shop and enables detailed evaluation.

2.5 Analiza stroškov in ogljičnega odtisa jeder

Številne livarne imajo omejen vpogled v natančne stroške na enoto, vključno s stroški vzdolž celotne vrednostne verige. Jasnost pri tem zagotavljajo sodobni programi za izračun z visokimi tehničnimi standardi. Na podlagi geometrije sestavnih delov in načrtovanih količin je mogoče natančno izračunati, koliko bo stalo jedro in kako visoke bodo pričakovane emisije CO_2. Orodja, kot je program za izračunavanje TSET, zagotavljajo zanesljive podatke o stroških in ekološki bilanci.

Stroški se izračunajo na podlagi standardnih vrednosti ali s posebnimi prilagoditvami za posamezen proizvodni obrat. V analizo se lahko vključijo podatki, specifični za obrat, kot so podatki, zbrani v digitalni pilotni kabini Laempe (»Laempe Digital Cockpit« – LDC). Ta sistem zbira informacije iz obrata za obdelavo jeder in omogoča podrobno vrednotenje.

Programska oprema LDC se lahko uporablja ne le za merjenje skupne učinkovitosti opreme (OEE), temveč tudi za ugotavljanje vzrokov za njeno slabšo učinkovitost: Ali so težave povezane z izpadi, izmetom ali časom cikla? LDC daje odgovore na ta vprašanja in konkretna priporočila za ukrepanje, da bi optimizirali postopke ter povečali gospodarnost in trajnost proizvodnje jeder.

2.6 Laempe-AR: Podpora v realnem času v primeru okvar

Družba Laempe ima obsežno strokovno znanje in izkušnje na področju vzdrževanja in popravil strojev in sistemov za polnjenje jeder. Sodobne tehnologije to znanje prenašajo neposredno na stranke. S pomočjo sistema Laempe-AR lahko servisni tehniki iz lokacij Laempe po vsem svetu v realnem času sodelujejo s strankami na

The LDC can be used not only to measure overall equipment effectiveness (OEE), but also to identify the causes of its impairment: Do the problems lie in downtime, rejects, or cycle time? The LDC provides answers to these questions and gives specific recommendations for action to optimize processes and make core production more economical and sustainable.

Slika 4. Laempe Digital Cockpit (LDC): Transparentnost procesov z uporabo podatkov: LDC zbira in analizira podatke o delovanju v realnem času za povečanje učinkovitosti in zmanjšanje stroškov v proizvodnji jeder.

Figure 4. Laempe Digital Cockpit (LDC): Process transparency through data: The LDC collects and analyzes real-time performance data to increase efficiency and reduce costs in the core shop.

2.6 Laempe-AR: Real-time support in the event of malfunctions

Laempe has extensive expertise in the maintenance and repair of core shooters and systems. This knowledge is passed on directly to customers by modern technologies. With the help of Laempe-AR, service technicians from Laempe locations worldwide can work together with customers kraju samem. Odpravljanje težav se izvaja skupaj z uporabo naprav, kot so očala za navidezno resničnost ali podobne rešitve.

Zlasti v času pomanjkanja kvalificiranih delavcev, omejene razpoložljivosti servisnih tehnikov in vse večjega povpraševanja po učinkovitih procesih ta tehnologija ponuja učinkovit način za hitro in ciljno usmerjeno reševanje težav. Sistem Laempe-AR ne pomaga le zmanjšati izpade proizvodnje, temveč strankam omogoča lažje zagotavljanje dolgoročne zanesljivosti delovanja njihovih sistemov.

2.7 Inovativne tehnologije veziva

Prihodnji razvoj postopkov za izdelavo veziv se vse bolj osredotoča na organske sisteme z nizko vsebnostjo topil in anorganska veziva. Zlasti anorganska veziva postajajo vse pomembnejša tudi na področju litja železa [1]. Uvedba anorganskih sistemov za hladno strjevanje predstavlja nadaljnji napredek, ki bistveno izboljšuje okoljsko združljivost in kakovost pri proizvodnji jeder.

3 Učinkovitost in kakovost z digitalno in hibridno proizvodnjo jeder

Prihodnost proizvodnje jeder je v združevanju preizkušenih proizvodnih metod z najsodobnejšo tehnologijo in avtomatizacijo. Integracija 3D-tiskanja, inteligentnih rešitev za avtomatizacijo in nadzornih sistemov, ki temeljijo na podatkih, lahko bistveno poveča učinkovitost in kakovost v proizvodnji jeder. Podjetja, kot je Laempe Mössner Sinto GmbH, tu prevzemajo pionirsko vlogo in postavljajo inovativne standarde za proizvodnjo jeder prihodnosti.

Kombinacija notranje proizvodnje in sodelovanja s specializiranimi zunanjimi partnerji omogoča prilagodljivost spreminjajočim se zahtevam trga, hkrati pa

on site in real time. Troubleshooting is carried out jointly using devices such as VR glasses or similar solutions.

Especially in times of a shortage of skilled workers, limited availability of service technicians, and increasing demand for efficient processes, this technology offers an effective way to solve problems quickly and in a targeted manner. Laempe-AR not only helps to minimize downtimes but also supports customers in ensuring the long-term operational reliability of their systems.

2.7 Innovative binder technologies

The future development of binder processes is increasingly focusing on low-solvent organic systems and inorganic binders. Inorganic binders in particular are also becoming increasingly important in the field of iron casting [1]. The introduction of cold-curing inorganic systems represents further progress that significantly improves both environmental compatibility and quality in core production.

3 Efficiency and quality through digital and hybrid core production

The future of core production is in combining proven production methods with state-of-the-art technology and automation. The integration of 3D printing, intelligent automation solutions, and data-driven control systems can significantly increase efficiency and quality in core production. Companies such as Laempe Mössner Sinto GmbH are taking on a pioneering role here and setting innovative standards for the core production of tomorrow.

The combination of in-house production and collaboration with specialized external partners enables flexible adaptation to changing market requirements while optimizing costs at the same time. This optimizira stroške. Ta hibridni in digitalizirani pristop bo trajno vplival na livarsko industrijo ter odprl nove možnosti za povečanje učinkovitosti in tehnološkega napredka.

4 Zaključek

Prihodnost proizvodnje jeder je v prevzemanju hibridne in digitalne paradigme. Z uporabo tehnologij, kot so 3D-tiskanje, nadzorni sistemi, ki jih poganja umetna inteligenca, in sodobna anorganska veziva, lahko livarne dosežejo večjo učinkovitost, natančnost in prilagodljivost. Vključevanje teh tehnologij ne povečuje le stroškovne učinkovitosti, temveč prispeva tudi k bolj trajnostni vrednostni verigi.

Podjetja, kot je Laempe Mössner Sinto, so pionirji te preobrazbe, saj ponujajo popolnoma integrirane sisteme – od osnovnih strojev za zajem do digitalnih platform in servisnih rešitev na daljavo. Njihov pristop omogoča livarnam, da izberejo najprimernejšo proizvodno metodo za vsako vrsto jedra, ki jo podpirajo podatki v realnem času in razširljiva avtomatizacija.

Navsezadnje ta razvoj spodbuja novo raven prilagodljivosti in preglednosti v obratu za obdelavo jeder, s čimer se industrija lahko spopade z vse večjo kompleksnostjo, pomanjkanjem delovne sile in okoljskimi zahtevami.

hybrid and digitalized approach will have a lasting impact on the foundry industry and opens up new prospects for increasing efficiency and technological progress.

4 Conclusion

The future of core production lies in embracing a hybrid and digital paradigm. By leveraging technologies such as 3D printing, AI-driven control systems, and modern inorganic binders, foundries can achieve greater efficiency, precision, and adaptability. The integration of these technologies not only enhances cost-effectiveness but also contributes to a more sustainable value chain.

Companies like Laempe Mössner Sinto are pioneering this transformation by offering fully integrated systems — from core shooting machines to digital platforms and remote service solutions. Their approach enables foundries to choose the most suitable production method for each core type, supported by real-time data and scalable automation.

Ultimately, this evolution fosters a new level of flexibility and transparency in the core shop, equipping the industry to tackle rising complexity, labor shortages, and environmental demands.

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Analiza kakovosti ingotov iz različnih aluminijevih zlitin

Analysis of the quality of different aluminum alloy ingots

Povzetek

Pretekle raziskave so pokazale, da se lahko kakovost ingotov, ki jih proizvedejo različni dobavitelji primarnih ali sekundarnih zlitin, bistveno razlikuje. Tako lahko vsebnost nečistoč v ingotih, ki se uporabljajo kot vložek, vpliva na kakovost tekoče kovine in ulitkov iz nje. V tem delu je bila uporabljena spremenjena tehnika preskusa z zmanjšanim tlakom (RPT), ki temelji na pretaljevanju vzorcev, pridobljenih iz ingotov, za ugotavljanje kakovosti primarnih ingotov iz zlitine AlSi9Mn, izdelanih s tehnikama horizontalnega polkontinuiranega litja (HDC) in gravitacijskega litja. Za ocenjevanje kakovosti kovine je bila opravljena analiza slik prečnih prerezov. Določeni so bili delež površine s porami, številčna gostota, normaliziran indeks bifilma in normaliziran skupni obseg por ter analizirana razmerja med različnimi metrikami. Opravljena je bila primerjava rezultatov z oceno kakovosti taline staljenih serij, izdelanih iz ingotov. Izvedene so bile simulacije strjevanja, termična analiza in mikrostrukturne preiskave, da bi ugotovili pogoje strjevanja tradicionalnih in pretaljenih vzorcev za preskus z zmanjšanim tlakom. Na podlagi rezultatov je razvidno, da imajo ingoti, uliti s tehniko horizontalnega polkontinuiranega litja, nižje koncentracije oksidov in plinov, kar je mogoče pripisati razlikam v tehnikah priprave taline in ulivanja ingotov. Primerjava parametrov, ocenjenih z analizo slik, je pokazala, da obstaja močna linearna povezava med normaliziranim indeksom bifilma in normaliziranim skupnim obsegom por. Izpostavljeni so možni viri napak pri ocenjevanju kakovosti ingotov.

Ključne besede: aluminijeva zlitina, ingot; kakovost kovine; preskus z zmanjšanim tlakom, bifilm, litje

Abstract

Previous research has revealed that the quality of ingots produced by different primary or secondary alloy suppliers can differ significantly. In this way, the quality of the liquid metal and the castings made from it can be affected by the impurity content of the ingots used as charge material. In this work, a modified reduced pressure test (RPT) technique, which is based on the remelting of samples extracted from ingots, was applied to investigate the quality of primary AlSi9Mn ingots made by horizontal direct-chill (HDC) casting and gravity casting techniques. For the evaluation of metal quality, image analysis of the cross-sections was applied. Pore area fraction, number density, normalized Bifilm-Index, and normalized total pore perimeter were determined, and the relationships between the different metrics were analyzed. The results were compared with the melt quality assessment of the as-melted batches made from the ingots. Solidification simulations, thermal analysis, and microstructural investigations were conducted to investigate the solidification conditions of traditional and remelted RPT samples. Based on the results, the HDC cast ingots possess lower oxide and gas concentrations, which can be traced back to the differences in the melt preparation and casting technologies of the ingots. The comparison of the parameters evaluated by image analysis revealed that there is a strong linear relationship between the normalized Bifilm-Index and the normalized total pore perimeter. The possible sources of error in ingot quality evaluation are highlighted.

Keywords: aluminum alloy; ingot; metal quality; reduced pressure test; bifilm; casting

1 Uvod

Ne glede na tehnologijo litja, ki se uporablja za izdelavo ulitih sestavnih delov, igra kakovost taline bistveno vlogo pri zagotavljanju visoke strukturne celovitosti, mehanskih lastnosti in preprečevanju napak pri litju, kot so poroznost, puščanje, pokanje v vročem in razpoke [1–3]. Že prvo od znanih desetih pravil, ki jih je oblikoval *Campbell* [4, 5], da bi določil temeljne zahteve za izdelavo visokokakovostnih kovinskih ulitkov, poudarja, da je pomembno »začeti z dobro kakovostno talino«. Da bi to dosegli, je treba skrbno izbrati, izvesti in nadzorovati korake taljenja, prenosa taline in obdelave taline. Vendar se lahko kakovost ingotov, ki jih proizvedejo različni dobavitelji primarnih ali sekundarnih zlitin, močno razlikuje. Tako na kakovost taline vpliva vsebnost nečistoč v ingotih, ki se uporabljajo kot vložek [6]. Vsi ingoti niso izdelani na enak način: proizvajalci kakovostnih ingotov uporabljajo linijsko razplinjevanje in filtre. Če izbrani dobavitelj ne uporablja ustreznega postopka obdelave taline, morajo livarne spremeniti svoje metode obdelave taline, da bi se izognile povečanju poroznosti in z oksidi povezanega izmeta [7]. Drugo ključno vprašanje je metoda litja ingotov. Če se ingoti ulivajo s turbulentnim litjem, so lahko učinki obdelave taline ovirani [8].

Grandfield [9] je izčrpno pregledal proizvodne metode pretaljevanja ingotov iz aluminija in aluminijevih zlitin. Najpogostejša tehnologija za proizvodnjo ingotov livarskih zlitin je gravitacijsko litje v odprte kokile, ki so navadno nameščena v transportno linijo za ingote **(Slika 1. (a)).** V ta namen se

1 Introduction

Regardless of the casting technology used for manufacturing cast components, liquid metal quality has an essential role in providing high structural integrity, mechanical performance, and the avoidance of casting defects such as porosity, leakage, hot tears, and cracks [1-3]. Even the first of the well-known ten rules, created by *Campbell* [4, 5] to provide the fundamental requirements for the manufacture of high-quality metal castings, emphasizes the importance of “starting with a good-quality melt”. To accomplish this, the melting, melt-transfer, and melt-processing steps need to be carefully selected, executed, and controlled. However, the quality of the ingots produced by different primary or secondary alloy suppliers can differ remarkably. In this way, the melt quality is affected by the impurity content of the ingots used as charge material [6]. Not all ingots are created the same way: quality ingot producers use in-line degassing and filters. If the selected supplier is not using appropriate melt treatment, the foundries need to modify their melt treatment methods to avoid an increase in porosity and oxide-related scrap [7]. Another critical issue is the casting method of the ingots. If the casting of ingots is performed by pouring turbulently, the effects of melt treatments can be hindered [8].

The production methods of remelting aluminum and aluminum alloy ingots were comprehensively reviewed by *Grandfield* [9]. The most common technology to produce foundry alloy ingots is gravity casting into navadno uporabljajo litoželezne ali jeklene kokile, polnjenje pa poteka z livnim kolesom ali avtomatskimi livnimi ponovcami. Hitrost transportne linije je običajno optimizirana za povečanje produktivnosti, pri čemer je treba upoštevati tudi hitrost strjevanja. Zato so kokile pogosto hlajene z vodo, da se doseže večja hitrost proizvodnje. Na kakovost zlitine in nastajanje oksidov med polnjenjem vplivajo predvsem zasnova livnega kolesa ali ponovce ter postopki ravnanja s talino in obdelave pred litjem. Proizvajalce ingotov zanima predvsem ohranjanje visokih proizvodnih hitrosti, pri čemer je nastajanje oksidov med ulivanjem čim manjše. Številne študije [10–12] kažejo, da je mogoče z optimizacijo faze polnjenja učinkovito zmanjšati nastajanje žlindre in vnašanje oksidov. Vendar pa tudi pri uporabi optimiziranega polnjenja kokile sama metoda ni brez oksidov in zajemanja zraka, zlasti pri običajnih proizvodnih stopnjah, ki se uporabljajo v industriji. Druga pogosta težava gravitacijsko ulitih ingotov je, da imajo običajno luknje zaradi krčenja, ki lahko vsebujejo celo vodo, kar je posledica vodnega hlajenja neposredno na ingotu ali neustreznega skladiščenja [13]. Zaradi tega obstaja nevarnost eksplozij, če se z vodo kontaminirani ingoti polnijo neposredno v talino [14]. Vedno bolj se uveljavlja uporaba linijskega razplinjevanja in filtrov iz keramične pene pred gravitacijskim litjem ingotov, kar bi lahko pripomoglo k zmanjšanju vsebnosti vključkov v kovini [7, 9].

Horizontalno polkontinuirano litje (HDC) je še ena pogosta tehnologija za proizvodnjo livarskih ingotov. HDC je postopek neprekinjenega litja, pri katerem se talina dovaja iz vmesne ponvice do kokil hlajenih z vodo, skozi ognjevarno prenosno cev **(Slika 1. (b)).** Valj za odvzem deluje z zahtevano hitrostjo litja. Palice, ulite s postopkom HDC, imajo strogo nadzorovane

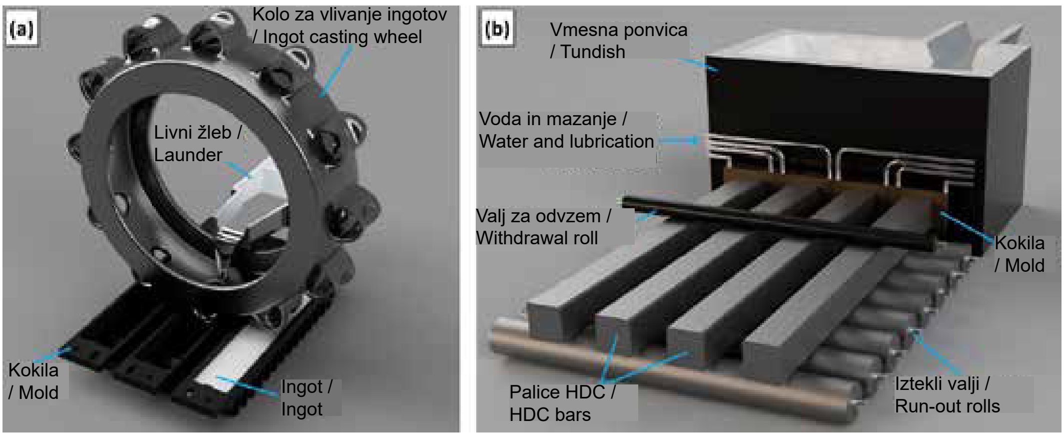
open molds that are typically assembled into an ingot conveyor line (**Figure 1 (a)**). Cast iron or steel molds are generally used for this purpose, and the filling is executed through a casting wheel or automated casting ladles. The speed of the conveyor line is usually optimized to maximize productivity, while the solidification rate also needs to be considered. For this reason, the molds are often water-cooled to achieve higher production rates. In terms of metal quality and dross formation during filling, the design of the casting wheel or ladle, as well as the upstream melt handling and treatment methods, are the main influences. Ingot producers are mainly interested in maintaining high-production rates, while dross formation during pouring is kept at a minimum. There are numerous studies [10-12] that show that by optimizing the filling stage, dross formation and oxide entrainment can be effectively lowered. However, even when optimized mold filling is utilized, the method itself is not free of oxide and air entrainment, especially at the common production rates applied by the industry. Another common problem of gravity-cast ingots is that they usually have shrinkage cavities, which can even contain water as a result of applying water cooling directly on the ingot or as a result of inappropriate storage [13]. This holds the risk of explosions if water-contaminated ingots are charged directly to liquid metal [14]. There has been a growing trend to apply in-line degassing and ceramic foam filters before gravity casting of the ingots, which could help in lowering the inclusion content of the metal [7, 9].

Horizontal direct-chill casting (HDC) is another common technology to produce foundry ingots. HDC is a continuous casting process in which liquid metal is fed from the tundish to water-cooled molds through a refractory transfer tube and an orifice plate dimenzije in običajno nimajo razpok ali lukenj zaradi krčenja. Ker postopek ne vključuje ulivanja in talina ne pada prosto, je koncentracija žlindre in ujetih oksidov veliko manjša kot pri litju v odprte kokile. Na zahtevanih dolžinah se palice odrežejo z žago za odrezovanje, ki je sinhronizirana z valjem za odvzem [9, 15]. Stroji za litje so običajno povezani s talilnimi pečmi prek sistema za odstranjevanje nečistoč iz kovin, ki vključuje enote za razplinjevanje in filtrske škatle [16, 17].

Pri izbiri dobavitelja materiala za vložek je treba kot pomembno nalogo obravnavati odkrivanje in količinsko določanje nečistoč, prisotnih v ingotih. Literatura za to nalogo navaja različne pristope. Večina teh metod za karakterizacijo temelji na preskusu z zmanjšanim tlakom (RPT). *Fox* in *Campbell* [18, 19] sta poročala, da je preskus RPT lahko učinkovito orodje za ocenjevanje kakovosti taline. Med strjevanjem pod zmanjšanim tlakom se plini, ki se zadržujejo med plastmi napak bifilma, raztezajo [20]. Poleg tega se topnost vodika v zlitini zmanjša zaradi nižjega delnega tlaka

(**Figure 1 (b)**). The withdrawal roll is driven at the required casting speed. HDC cast bars have tight dimensional controls and usually no cracks or shrinkage cavities. As the process does not involve any pouring action and there is no free-falling liquid metal, there is much lower dross and entrained oxide concentration than in open mold casting. At the required lengths, the bars are cut with a cut-off saw, which is synchronized with the withdrawal roll [9, 15]. The casting machines are generally connected to the melting furnaces through a metal launder system, which involves inline degassing units and filter boxes [16, 17].

The detection and quantification of impurities present in ingots should be considered as an important task when selecting the supplier of the charge material. There are different approaches available in the literature for this task. Most of these characterization methods are based on the reduced pressure test (RPT). *Fox* and *Campbell* [18, 19] reported that RPT can be an effective tool in the evaluation of liquid



Slika 1. Shematski prikaz (a) gravitacijskega litja (GC) v odprte kokile in (b) horizontalnega polkontinuiranega litja (HDC)

Figure 1. Schematic illustration of (a) gravity casting (GC) into open molds and (b) horizontal direct-chill casting (HDC)

vodika, kar povzroči večje izločanje H_2 [21]. Posledica teh dejavnikov je, da se napake dvojnega oksidnega filma znotraj vzorcev RPT razširijo, kar omogoča lažje odkrivanje z rentgensko radiografijo ali kvantitativno analizo slike na poliranem prerezu [18]. *Dispinar* in *Campbell* [22] sta uvedla tako imenovani indeks bifilma (BI), ki se lahko uporablja za količinsko opredelitev vsebnosti bifilma v talini na podlagi vsote največjih dolžin por, ugotovljenih na prečnem prerezu vzorcev RPT.

Dispinar in *Campbell* [23] sta preučila učinke zmanjšanja višine prostega padanja in turbulence znotraj livnega žleba na kakovost gravitacijsko ulitih sekundarnih livarskih ingotov. Njuna metoda za karakterizacijo je vključevala pretaljevanje ingotov v indukcijski peči in odvzem vzorcev RPT, nato pa sta ocenila gostoto in vrednosti indeksa bilfma. Z zmanjšanjem višine padanja in izboljšanjem pretoka v livnem žlebu z oblikovnimi spremembami, se je jasno izboljšala kakovost zlitin: gostota vzorcev RPT se je povečala, medtem ko se je indeks biflma učinkovito zmanjšal. Vendar so spremembe zmanjšale hitrost proizvodnje, ki je za nekatere dobavitelje ingotov pomembnejši parameter kot kakovost kovine. *Erzi* in drugi [6] so predlagali razmeroma zapleteno metodo za ocenjevanje kakovosti ingotov različnih dobaviteljev. Iz preiskovanih ingotov se pripravijo 10-kilogramske šarže, po taljenju pa se ulijejo vzorci za RPT, livnost in natezni preskus. Tako imenovani dobaviteljev indeks kakovosti se nato izračuna iz indeksa bifilma, dolžine livnosti in nateznih lastnosti. Metoda *Erzija* in *Tiryakioğluja* [24] vključuje izrez vzorca iz sredine preiskovanega ingota in njegovo mehansko obdelavo na točno določeno velikost lončka za vzorčenje RPT. Vzorec se stali v lončku in strdi v delnem vakuumu. Nato se z metalografskimi metodami ali

metal quality. During solidification under reduced pressure, the entrained gases between the layers of bifilm defects are expanded [20]. In addition, the solubility of hydrogen in the alloy is reduced by the lower hydrogen partial pressure, which results in enhanced H_2 precipitation [21]. The consequence of these factors is that double oxide film defects inside the RPT samples are expanded, which allows easier detection by X-ray radiography or quantitative image analysis on a polished section [18]. *Dispinar* and *Campbell* [22] introduced the so-called Bifilm-Index (BI), which can be used to quantify the bifilm content of the molten metal based on the sum of the maximum lengths of pores found on the cross-section of RPT samples.

Dispinar and *Campbell* [23] investigated the effects of reducing the free-falling height and the turbulence inside the casting launder on the quality of gravity-cast secondary foundry ingots. Their characterization method involved the remelting of the ingots in an induction furnace and taking RPT samples, then the density and the Bifilm-Index values were evaluated. There was a clear improvement in the metal quality by reducing the falling height and by improving the flow inside the launder by design modifications: the density of the RPT samples increased while the Bifilm-Index was effectively reduced. However, the production rate was lowered by the modifications, which tends to be a more important parameter for some ingot suppliers than metal quality. *Erzi* et al. [6] proposed a relatively complex method for assessing the quality of ingots from different suppliers. 10 kg charges are prepared from the investigated ingots, and after melting, RPT, spiral fluidity, and tensile test specimens are cast. The so-called Supplier’s Quality Index is then calculated from the Bifilm-Index, fluidity length, and računalniško tomografijo (CT) odkrijejo in količinsko opredelijo pore v vzorcu. *Erzi* in *Tiryakioğlu* sta s primerjavo rezultatov analize slike prečnega prereza vzorcev RPT in analize poroznosti z računalniško tomografijo ugotovila, da obe metodi dajeta podobne rezultate. Podoben pristop sta uporabila tudi *Hsu* in *Li* [25], ki sta pretaljene vzorce RPT uporabila za ugotavljanje vpliva različnih zasnov ulivnih sistemov in filtrov iz keramične pene na kakovost kovine. Njihova metoda je vključevala rezanje majhnih vzorcev (3 × 3 × 7 cm) in taljenje v lončkih za vzorčenje RPT pri 700 °C s časom zadrževanja v peči 1 uro.

Fox in *Campbell* [19] prav tako omenjata, da so bili med razvojem njunih testov pretaljevanja izvedeni začetni poskusi z isto metodo, ki sta jo predlagala *Erzi* in *Tiryakioğlu* [24] (tj. izdelava vzorca v točno določeni velikosti lončka za vzorčenje RPT in pretaljevanje v njej), ki je bila dolgotrajna in lahko povzroči zračne žepe med vzorcem in steno lončka, kar lahko med pretaljevanjem povzroči plinsko poroznost. Zato sta *Fox* in *Campbell* predlagala uporabo poroznega medija, kot je pesek ali aluminijev oksid, ki lahko med pretaljevanjem podpira vzorec v majhnem vsebniku, kot je jeklena posodica. Po našem vedenju ta metoda še ni bila uporabljena v nobenem objavljenem raziskovalnem delu, njeni podrobni tehnični parametri, ki omogočajo ustrezno preučitev kakovosti kovine, pa v literaturi niso pojasnjeni. Po navedbah omenjenih avtorjev je mogoče pri tej metodi uporabiti katero koli geometrijo vzorca. Vendar bi bilo praktično uporabiti geometrijo vzorca, temperaturo pretaljevanja in količino poroznega medija, ki omogočajo podobno hitrost strjevanja kot pri tradicionalnih vzorcih RPT. Hitrost strjevanja je ključni dejavnik pri nastajanju poroznosti [26–28]. Prevelika hitrost strjevanja lahko ovira rast por, medtem ko lahko prepočasno strjevanje

tensile properties. The method of *Erzi* and *Tiryakioğlu* [24] involves cutting out a sample from the middle of the investigated ingot and machining it to the exact size of the RPT sampling cup. The specimen is melted inside the cup and solidified in a partial vacuum. Then, the detection and quantification of pores in the sample are conducted with either metallographic methods or computed tomography (CT). By comparing the results of the image analysis of the cross-section of the RPT samples and the CT porosity analysis, *Erzi* and *Tiryakioğlu* concluded that both methods yield similar results. A similar approach was utilized by *Hsu* and *Li* [25], who used remelted RPT samples for the characterization of the effect of different gating system designs and ceramic foam filters on the metal quality. Their method involved sectioning small samples (3x3x7 cm) and remelting them in the RPT sampling cups at 700 °C with a furnace residence time of 1 hour.

Fox and *Campbell* [19] also mention that during the development of their remelting tests, initial trials were carried out with the same method suggested by *Erzi* and *Tiryakioğlu* [24] (i.e., machining a sample to the exact size of the RPT sampling cup and remelting in it), which were time-consuming and can result in air pockets being trapped between the sample and the crucible wall, which can cause air-entrainment during remelting. For this reason, *Fox* and *Campbell* suggested the use of a porous medium such as sand or alumina that can support the specimen in a small container, like a steel cup, during remelting. To the best of our knowledge, this method has not been adopted by any published research work yet, and its detailed technical parameters that allow proper investigation of metal quality are not clarified in the literature. According v delnem vakuumu povzroči odstranjevanje plina v obliki mehurčkov, ki počijo na površini (podobno kot pri vakuumskem razplinjevanju) [29]. Zato je bil namen pričujočega raziskovalnega dela preizkusiti metodo *Foxa* in *Campbella* za opredelitev kakovosti ingotov iz aluminijevih zlitin in raziskati pogoje strjevanja med uporabo te metode. V ta namen so bile izvedene simulacije strjevanja, izbrani parametri pa so bili preizkušeni s preiskavo kakovosti ingotov iz primarne aluminijeve zlitine, proizvedenih z različnimi tehnologijami. Opravljena je bila primerjava rezultatov z oceno kakovosti taline staljenih serij, izdelanih iz ingotov.

3 Materiali in preskusni postopek

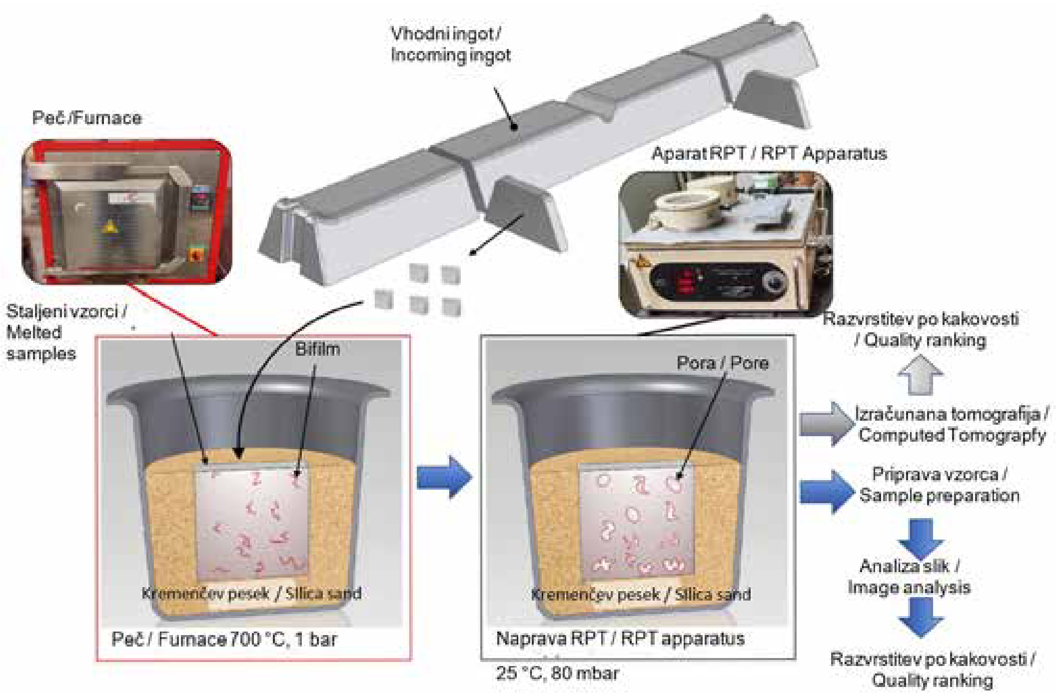
Predlagani postopek pretaljevanja je shematično prikazan na **Sliki 2.** Majhni vzorci so izdelani iz ingotov preiskovane zlitine in staljeni v kremenčevem pesku pri 700 °C. Kot talilni medij smo uporabili nevezan kremenčev pesek s povprečno velikostjo zrn 0,35 mm. Za te preizkuse je bil izbran vzorec velikosti 20 × 20 × 10 mm, ki se je zlahka prilegel v posodico za vzorec RPT. Po taljenju se vzorec prenese v vakuumsko komoro naprave RPT. Po strjevanju je mogoče vzorce preučiti z računalniško tomografijo ali z analizo slik prečnih prerezov, narejenih po ustrezni metalografski pripravi. V tem delu je bil izbran slednji pristop.

Izbira sipkega peska kot talilnega medija je temeljila na delu *Foxa* in *Campbella* [19], ki sta poročala, da se pri pretaljevanju vzorcev (ki so obdelani na natančno velikost jeklenih posodic) v jeklenih posodicah lahko med vzorcem in steno lončka ujamejo zračni žepi, kar lahko med pretaljevanjem povzroči zajetje zraka. Ker ima sipek pesek visoko prepustnost

to the mentioned authors, any sample geometry can be used for this method. However, it would be practical to use a sample geometry, remelting temperature, and porous medium quantity that allows a similar solidification rate as in the case of traditional RPT samples. The solidification rate is a critical factor in porosity formation [26-28]. Too high solidification speed can hinder pore growth, while too slow solidification under partial vacuum can result in gas removal in the form of bubble bursting on the surface (similarly to vacuum degassing) [29]. Consequently, the present research work aimed to test the method of *Fox* and *Campbell* for the characterization of the quality of aluminum alloy ingots and to investigate the solidification conditions during the utilization of the method. For this, solidification simulations were conducted, and the selected parameters were tested by investigating the quality of primary aluminum alloy ingots produced by different technologies. The results were compared with the melt quality assessment of as-melted batches made from the ingots.

3 Materials and Experimental Procedure

The proposed remelting procedure is schematically illustrated in **Figure 2**. Small samples are machined from the investigated alloy ingots and melted in silica sand at 700 °C. We used unbonded loose silica sand as a melting medium with an average grain size of 0.35 mm. For these tests 20 × 20 × 10 mm sample size was selected, which fit easily into the RPT sample cup. After melting, the sample is taken to the vacuum chamber of the RPT apparatus. Following solidification, the specimens can be investigated by computed tomography or by the image analysis of cross-



Slika 2. Shema ocenjevanja kakovosti materiala ingota

Figure 2. The scheme for the quality assessment of the ingot material

za pline, zrak med zrni peska, ki obdajajo vzorec kovine, ne more vstopiti v vzorec kovine, saj bi za vstop v tekočo kovino skozi površinsko oksidno plast potreboval večji tlak kot za izstop skozi pore med zrni peska.

V prvem koraku naše preiskave smo izvedli simulacije strjevanja s pomočjo modula za gravitacijsko litje programske opreme za simulacijo NovaFlow&Solid, da bi raziskali razlike med hitrostjo strjevanja tradicionalnih in pretaljenih vzorcev RPT. Najprej je bilo simulirano strjevanje tradicionalnega vzorca RPT **(Slika 3. (a)),** ulitega iz Al-9,5%Si-0,4%Mn-0,15% Fe (teža 90 g), pri temperaturi ulivanja 700 °C. Za orodje je bila izbrana jeklena čaša (s toplotno prevodnostjo 26 W/m·K), segreta na 300 °C, z 0,8 mm debelo ognjevzdržno prevleko (s toplotno

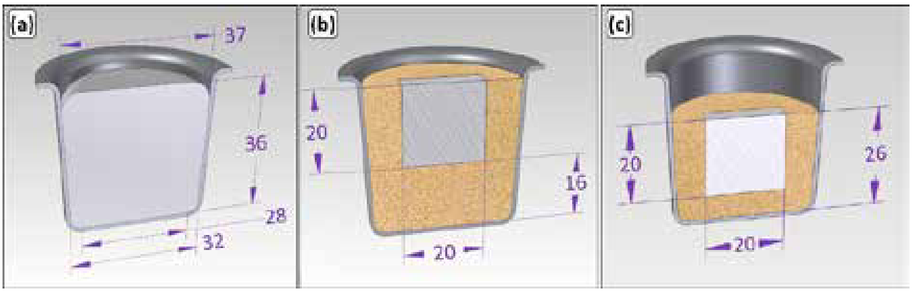
sectional images made after appropriate metallographic preparation. The latter approach was chosen in this work.

The selection of loose sand as a melting medium was based on the work by *Fox* and *Campbell* [19], who reported that remelting samples (which are machined to the exact size of the steel cups) in steel cups can result in air pockets being trapped between the sample and the crucible wall, which can cause air-entrainment during remelting. As loose sand has high gas permeability, the air between the sand grains surrounding the metal sample cannot enter the metal sample, as it would require more pressure to enter the liquid metal through the surface oxide layer than escaping through the pores between the sand grains.

prevodnostjo 0,25 W/m-K). Nato smo simulirali strjevanje pretaljenega vzorca velikosti 20 × 20 × 10 mm s kremenčevim peskom kot materialom orodja (z izbrano toplotno prevodnostjo 0,3 W/m-K [30]) in jekleno čašo RPT kot posodo **(Slika 3. (b, c)).** Začetna temperatura vzorca in orodja je bila 700 °C. Med simulacijami sta bili preizkušeni dve količini peska: 55 g, kar zadostuje za popolno zapolnitev jeklene čaše **(Slika 3. (b)),** in 30 g **(Slika 3. (c)),** kar je bilo izbrano zaradi skrajšanja časa strjevanja. Za poskuse v realnih okoliščinah je bila izbrana količina 30 g peska. Razlog za to izbiro je, da je bilo med predhodnimi preskusi s posodicami za vzorčenje, popolnoma napolnjenimi s peskom, ugotovljeno, da je bila zgornja površina vzorca popolnoma tekoča tudi po 1,5 minute, na vrhu vzorca pa so se pojavili mehurčki plina, kar lahko resno spremeni natančnost ocene kakovosti.

Preiskovani ingoti AlSi9Mn so bili izdelani z dvema različnima tehnologijama: s horizontalnim polkontinuirnim litjem **(Slika 4. (a, b))** in gravitacijskim litjem v odprto kokilo **(Slika 4. (c, d)).** Iz obeh vrst ingotov smo izrezali dve 1 cm debeli rezini, nato pa iz vsake rezine pridobili 5 vzorcev, kot je razvidno iz **Slik 4 (b)** in **(d)** (10 vzorcev za obe vrsti ingotov). Pred taljenjem smo

As the first step of our investigation, we conducted solidification simulations with the aid of the gravity casting module of the NovaFlow&Solid simulation software to investigate the differences between the solidification rates of traditional and remelt RPT samples. First, the solidification of a traditional RPT sample (**Figure 3 (a)**) cast from Al-9.5%Si-0.4%Mn-0.15%Fe (weighing 90 g) was simulated with a casting temperature of 700 °C. The mold was selected to be a steel cup (with a thermal conductivity of 26 W/m·K) preheated to 300 °C with a 0.8 mm thick refractory coating (with a thermal conductivity of 0.25 W/m·K). Then, the solidification of a remelted sample with sizes of 20 × 20 × 10 mm was simulated with silica sand mold material (with a selected thermal conductivity of 0.3 W/m·K [30]) and the RPT steel cup as a container (**Figure 3. (b, c)**). The starting temperature of the sample and the mold was 700 °C. During the simulations, two sand quantities were tested: 55 g, which is enough to fill the steel cup **(Figure 3. (b))**, and 30 g (**Figure 3. (c)**), which was selected in an attempt to decrease solidification time. For real-life experiments, the 30 g sand quantity was chosen. The reason for this choice is that during preliminary tests with sampling cups filled fully with sand, it was discovered



Slika 3. Prečni prerez geometrij, uporabljenih za simulacije strjevanja, (a) vzorec RPT in (b, c) vzorci, pretaljeni v peščeni podlagi

Figure 3. Cross-sectional view of the geometries used for solidification simulations, (a) RPT specimen and (b, c) samples remelted in sand support

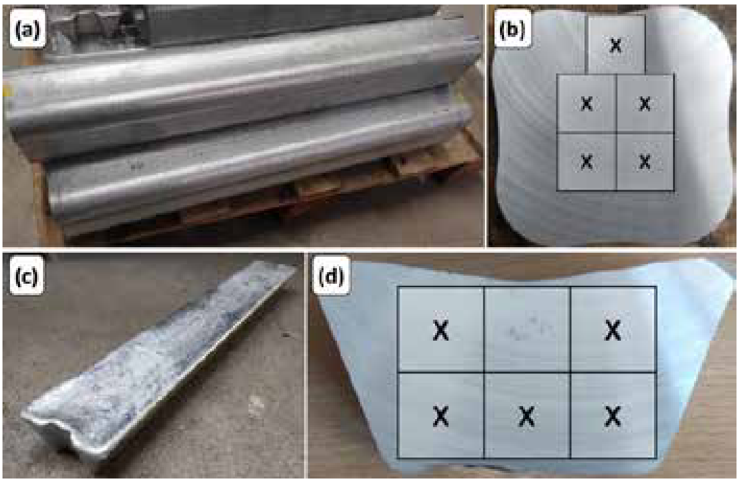
vzorce 1 uro hranili pri 500 °C v peči, da bi odstranili morebitne nečistoče in hidrokside, ki so nastali med rezanjem vzorcev. Pred prvo uporabo je bil pesek, ki je bil uporabljen kot talilno sredstvo, predhodno segret in 1 uro vzdrževan pri 700 °C, da se odstranijo morebitne hlapne nečistoče in olajša postopek taljenja vzorcev zlitine. Vzorci zlitine so bili vstavljeni v predhodno segret pesek in 15 minut vzdrževani pri 700 °C. Relativna vlažnost v delavnici je bila med vsemi poskusnimi fazami med 50 % in 60 %.

Na podlagi predhodne toplotne analize je 15 minut dovolj, da se vzorci stalijo in dosežejo temperaturo peska. Vzorci so se strdili v vakuumski komori naprave RPT s tlakom 80 mbar in 6 minutami zadrževanja. Čeprav za utrjevanje peska ni bilo uporabljeno vezivo, so vzorci odlično ohranili obliko **(Slika 5)**

Kot dodaten preizkus so bili tradicionalni vzorci RPT odvzeti iz vzorcev

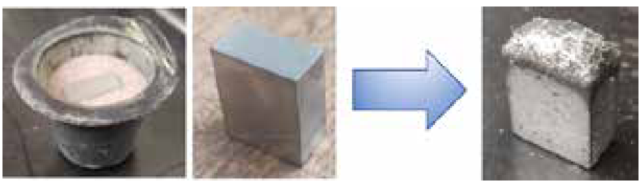
that the top surface of the specimen was completely liquid even after 1.5 minutes, and gas bubbles were bursting at the top of the sample, which can seriously alter the accuracy of quality evaluation.

The investigated AlSi9Mn ingots were manufactured by two different technologies: horizontal direct-chill casting **(Figure 4 (a, b))** and open mold gravity casting (**Figure 4 (c, d)**). Two, 1 cm thick slices were cut from both types of ingots, then 5 samples were extracted from each slice, as can be seen in **Figure 4 (b)** and **(d)** (10 samples for both ingot types). Before melting, the samples were held at 500 °C for 1 hour in a muffle furnace to remove any possible contaminations and hydroxides formed during the cutting of the samples. Before the first use, the sand being used as a melting medium was preheated and held at 700 °C for 1 hour to remove any possible volatile impurities and to facilitate the melting process of the alloy samples.



Slika 4. (a, b) Horizontalni polkontinuirano uliti in (c, d) gravitacijsko uliti ingoti, mesta vzorčenja so označena v (b) in (d)

Figure 4. (a, b) Direct-chill cast and (c, d) gravity cast ingots, sampling places are indicated in (b) and (d)



Slika 5. Ohranjanje oblike med pretaljevanjem in strjevanjem pod zmanjšanim tlakom

Figure 5. Shape retention during remelting and solidification under reduced pressure

ingotov (teža 500 g), ki so bili staljeni v glineno-grafitnem lončku pri 700 °C. Takoj po doseganju temperature litja so bili uliti 3 vzorci. Metoda vzorčenja je podrobno opisana v ref. [31]. Kemijska sestava vzorcev ingotov je bila analizirana z optično emisijsko spektroskopijo, ki je pokazala minimalno razliko med obema vrstama ingotov **(Preglednica 1).**

Preglednica 1. Koncentracija legirnih elementov v preučevanih ingotih iz aluminijevih zlitin (masni %)

Table 1. Concentration of the alloying elements of the studied aluminum alloy ingots (wt. %)

Vzorec / Sample	Litje HDC / HDC cast	Gravitacijsko litje / Gravity cast
Si	9,38	8,81
Fe	0,145	0,134
Mn	0,515	0,474
Zn	0,004	0,021
Ti	0,013	0,072
Sr	0,011	0,014
Zr	0,001	0,103
∑ drugo	najv. / max 0,10	najv. / max 0,10

Preskusi termične analize so bili opravljeni na vzorcih s tradicionalno geometrijo RPT in geometrijo pretaljenih vzorcev. Za te preizkuse je bil uporabljen termočlen tipa K s premerom 1 mm, ki je bil zaščiten z ovojem iz nerjavnega jekla. V obeh primerih so bile posodice RPT nameščene na izolacijski ognjevzdržni blok. Preden smo termočlen navpično spustili v pretopljeni vzorec RPT, smo ga s pihalnim gorilnikom segreli na približno 650 °C, da bi preprečili odvajanje odvečne toplote iz majhnega vzorca. Pri tradicionalni geometriji RPT je bila jeklena čaša predhodno segreta na 300 °C. Podatke o temperaturi je zbiral sistem za zbiranje podatkov (National Instruments NI-9211), povezan z osebnim računalnikom, s frekvenco vzorčenja 4 Hz.

The alloy samples were plugged into the preheated sand and were held at 700 °C for 15 minutes. The relative humidity levels in the workshop were between 50 % and 60 % during all experimental steps.

Based on preliminary thermal analysis, 15 minutes is enough for the specimens to melt and reach the temperature of the sand. The samples were solidified in the vacuum chamber of an RPT apparatus with 80 mbar pressure and 6 minutes of residence time. Although no binder was used to cure the sand, the shape retention of the specimens was excellent **(Figure 5).**

As an additional test, traditional RPT samples were taken from ingot samples (weighing 500 g), which were melted in a clay-graphite crucible at 700 °C. 3 samples were cast immediately after reaching the casting temperature. The sampling method is described in detail in ref. [31]. The chemical composition of the ingot samples was analyzed with optical emission spectroscopy, which showed a minimal difference between the two types of ingots **(Table 1)**.

Thermal analysis tests were conducted on samples with the traditional RPT and remelt sample geometries. For these tests, a K-type thermocouple with a 1 mm diameter was used, which was protected by a stainless steel sheath. In both cases, the RPT cups were placed on an insulating refractory block. Before the thermocouple was vertically lowered into the remelted RPT sample, it was preheated to approximately 650 °C with a blow torch, to avoid excess heat extraction from the small-sized sample. In the case of the traditional RPT geometry, the steel cup was preheated to 300 °C. The temperature data was collected by a data acquisition system (National Instruments NI-9211) linked to a personal computer at a 4 Hz sampling frequency.

Vzorce RPT (pretaljene in tradicionalne) smo prerezali na pol in jih zbrusili z brusnimi papirji SiC z zrnatostjo 180, 320 in 500. S skenerjem smo naredili slike prečnega prereza z ločljivostjo 1000 dpi, nato pa smo za analizo slik uporabili programsko opremo MATLAB Image Processing Toolbox™ (kot je opisano v referenci [32]). Pore s površino, manjšo od 30 pik (0,0194 mm^2), niso bile upoštevane. Za mikrostrukturno analizo smo vzorce dodatno zbrusili do zrnatosti 2400 in jih spolirali z diamantno suspenzijo velikosti 3 in 1 µm. Izvedene so bile meritve razdalje med sekundarnimi dendritnimi vejami (SDAS). Povprečna razdalja SDAS je bil ocenjena z mikrografijami prečnih prerezov pretaljenih in tradicionalnih vzorcev RPT. Za vsak vzorec je bilo opravljenih 20 meritev v 4 različnih vidnih poljih (80 meritev/vzorec).

Na podlagi rezultatov analize slik je bil izračunan indeks bifilma (BI [mm]) kot [33]:

$$BI = \sum L_{max} , \qquad \text{En. 1}$$

kjer je L_{max} največja dolžina (dolžina glavne osi) por [mm]. Bifilm-Index, normaliziran na površino vzorca (NBI [mm/cm^2]), je bil ocenjen kot:

$$NBI = \frac{\sum L_{max}}{A_{Sample}} , \qquad \text{En. 2}$$

kjer je A_{sample} [cm^2] površina prečnega prereza vzorcev. Gostota števila por (N_d [cm^{-2}]):

$$N_d = \frac{N}{A_{Sample}} \qquad \text{En. 3}$$

kjer je N [-] skupno število por. Delež površine por (A_f [%]):

$$A_f = \frac{\sum A_P}{A_{Sample}} \cdot 100 \qquad \text{En. 4}$$

kjer je A_p [cm^2] površina pore. Poleg tega je bil izračunan tudi normalizirani skupni obseg por (NTPP) [mm/cm^2]:

$$NTPP = \frac{\Sigma P_P}{A_{Sample}} \qquad \text{En. 5}$$

kjer je P_P [mm] obseg pore. Faktor oblike (S_F) por je bil izračunan kot [33]:

The RPT samples (both remelted and traditional) were cut in half and ground with SiC grinding papers with grit sizes 180, 320, and 500. A scanner was used to make cross-sectional images with 1000 dpi resolution, and then the MATLAB Image Processing Toolbox™ software was used for image analysis (as described in ref. [32]). Pores with an area smaller than 30 pixels (0.0194 mm^2) were not taken into account. For microstructural analysis, samples were further ground up to 2400 grit size and polished with 3 and 1 µm diamond suspensions. Secondary dendrite arm spacing (SDAS) measurements were conducted. The average SDAS was evaluated by micrographs made from the cross-sections of remelted and traditional RPT samples. For each specimen, 20 measurements were made in 4 different fields of view (80 measurements/sample).

Based on the results of the image analysis, Bifilm-Index (BI [mm]) was calculated as [33]:

$$BI = \sum L_{max} , \qquad \text{Eq. 1}$$

where L_{max} is the maximum length (major axis length) of pores [mm]. Bifilm-Index normalized to sample area (NBI [mm/cm^2]) was evaluated as:

$$NBI = \frac{\sum L_{max}}{A_{Sample}} , \qquad \text{Eq. 2}$$

where A_{sample} [cm^2] is the cross-sectional area of the samples. The pore number density (N_d [cm^{-2}]):

$$N_d = \frac{N}{A_{Sample}} \qquad \text{Eq. 3}$$

where N [-] is the total number of pores. The pore area fraction (A_f [%]):

$$A_f = \frac{\sum A_P}{A_{Sample}} \cdot 100 \qquad \text{Eq. 4}$$

where A_p [cm^2] is the area of a pore. Additionally, the normalized total pore perimeter (NTPP) [mm/cm^2] was also calculated as:

$$S_F = \frac{4\pi A_P}{P_p^{\,2}} \quad \text{En. 6}$$

pri čemer bi bil S_F popolnega kroga enak 1.

4 Rezultati in razprava

4.1 Simulacije strjevanja

Slika 6 prikazuje simulirane temperaturne porazdelitve na prečnih prerezih tradicionalnih **(Slika 6 (a))** in pretaljenih vzorcev RPT **(Slika 6 (b, c))** v različnih fazah strjevanja. **Slika 6. (b)** prikazuje primer, ko je bilo kot porozni medij uporabljenih 55 g, in **Slika 6. (c),** ko je bilo kot porozni medij uporabljenih 30 g kremenčevega peska. V vseh primerih je bila začetna temperatura taline 700 °C v skladu z eksperimentalnimi parametri. Vendar je bila temperatura orodja precej drugačna: jeklena čaša tradicionalnega vzorca RPT je bila nastavljena na 300 °C, medtem ko sta bila peščena podpora in jeklena čaša pretaljenih vzorcev nastavljena na 700 °C.

Slika 7 povzema lokalne čase strjevanja **(Slika 7. (a-c))** in čase strjevanja **(Slika 7. (d-f))** na prečnih prerezih vzorcev. Lokalni čas strjevanja (t_f [s]) je opredeljen kot čas, ki je potreben na danem mestu v ulitku, da temperatura pade z likvidus na neuravnoteženo solidus temperaturo, medtem ko se čas strjevanja (t_{sol} [s]) razume kot čas, ki je potreben na danem mestu v ulitku, da temperatura pade s temperature ulitka na neuravnoteženo solidus temperaturo. Skupni čas strjevanja (t_{total} [s]) je čas, potreben za doseganje 0 % deleža tekoče faze v celotnem ulitku od trenutka ulivanja. Pretaljeni vzorci se začnejo strjevati pozneje kot tradicionalni vzorci RPT, kar je posledica predgretega peščenega polnila. V primeru uporabe 55 g peska se pod vzorcem ustvari vroče mesto **(Slika 6 (b)),** kar podaljša čas strjevanja in

$$NTPP = \frac{\Sigma P_P}{A_{Sample}} \quad \text{Eq. 5}$$

where P_P [mm] is the perimeter of a pore. The shape factor (S_F) of the pores was calculated as [33]:

$$S_F = \frac{4\pi A_P}{P_p^{\,2}} \quad \text{Eq. 6}$$

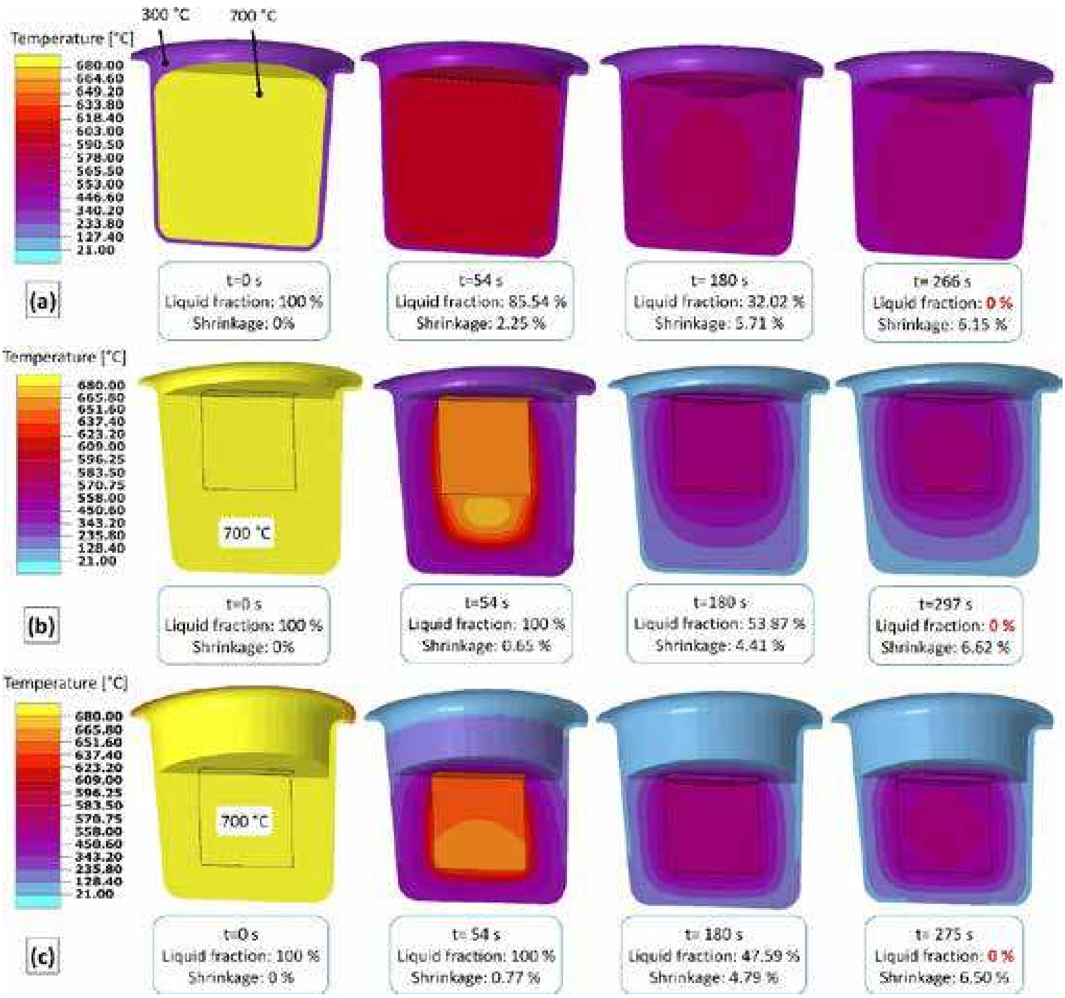
where a perfect circle would have an S_F of 1.

4 Results and discussion

4.1 Solidification simulations

Figure 6 shows the simulated temperature distributions at the cross sections of traditional **(Figure 6 (a))** and remelted RPT samples **(Figure 6 (b, c))** at different stages of the solidification. **Figure 6 (b)** presents the case when 55 g and **Figure 6. (c)** when 30 g of silica sand was used as a porous medium. In all cases, the starting temperature of the liquid metal was 700 °C in accordance with the experimental parameters. The mold temperature, however, was rather different: the steel cup of the traditional RPT sample was set to 300 °C, while the sand support and steel cup of the remelted specimens were set to 700 °C.

Figure 7 summarizes the local solidification times **(Figure 7 (a-c))** and solidification times **(Figure 7 (d-f))** at the cross sections of the samples. Local solidification time (t_f [s]) is defined as the time taken at a given location in a casting for the temperature to fall from the liquidus to the non-equilibrium solidus, while solidification time (t_{sol} [s]) is interpreted as the time needed at a given location in a casting for the temperature to fall from the casting temperature to the non-equilibrium solidus. The total solidification time (t_{total} [s]) is the time needed to reach 0 % liquid phase fraction in the whole casting, starting from the moment of casting. The



Slika 6. Prečni prerez porazdelitve temperature glede na simulacije strjevanja (a) tradicionalnih in (b,c) pretaljenih vzorcev RPT v različnih fazah procesa strjevanja. (b) predstavlja primer, ko je bilo za talilno sredstvo uporabljenih 55 g in (c), ko je bilo uporabljenih 30 g kremenčevega peska

Figure 6. Cross-sectional view of the temperature distribution according to solidification simulations of (a) traditional and (b, c) remelted RPT samples at different stages of the solidification process. (b) presents the case when 55 g and (c) when 30 g of silica sand was used as a melting medium

povzroči, da je skupni čas strjevanja 297 s **(Slika 7 (e)).** Po drugi strani pa je pri uporabi 30 g peska kot polnila skupni čas strjevanja precej podoben kot pri tradicionalnem RPT (z razliko 9 s).

Čeprav so skupni časi strjevanja tradicionalnih vzorcev RPT in vzorcev, remelted samples start to solidify later than the traditional RPT specimen, which is a consequence of the preheated sand filling. In the case of using 55 g sand, a hot spot is formed under the specimen **(Figure 6 (b)),** which increases the solidification time and results in a total solidification time of 297 s pretaljenih v 30 g peska, precej podobni, je lokalni čas strjevanja pri pretaljenem kosu izrazito krajši **(Slika 7 (c)).** Ker je finost mikrostrukture odvisna od lokalnega časa strjevanja, bi bila zgolj na podlagi simulacij uporaba 55 g peska boljša izbira v smislu zagotavljanja podobnih pogojev strjevanja kot v primeru tradicionalnega vzorca RPT. Po drugi strani pa so predhodni preskusi pokazali, da se pri uporabi posodic za vzorčenje, popolnoma napolnjenih s peskom, mehurčki na vrhu vzorcev zaradi zapoznelega začetka postopka strjevanja bolj razpočijo. Zato je bilo med dejanskimi poskusi uporabljenih 30 g peščenega polnila.

4.2 Analiza mikrostrukture in termična analiza

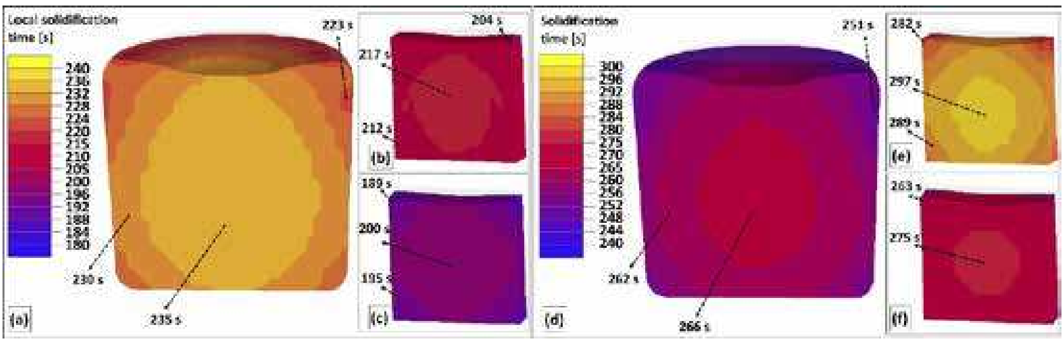
Da bi ugotovili, ali so bili lokalni časi strjevanja pretaljenih vzorcev res podobni kot pri tradicionalnih vzorcih RPT, smo izvedli meritve razdalje SDAS. Ocenjevanje SDAS je koristno orodje, ki se lahko uporablja za napovedovanje lokalnih časov strjevanja različnih zlitin [34–36]. Povprečna razdalja SDAS je bila izračunana z meritvami,

(Figure 7.(e)). On the other hand, applying 30 g of sand as a filler results in a rather similar total solidification time as in the case of the traditional RPT (with a 9 s difference).

Although the total solidification times of traditional RPT specimens and samples remelted in 30 g sand are rather similar, the local solidification time is remarkably less for the remelted piece **(Figure 7 (c)).** As the fineness of the microstructure is controlled by the local solidification time, based solely on the simulations, using 55 g sand would be a better choice in terms of providing similar solidification conditions as in the case of traditional RPT. On the other hand, preliminary tests revealed that using sampling cups filled fully with sand results in a more significant bubble bursting at the top of the samples due to the delayed start of the solidification process. For this reason, 30 g of sand filling was used during real-life experiments.

4.2 Microstructural investigation and thermal analysis

To investigate whether the local solidification times of remelted samples were indeed similar to those of the traditional RPT



Slika 7. (a-c) Lokalni časi strjevanja in (d-f) s časi strjevanja na prerezih (a, d) tradicionalnih vzorcev RPT in vzorcev, pretaljenih v (b, e) 55 g in (c, f) 30 g kremenčevega peska

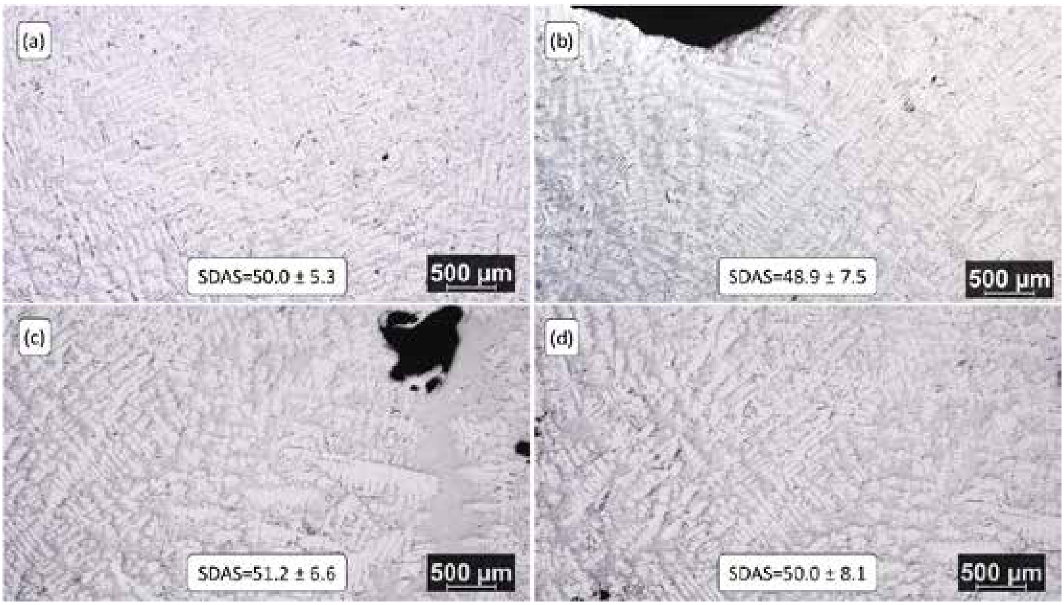
Figure 7. (a-c) Local solidification times and (d-f) solidification times at the cross-sections of (a, d) traditional RPT specimens and samples remelted in (b, e) 55 g and (c, f) 30 g silica sand

opravljenimi na mikrografih pretaljenih **(Slika 8 (a, c))** in tradicionalnih vzorcev RPT **(Slika 8 (b, d)).** V vsakem primeru je povprečna razdalja SDAS približno 50 µm z zanemarljivim odstopanjem, kar pomeni, da razlike v lokalnih časih strjevanja, ki jih kažejo simulacije, nimajo bistvenega vpliva na razdalje med sekundarnimi dendritnimi vejami vzorcev.

Podobno kot pri simulacijah tudi rezultati termične analize kažejo na precejšnjo razliko v lokalnih časih strjevanja (približno 56 s), medtem ko je razlika v skupnih časih strjevanja manjša **(Slika 9).** Opozoriti je treba, da bi lahko bila razlika med strjevanjem brez termočlenov manjša, saj lahko termočlen odvede nekaj toplote, ta učinek pa je pomembnejši v primeru majhnega pretaljenega vzorca.

samples, SDAS measurements were conducted. Evaluating SDAS is a useful tool that can be used for the prediction of local solidification times of different alloys [34-36]. The average SDAS was calculated by measurements made on micrographs taken from remelted **(Figure 8 (a, c))** and traditional RPT samples **(Figure 8 (b, d))**. In each case, the average SDAS is around 50 µm with negligible variation, which means the differences in the local solidification times indicated by the simulations do not have a significant effect on the secondary dendrite arm spacings of the samples.

Similarly to the simulations, the thermal analysis results also indicate a remarkable difference in the local solidification times (approximately 56 s), whereas there is a smaller difference in total solidification times **(Figure 9)**. It should be noted that the difference could be less significant during



Slika 8. Slike mikrostrukture preiskovanih vzorcev: (a) pretaljen ulitek HDC, (b) tradicionalni ulitek HDC, (c) pretaljen gravitacijski ulitek in (d) gravitacijski tradicionalni ulitek

Figure 8. Microstructural images of the investigated samples: (a) HDC cast remelted, (b) HDC cast traditional, (c) gravity cast remelted, and (d) gravity cast traditional

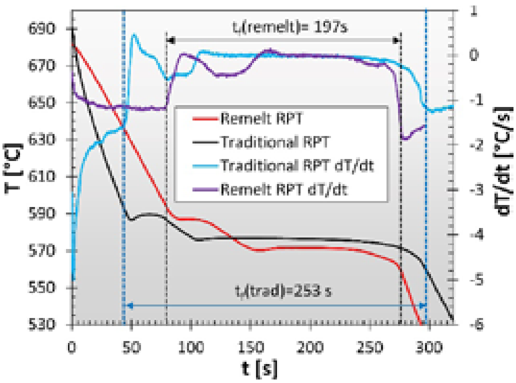


Figure 9. Cooling curves of traditional and remelt RPT samples

Slika 9. Krivulje ohlajanja tradicionalnih in pretaljenih vzorcev RPT

Znano je, da lahko razmik med sekundarnimi dendritnimi vejami (SDAS [m]) ocenimo iz lokalnih časov strjevanja (t_f [s]) po naslednji formuli [37]:

$$SDAS = K\left(Mt_f\right)^{1/3} \qquad \text{En. 7}$$

kjer je

$$M = -\frac{\Gamma D}{m(1-k)(c_E - c_0)}\ln\left(\frac{c_E}{c_0}\right) \qquad \text{En. 8}$$

K je numerična konstanta, ki po *Feurerju* in *Wunderlinu* [38] znaša 5,5, in $128^{1/3} \approx 5,0$ po *Kirkwoodu* [39]. Γ je Gibbs-Thomsonov koeficient [K·m], D je difuzivnost atomov topljenca v tekočini [m²/s], C_E pomeni evtektično sestavo (12,6 mas. % v sistemu Al-Si), C_0 je koncentracija topljenca (9 masnih %), m je naklon krivulje likvidusa (6,6 °C/mt. % za Al-Si) in k je porazdelitveni koeficient, ki znaša 0,13 za Si v Al [34]. Γ je podan kot

$$\Gamma = \frac{\sigma_{SL}}{\Delta S_f} \qquad \text{En. 9}$$

kjer je σ_{SL} medfazna energija trdne in tekoče snovi [J/m²], ΔS_f je entropija zlivanja [J/K·m³]. Če uporabimo σ_{SL} = 0,15 J/m² [40] in $\Delta S_f = 1{,}112\cdot10^6$ J/K·m³ [41], je Γ $1{,}349\cdot10^{-7}$ K·m. Če je D = $2{,}05\cdot10^{-9}$ m²/s

solidification without thermocouples, as some heat may be conducted away by the thermocouple, which has a more significant effect in the case of the small-sized remelted sample.

It is well-known that the secondary dendrite arm spacing (SDAS [m]) can be estimated from the local solidification times (t_f [s]) according to the following formula [37]:

$$SDAS = K\left(Mt_f\right)^{1/3} \qquad \text{Eq. 7}$$

where

$$M = -\frac{\Gamma D}{m(1-k)(c_E - c_0)}\ln\left(\frac{c_E}{c_0}\right) \qquad \text{Eq. 8}$$

K is a numerical constant, which is 5.5 according to *Feurer* and *Wunderlin* [38], and $128^{1/3} \approx 5.0$ according to *Kirkwood* [39]. Γ is the Gibbs-Thomson coefficient [K·m], D is the diffusivity of solute atoms in liquid [m²/s], C_E denotes the eutectic composition (12.6 wt. % in the Al-Si system), C_0 is the solute concentration (9 wt. %), m is the slope of the liquidus curve (6.6 °C/wt. % for Al-Si), and k is the distribution coefficient, which is 0.13 for Si in Al [34]. Γ is given as

$$\Gamma = \frac{\sigma_{SL}}{\Delta S_f} \qquad \text{Eq. 9}$$

where σ_{SL} is the solid/liquid interfacial energy [J/m²], ΔS_f is the entropy of fusion [J/K·m³]. Using σ_{SL} = 0.15 J/m² [40] and $\Delta S_f = 1.112\cdot10^6$ J/K·m³ [41], Γ is $1.349\cdot10^{-7}$ K·m. If D = $2.05\cdot10^{-9}$ m²/s (which was calculated at 590 °C liquidus temperature based on ref. [42]), the experimentally measured 50 µm SDAS is given by **Eq. 7** at 223 s when 5.0 and 167 s when 5.5. By comparing the measured and calculated local solidification times **(Table 2)**, the matching between the values is relatively good when the numerical constant of *Kirkwood* [39] is used. Also, it is worth noting that the local and total solidification times acquired by solidification simulations are also in accordance with the experimental results. Based on the (kar je bilo izračunano pri temperaturi 590 °C likvidusa na podlagi literature [42]), je eksperimentalno izmerjeni 50 µm SDAS podan z **enačbo 7** pri 223 s, ko je 5,0, in 167 s, ko je 5,5. Če primerjamo izmerjene in izračunane lokalne čase strjevanja **(Preglednica 2),** ugotovimo, da se vrednosti razmeroma dobro ujemajo, če uporabimo številčno konstanto *Kirkwooda* [39]. Prav tako je treba omeniti, da so tudi lokalni in skupni časi strjevanja, pridobljeni s simulacijami strjevanja, v skladu z eksperimentalnimi rezultati. Na podlagi zgoraj opisanih rezultatov lahko rečemo, da obstajajo nekatere razlike med lokalnimi časi strjevanja tradicionalnih in pretaljenih vzorcev RPT, vendar so te razlike premajhne, da bi jih bilo mogoče dokazati z analizo mikrostruktur. To pomeni, da razlike v lokalnih hitrostih strjevanja ne vplivajo bistveno na nastanek por.

Preglednica 2. Primerjava izmerjenih in izračunanih časov strjevanja

Table 2. Comparison of measured and calculated solidification times

Parameter / Parameter	Tradicionalni / Traditional RPT	Pretaljeni / Remelted RPT
t_f (izmerjeno s / measured by TA) [s]	253	197
t_f (simulirano / simulated) [s]	223–235	189–200
t_f (izračunano iz / calculated from SDAS, Kirkwood [39]) [s]	223	
t_f (izračunano iz SDAS, Feurer in Wunderlin [38]) [s]	167	
t_{total} (izmerjeno s / measured byTA) [s]	297	276
t_{total} (simulirano / simulated) [s]	266	275

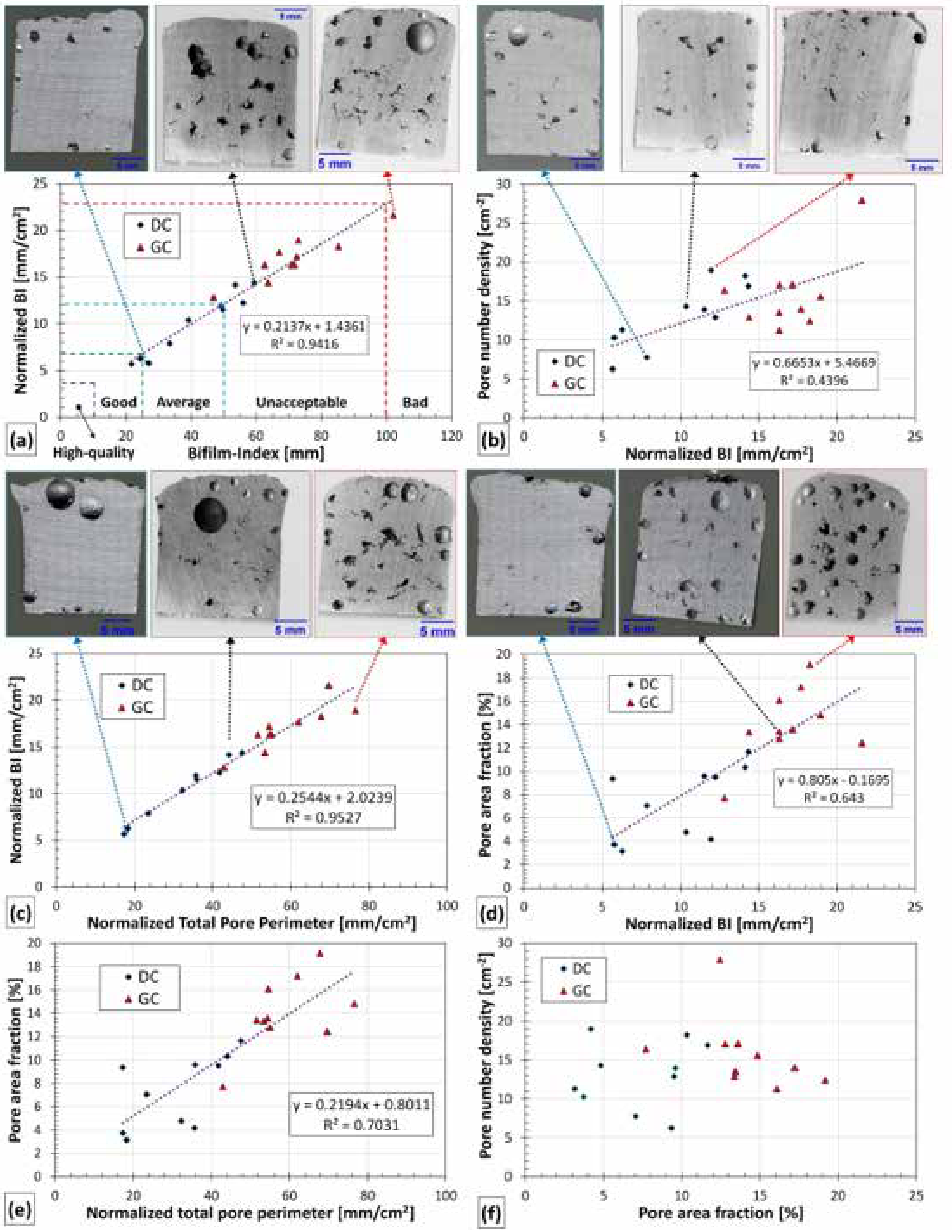
4.3 Ocena kakovosti

V **Preglednici 3** so povzeti rezultati analize slik pretaljenih vzorcev RPT, na **Sliki 10** pa je prikazana primerjava posameznih parametrov, ocenjenih med analizo. Na results detailed above, it can be said that there are some differences between the local solidification times of traditional and remelted RPT samples, but these differences are too small to be evinced by microstructural investigations. This means that pore formation is not notably affected by the differences in the local solidification rates.

4.3 Quality evaluation

Table 3 summarizes the image analysis results of remelted RPT samples, while **Figure 10.** shows the comparison of the individual parameters evaluated during the analysis. **Figure 11.** summarizes the distribution of maximum pore diameters **(Figure 11. (a, b))** and shape factors **(Figure 11. (c, d))** of the pores found within the 10 DC and 10 GC remelted samples. The compiled results in **Table 3** show clear differences between the porosity parameters of the specimens extracted from the ingots cast by the two technologies: the gravity cast ingot possesses higher values, which indicates higher impurity content. The average pore area fraction is almost double, and the average BI is more than one and a half times the values of the direct-chill cast ingot. Based on this, the bifilm and gas content (solute hydrogen and entrained air) of the gravity cast ingot is remarkably higher, which is in agreement with the results of *Erzi* and *Tiryakioğlu* [24], who found that the quality of DC cast AlSi7Mg0.3 ingots was more favorable than that of the gravity cast ingots. According to *Uludağ* et al. [43], the melt quality can be categorized by the BI values as follows:

- 0 mm ≤ BI ≤ 10 mm: high-quality melt,
- 10 mm ≤ BI ≤ 25 mm: good quality,
- 25 mm ≤ BI ≤ 50 mm: average quality,
- 50 mm ≤ BI ≤ 100 mm: unacceptable



Slika 10. (a-f) Primerjava različnih parametrov, ocenjenih s slikovno analizo pretaljenih vzorcev (DC: polkontinuirano ulivanje, GC: gravitacijsko litje ingota)

Figure 10. (a-f) Comparison of different parameters evaluated by the image analysis of remelted samples (DC: direct-chill cast, GC: gravity cast ingot)

Sliki 11 je povzeta porazdelitev največjih premerov por **(Slika 11 (a, b))** in koeficientov oblike **(Slika 11. (c, d))** por, najdenih v 10 vzorcih DC in 10 vzorcih GC, ki so bili pretaljeni. Rezultati, zbrani v **Preglednici 3**, kažejo jasne razlike med parametri poroznosti vzorcev, pridobljenih iz ingotov, ulitih z obema tehnologijama: gravitacijsko ulit ingot ima višje vrednosti, kar kaže na večjo vsebnost nečistoč. Povprečni delež površine por je skoraj dvakrat večji, povprečni indeks BI pa več kot enkrat in pol večji od vrednosti polkontinuirano ulitega ingota. Na podlagi tega je vsebnost bifilma in plinov (raztopljenega vodika in zajetega zraka) v gravitacijsko ulitem ingotu izrazito višja, kar je v skladu z rezultati *Erzija* in *Tiryakioğluja* [24], ki sta ugotovila, da je kakovost ingotov AlSi7Mg0.3, ulitih z DC, ugodnejša od kakovosti gravitacijsko ulitih ingotov. Po *Uludağu* in drugih [43] je kakovost taline mogoče razvrstiti v naslednje kategorije glede na vrednosti indeksa BI:

- 0 mm ≤ BI ≤ 10 mm: visokokakovostna talina,
- 10 mm ≤ BI ≤ 25 mm: dobra kakovost,
- 25 mm ≤ BI ≤ 50 mm: povprečna kakovost,
- 50 mm ≤ BI ≤ 100 mm: nesprejemljiva kakovost,
- BI ≥ 100 mm: slaba kakovost, ki se ji je treba izogniti.

quality,

- BI ≥ 100 mm: bad quality that should be avoided.

Based solely on this scale, the DC cast ingot falls into the „average quality" category, while the gravity cast ingot belongs to the „unacceptable quality" category. However, it should be emphasized that the remelted samples of this study have a smaller cross-section than traditional RPT samples, which were presumably used for the establishment of the quality scale of *Uludağ* et al, so even stricter BI limits should be used for the categorization in our case. There are several studies [22, 44-49] that showed that BI values correlate with mechanical properties, which means that the mechanical properties of castings made from the two investigated types of ingots could differ (using the same technological parameters). This presumption will be investigated in a future study.

Because the cross-sectional area of the samples was relatively constant, there is a strong correlation between BI and NBI values **(Figure 10. (a))**. By comparing pore number density and NBI results **(Figure 10. (b))**, we only found a poor correlation, which is in accordance with the results of *Uludağ* et al. [43], but somewhat contradicts the results of *Dispina*r and *Campbell* [44, 49] who found a strong linear correlation

Preglednica 3. Rezultati analize slik pretaljenih vzorcev

Table 3. Image analysis results of remelted samples

Parameter / Parameter	Polkontinuirano ulivanje / Direct-chill cast (DC)	Gravity cast / Gravitacijsko litje (GC)
Delež površine por / Pore area fraction (Af) [%]	7.33±3.14	14.07±3.10
Gostota števila por / Pore number density (Nd) [cm^{-2}]	13.07±4.26	15.82 ± 4.71
Normalizirani skupni obseg por / Normalized total pore perimeter (NTPP) [mm/cm^2]	31.40±11.55	58.81±10.04
Bifilm-Index (BI) [mm]	41.37±14.02	71.55±14.50
Normalizirani indeks bifilma / Normalized Bifilm-Index (NBI) [mm/cm^2]	10.01±3.38	16.99±2.42

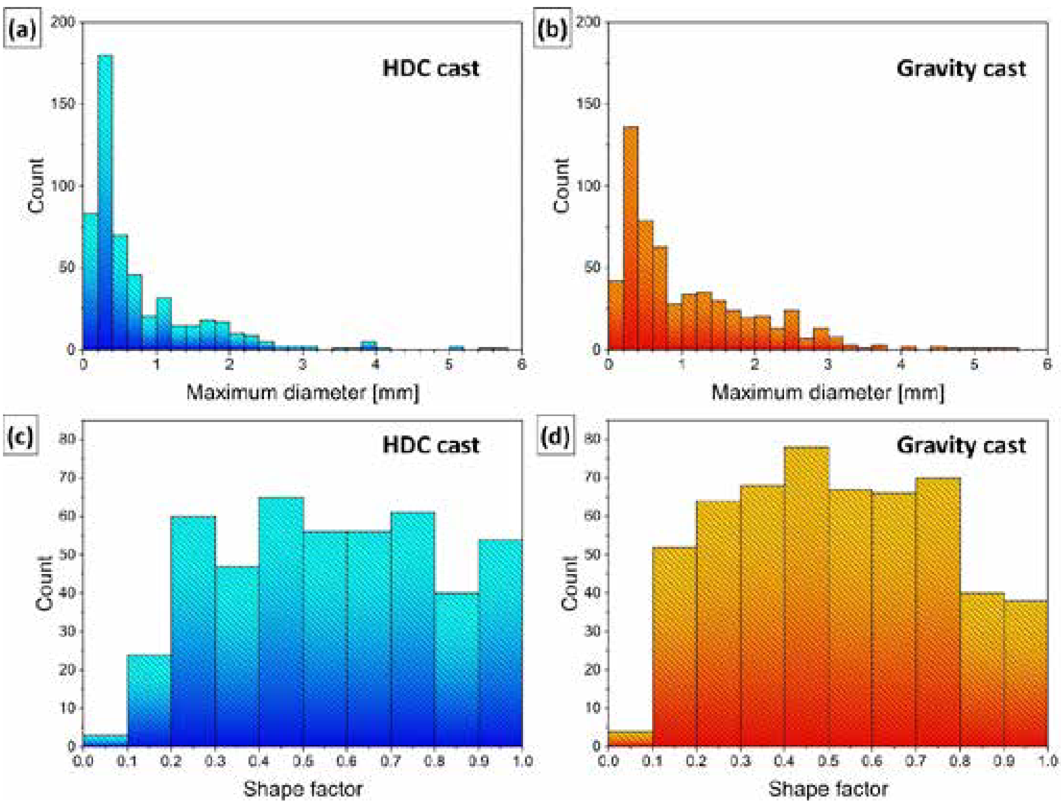
Zgolj na podlagi te lestvice sodi DC-ulit ingot v kategorijo »povprečne kakovosti«, medtem ko gravitacijsko ulit ingot spada v kategorijo »nesprejemljive kakovosti«. Vendar je treba poudariti, da imajo pretaljeni vzorci te študije manjši prečni prerez kot tradicionalni vzorci RPT, ki so bili domnevno uporabljeni za določitev lestvice kakovosti *Uludağa* in drugih, zato je treba v našem primeru za kategorizacijo uporabiti še strožje meje indeksa BI. Več študij [22, 44–49] je pokazalo, da vrednosti BI korelirajo z mehanskimi lastnostmi, kar pomeni, da bi se lahko mehanske lastnosti ulitkov, izdelanih iz obeh preučevanih vrst ingotov, razlikovale (ob uporabi enakih tehnoloških parametrov). To domnevo bomo preučili v prihodnji študiji.

Ker je bila površina prečnega prereza vzorcev razmeroma konstantna, obstaja močna korelacija med vrednostmi BI in NBI **(Slika 10 (a)).** S primerjavo gostote števila por in rezultatov NBI **(Slika 10 (b))** smo ugotovili le slabo korelacijo, kar je v skladu z rezultati *Uludağa* in drugih [43], vendar nekoliko nasprotuje rezultatom *Dispinarja* in *Campbella* [44, 49], ki sta ugotovila močno linearno korelacijo med številom por in vrednostmi BI za različne zlitine. Vendar je treba opozoriti, da število por in skupni premer por (BI) nista nujno medsebojno povezana. Močna korelacija je pričakovana, kadar ima večina por podoben premer. Teoretično pa lahko enak indeks BI dosežemo s številnimi majhnimi porami ali z nekaj večjimi porami. Če si ogledamo slike prečnega prereza na **Sliki 10 (a-d)** lahko vidimo, da so v nekaterih primerih razlike v velikosti por velike, kar pojasnjuje slabo korelacijo na **Sliki 10 (b).** Poročali so, da v večini primerov premer por v vzorcih RPT sledi lognormalni porazdelitvi [43, 50] in da ima večina por podoben premer, kar pomeni, da lahko pričakujemo neko vrsto korelacije med številom por in indeksom between the number of pores and BI values for different alloys. However, it is worth noting that the number of pores and total pore diameter (BI) are not necessarily interrelated. A strong correlation is expected when most of the pores have similar diameters. However, in theory, the same BI can be reached with numerous small pores or with a few larger ones. By looking at the cross-sectional images in **Figure 10 (a-d)**, it can be seen that there are cases when the differences in the sizes of the pores are remarkable, which explains the poor correlation in **Figure 10 (b)**. It was reported that in most cases, the diameter of the pores in RPT samples follows the lognormal distribution [43, 50], and it is common that most of the pores have a similar diameter, which means that some type of correlation between the number of pores and BI can be expected. However, there could be circumstances that can contribute to non-uniform pore size distribution, as it was reported by *LaOrchan* et al. [51]. In the case of short-freezing range alloys (like 413), a solid shell may form on the surface of the RPT sample, which can result in a large central pore caused by shrinkage. In our case, the distribution of maximum pore diameters **(Figure 11 (a, b)** show that most of the pores fall into the size range of 0.2-0.4 mm for both HDC and GC samples. However, there is a significant fraction within the size range of 1-2 mm, especially in the case of GC specimens, which explains the poor fitting in **Figure 10 (b)**.

There is an excellent linear correlation between NBI and NTPP with an R^2 value of 0.9527 **(Figure 10. (c))**. It was reported by *Uludağ* et al. [43] that there is a strong relationship between the total volume of pores and BI. However, a relationship between the total pore perimeter (and its normalized values) and BI has not been published yet. *Dispinar* and *Campbell*

BI. Vendar pa lahko obstajajo okoliščine, ki lahko prispevajo k neenakomerni porazdelitvi velikosti por, kot so poročali *LaOrchan* in drugi [51]. Pri zlitinah s kratkim območjem strjevanja (kot je 413) lahko na površini vzorca RPT nastane trdna lupina, ki lahko povzroči veliko osrednjo poro zaradi krčenja. V našem primeru porazdelitev največjih premerov por **(Slika 11. (a, b)** kaže, da je večina por v območju velikosti 0,2–0,4 mm pri vzorcih HDC in GC. Vendar pa je precejšen delež v območju

[52] highlighted that the maximum pore diameter is an approximation of the bifilm length. Based on this assumption, the main idea behind NTPP is that pore perimeter can be used as a rough 2-dimensional approximation of bifilm surface area (naturally, it is an overestimate as bifilms are expanded during solidification). From this point of view, NTPP is a 2-dimensional version of the Bifilm Spatial Index (BSI) introduced by *Song* et al. [53]. If we assume that each pore has a perfectly circular cross-section, the relationship between



Slika 11. Porazdelitev (a, b) največjih premerov por (c, d) in koeficientov oblike por v (a, c) vzorcih HDC in (b, c) gravitacijsko litih vzorcih. Pri analizi so bili združeni podatki o porah 10-10 pretaljenih vzorcev.

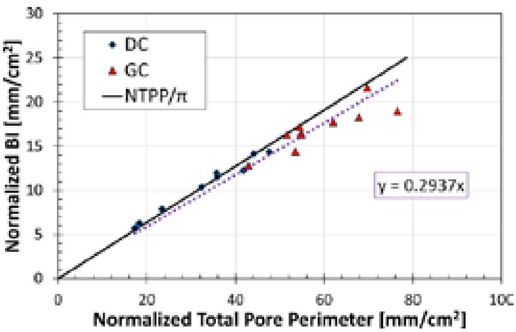
Figure 11. Distribution of (a, b) maximum pore diameters (c, d) and pore shape factors in (a, c) HDC and (b, c) gravity cast samples. For the analysis, the pore data of the 10-10 remelted samples were merged

velikosti 1–2 mm, zlasti pri vzorcih GC, kar pojasnjuje slabo prileganje na **Sliki 10. (b).**

Med NBI in NTPP obstaja odlična linearna korelacija z vrednostjo R^2 0,9527 **(Slika 10. (c)).** *Uludağ* in drugi [43] so poročali, da obstaja močna povezava med skupno prostornino por in indeksom bifilma. Vendar razmerje med skupnim obsegom por (in njegovimi normaliziranimi vrednostmi) in indeksom BI še ni bilo objavljeno. *Dispinar* in *Campbell* [52] sta poudarila, da je največji premer por približek dolžine bifilma. Na podlagi te predpostavke je vodilna ideja pri NTPP, da se obseg por lahko uporabi kot grob dvodimenzionalni približek površine bifilma (seveda gre za precenjeno oceno, saj se bifilmi med strjevanjem razširijo). S tega vidika je NTPP dvodimenzionalna različica prostorskega indeksa bifilma (BSI), ki so ga predstavili *Song* in drugi [53]. Če predpostavimo, da ima vsaka pora popolnoma okrogel prečni presek, bi moralo biti razmerje med skupnim obsegom por in indeksom BI (ter njunimi normaliziranimi vrednostmi) preprosto faktor, ki je enak vrednosti π **(Slika 12. (a)).** V tem primeru bi moral biti π^{-1} = 0,3183-kratnik NTPP. Če prestavimo regresijsko premico, da preseka os ordinato pri vrednosti 0, dobimo razmerje, ki je precej blizu teoretičnemu: NBI = 0,2937NTPP. Razlika je predvsem posledica dejstva, da pore niso popolnoma sferične in da njihovi prečni preseki niso popolnoma okrogli. Na **Sliki 12 (a)** lahko vidimo, da se vrednosti vzorcev GC bolj razlikujejo od teoretičnega razmerja, kar pomeni, da so pore v teh vzorcih manj sferične. To potrjujejo podatki o koeficientu oblike na **Sliki 11 (c, d),** ki kaže, da je v vzorcih HDC, ki imajo koeficient oblike med 0,9 in 1,0, več por. Povprečni koeficient oblike por v vzorcih HDC in GC je 0,65 oziroma 0,57.

Rezultati deleža površine por slabo korelirajo z normaliziranim indeksom BI

the total pore perimeter and BI (and their normalized values) should be simply a factor equal to the value of π **(Figure 12. (a))**. In this case, NBI should be π^{-1}=0.3183 times NTPP. If we force the regression line to intercept the axis of ordinates at 0, we get a relationship, which is pretty close to the theoretical one: NBI=0.2937NTPP. The difference is mainly caused by the fact that pores are not perfectly spherical, and their cross-sections are not perfectly circular. We can see in **Figure 12. (a)** that the values of GC samples differ more significantly from the theoretical relationship, meaning that the pores are less spherical in these specimens. This is supported by the shape factor data in **Figure 11 (c, d)**, which shows that there are more pores in HDC samples, which have a shape factor between 0.9 and 1.0. The average shape factor of the pores found in HDC and GC specimens is 0.65 and 0.57, respectively.



Slika 12. Razmerje med NBI in NTPP v teoretičnem primeru, ko so pore popolnoma sferične (črna črta), v primerjavi z eksperimentalnimi podatki

Figure 12. Relationship between NBI and NTPP in the theoretical case, when the pores are perfectly spherical (black line), compared with the experimental data

The pore area fraction results correlate poorly with normalized BI **(Figure 10. (d))** and NTPP **(Figure 10. (e))**, which can also

(Slika 10 (d)) in NTPP **(Slika 10 (e)),** kar je mogoče razložiti tudi z odstopanjem por od sferične oblike. Med gostoto števila por in deležem površine por ni bila ugotovljena povezava **(Slika 10 (f)).** Upoštevajte, da bi moralo teoretično vsako razmerje, predstavljeno na **Sliki 10,** presekati ordinatno os pri vrednosti 0. Da bi dobili reprezentativne vrednosti R^2, regresijske premice niso morale biti presečne pri vrednosti 0.

4.4 Tradicionalni vzorci RPT

Rezultati analize slik tradicionalnih vzorcev RPT **(Slika 13),** ulitih iz pretaljenih delov ingotov, kažejo podobno razliko med polkontinuirano ulitimi ingoti in gravitacijsko ulitimi ingoti, kot je prikazano v **Preglednici 3**. Skoraj vsi preučeni parametri so višji pri vzorcih gravitacijsko ulitih ingotov **(Slika 13 (a)),** kar kaže na večjo vsebnost bifilma in plina. Edina izjema je gostota števila por, ki je večja pri polkontinuirano ulitih ingotih **(Slika 13 (b)).** To večje število por je najverjetneje posledica večje nagnjenosti k nastanku poroznosti zaradi krčenja v tradicionalnih vzorcih RPT. V naši prejšnji študiji [54] smo ugotovili, da se je po večkratni obdelavi z rotacijskim razplinjevanjem (s čistilnim plinom Ar) v tradicionalnem vzorcu RPT zaradi nizke vsebnosti vodika in bifilma oblikovala velika osrednja krčilna pora. Vendar se lahko ta osrednja krčilna pora na površini prereza vzorca pojavi kot več majhnih por. V tem primeru, zlasti pri 3. polkontinuirano ulitem vzorcu RPT, je situacija podobna: obstaja osrednja krčilna pora, ki se na prečnem prerezu pojavi v obliki ločenih por, kar poveča gostoto števila por.

Rezultati NBI, A_f in NTPP se dobro ujemajo z rezultati pretaljenih vzorcev, pri čemer je očitno, da ima horizontalno

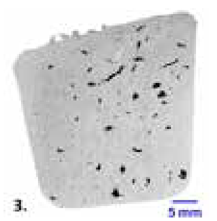
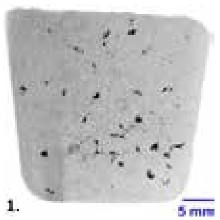
be explained by the deviation of the pores from the spherical shape. No relationship was found between pore number density and pore area fraction **(Figure 10. (f)).** Note that in theory, each relationship is presented in **Figure 10.** should intercept the axis of ordinates at 0. However, to get representative R^2 values, the regression lines were not forced to intercept at 0.

4.4 Traditional RPT samples

The results of the image analysis of traditional RPT samples **(Figure 13)** cast from remelted ingot pieces show a similar difference between DC and gravity cast ingots as in **Table 3**. Almost every investigated parameter is higher for gravity cast ingot samples **(Figure 13 (a))**, which indicates higher bifilm and gas content. The only exception is the pore number density, which is higher in the case of DC cast ingot **(Figure 13 (b)).** This higher number of pores is most probably a result of the higher tendency to shrinkage porosity formation in traditional RPT samples. In our previous study [54], we found that after multiple rotary degassing treatments (with Ar purging gas), a large central shrinkage pore formed in a traditional RPT sample as a result of low hydrogen and bifilm content. However, this central shrinkage pore may appear as several small pores on a sectioned sample surface. In this case, especially for the 3rd DC RPT sample, the situation is similar: there is a central shrinkage pore, which appears as separate pores on the cross-section, which increases pore number density.

NBI, A_f, and NTPP results correlate well with those of the remelted samples, and it is evident that the HDC casting ingot possesses lower oxide and gas concentration. This can be traced back to the differences in the melt preparation and casting technologies. As was highlighted in polkontinuirano uliti ingot nižjo koncentracijo oksidov in plinov. Razlog za to so razlike v tehnologijah priprave taline in litja. Kot je bilo poudarjeno v uvodu, postopek horizontalnega polkontinuiranega litja ne vključuje litja in taline, ki prosto pada, zato med litjem ne prihaja do nastajanja bifilma. Poleg tega so enote za litje običajno povezane s talilnimi pečmi prek sistema za odstranjevaje nečistoč iz kovin, ki vključuje linije za razplinjevanje in filtrske škatle [16,

the introduction, the HDC casting process does not involve any pouring action, and there is no free-falling liquid metal, so there is no bifilm formation during casting. Also, the casting units are generally connected to the melting furnaces through a metal launder system, which involves in-line degassing units and filter boxes [16, 17]. For these reasons, metal cleanliness is often superior to gravity cast ingots, which is supported by our experimental results.

a)				
Parameter	1.	2.	3.	Povprečje / Average
BI [mm]	112,76	132,03	93,01	112,6 ±19,51
NBI [mm/cm^2]	9,21	11,57	8,37	9,72 ±1,66
Af [%]	4,52	5,82	3,01	4,45 ±1,41
Nd [cm^{-2}]	9,31	11,12	10,07	10,17 ±0,91
NTPP [mm/cm^2]	29,50	38,76	26,33	31,53 ±6,46
b)				
Parameter	1.	2.	3.	Povprečje / Average
BI [mm]	103,71	87,85	72,84	88,13 ±15,44
NBI [mm/cm^2]	9,43	7,81	6,69	7,98 ±1,38
Af [%]	2,62	1,57	1,14	1,78 ±0,76
Nd [cm^{-2}]	16,46	15,20	15,07	15,57 ±0,77
NTPP [mm/cm^2]	32,32	25,39	21,88	26,53 ±5,31

Slika 13. Rezultati analize slik kosov RPT, ulitih iz pretaljenih (a) gravitacijsko ulitih in (b) HDC-ulitih vzorcev ingotov

Figure 13. Results of the image analysis of RPT pieces cast from remelted (a) gravity cast and (b) HDC cast ingot samples

17]. Iz teh razlogov je čistost kovine pogosto boljša kot pri gravitacijsko ulitih ingotih, kar potrjujejo tudi naši eksperimentalni rezultati.

4.5 Možni viri napak pri ocenjevanju kakovosti

Tiryakioğlu in drugi [55] so poročali, da v vzorcih RPT obstajajo bifilmi, ki se med strjevanjem ne odprejo in napihnejo v pore. Zato *Olofsson* in drugi [56] navajajo, da je poroznost le vidni (ali lažje zaznavni) del poškodb zaradi zajemanja zraka. To kaže, da RPT običajno podcenjuje količino bifilma. Število neodprtih bifilmov (skritih poškodb zaradi zajemanja zraka) je lahko še posebej veliko, kadar je vsebnost raztopljenega vodika v materialu nizka [57]. Na podlagi tega bi lahko v vzorcih obstajali neodprti bifilmi, ki jih med našim pregledom nismo zaznali, kar pomeni, da so količinsko opredeljeni le tisti bifilmi, ki lahko med strjevanjem tvorijo pore. Ta negotovost trenutno velja za večino (če ne za vse) metod ocenjevanja kakovosti taline, ki temeljijo na preskusih z zmanjšanim tlakom. Vendar pa je treba poudariti, da so se pore v ponovno taljenih vzorcih v primerjavi s tradicionalnimi vzorci RPT povečale, kar je neposredno razvidno iz višjih vrednosti deleža površine por v ponovno taljenih vzorcih **(Preglednica 3 in Slika 13).** Razlog za to je mogoče iskati v tem, da so ponovno taljeni vzorci sprva dlje časa v tekočem stanju **(Slika 9),** kar omogoča popolnejše napihovanje bifilma. S tega vidika pretaljeni vzorci zagotavljajo natančnejše informacije o vsebnosti bifilma kot tradicionalni vzorci RPT.

Ker so pretaljeni vzorci razmeroma majhni, se pojavi sum, da lahko talina absorbira vodik iz atmosfere v peči ali pa izgublja vodik zaradi naravnega razplinjevanja [58]. Prva možnost je bila preizkušena s pretaljenjem vzorca,

4.5 Possible sources of error in quality evaluation

Tiryakioğlu et al. [55] reported that there are bifilms in RPT samples that fail to open up and inflate into pores during solidification. For this reason, it is stated by *Olofsson* et al. [56] that porosity is only the visible (or the more easily detectable) part of the entrainment damage. This indicates that RPT tends to underestimate the bifilm quantity. The number of unopened bifilms (hidden entrainment damage) can be especially high when the solute hydrogen content is low [57]. Based on this, there could be unopened bifilms in the samples that were not detected during our investigation, which means that only those bifilms are quantified that can form pores during solidification. This uncertainty currently applies to most (if not all) melt quality evaluation methods, which rely on reduced-pressure tests. However, it should be highlighted that the pores have grown larger in remelted samples compared to traditional RPT specimens, which can be directly seen in the higher pore area fraction values of remelt samples **(Table 3 and Figure 13)**. The possible reason for this is that initially, the remelted samples stay in the liquid state for a longer time **(Figure 9)**, which allows a more complete bifilm inflation. From this point of view, remelted samples provide more accurate information about the bifilm content than traditional RPT specimens.

As the remelted samples are relatively small, the suspicion arises that the liquid metal may absorb hydrogen from the furnace atmosphere, or it may lose hydrogen due to natural degassing [58]. The former possibility was tested by remelting a sample extracted from a degassed batch that had a density of 2.67 g/cm^3. After remelting and solidifying in a vacuum chamber at 80 mbar, the density pridobljenega iz razplinjene serije z gostoto 2,67 g/cm^3. Po pretaljevanju in strjevanju v vakuumski komori pri tlaku 80 mbar je gostota vzorca ostala enaka, kar kaže, da absorpcija vodika v 15 minutah taljenja ni predstavljala težave. Avtorji menijo, da je naravno razplinjevanje zanemarljivo tudi ob upoštevanju, da se med enournim predgrevanjem pri 500 °C in postopkom taljenja na površini vzorca tvori razmeroma debela oksidna plast. Poročali so, da sta stopnji absorpcije in desorpcije vodika skozi neporušeno oksidno plast tekočega Al pri temperaturah pod 800 °C približno 1–3 $ml{\cdot}m^{-2}{\cdot}h^{-1}$. Ta hitrost reakcije se z nenehnim motenjem površine taline poveča na 10^4 ali 10^5 $ml{\cdot}m^{-2}{\cdot}h^{-1}$ [59]. V preučevanem primeru je praktični pomen tega ta, da lahko zanemarimo prenos vodika med vzorcem in atmosfero v peči, razen če je oksidna plast na površini taline motena. Pri tradicionalnih vzorcih RPT se zdi, da je sčasoma do določene mere prišlo do naravnega razplinjevanja, saj je bil delež površine por bistveno manjši pri tretjih vzorcih RPT, ki so bili uliti približno 15 minut po odvzemu prvih vzorcev **(Slika 13).** S tega vidika je mogoče s pretaljenimi vzorci dobiti natančnejše rezultate.

Prav tako je treba omeniti, da pri preiskavah pretaljevanja niso bili upoštevani deli z luknjami zaradi krčenja na osrednjem delu ingota **(Slika 4 (d)).** Če so povezani s površino (ali jih sproži bifilm), imajo ti deli že oksidirano površino, kar poveča oksidacijsko obremenitev serij, izdelanih s taljenjem teh ingotov. Ta metoda preiskave tega očitno ne odraža.

5 Zaključek

Na podlagi eksperimentalnih rezultatov, podrobno opisanih v tej študiji, je mogoče oblikovati naslednje sklepe:

of the sample remained the same, which indicates that hydrogen absorption was not an issue during the 15 minutes of the melting procedure. It is the authors' opinion that natural degassing is also negligible, taking into account that a relatively thick oxide layer forms on the sample surface during the 1-hour-long preheating at 500 °C and the melting procedure. It was reported that the absorption and desorption rates of hydrogen through an undisturbed oxide layer of liquid Al at temperatures below 800 °C are about 1–3 $ml{\cdot}m^{-2}{\cdot}h^{-1}$. This reaction rate is increased to 10^4 or 10^5 $ml{\cdot}m^{-2}{\cdot}h^{-1}$ by the continuous disturbance of the melt surface [59]. In the examined case, the practical meaning of this is that unless the oxide layer on the melt surface is disturbed, hydrogen transport between the sample and the furnace atmosphere can be neglected. By taking traditional RPT specimens, it appears that with time, natural degassing occurred to some degree as the pore area fraction was significantly less in the case of the 3rd RPT samples, which were cast approximately 15 minutes after taking the 1st samples **(Figure 13)**. From this point of view, remelted samples provide more accurate results.

It is also worth noting that for the remelting investigations, the parts with shrinkage cavities in the central region of the ingot were not considered **(Figure 4 (d))**. These, if they are connected to the surface (or initiated by a bifilm) already have an oxidized surface, which increases the oxide load of the batches made by melting these ingots. This is clearly not reflected by this investigation method.

5 Conclusion

Based on the experimental results detailed in this study, the following conclusions can be drawn:

- Metodo vrednotenja kakovosti, ki sta jo predlagala *Fox* in *Campbell* [19], je mogoče uspešno uporabiti za določanje vsebnosti bifilma in plina (vodika in zajetega zraka) v trdnih materialih ingota. Metodo je mogoče uporabiti za ocenjevanje kakovosti vseh vrst trdnih vzorcev, kot so deli ulitih delov ali tekočih sistemov.
- Simulacije strjevanja, termična analiza in mikrostrukturne preiskave so pokazale, da so z uporabo predlagane geometrije vzorca in tehnike pretaljevanja razlike v pogojih strjevanja tradicionalnih in pretaljenih vzorcev RPT premajhne, da bi jih lahko odkrili z mikrostrukturnimi preiskavami.
- Horizontalno polkontinuirano uliti ingoti imajo nižje koncentracije bifilma in plina, kar je mogoče pripisati razlikam v tehnologijah ulivanja ingotov: gravitacijsko uliti ingoti se vlivajo turbulentno, kar povzroča močnejši zajem zraka in oksidnega filma. K slabši kakovosti kovine prispevajo tudi luknje zaradi krčenja v gravitacijsko ulitih ingotih.
- Obstaja močna linearna korelacija med normaliziranimi vrednostmi indeksa bifilma in skupnim obsegom por, kar kaže, da se indeks bifilma lahko uporablja za napovedovanje skupne površine por.

- The quality evaluation method proposed by *Fox* and *Campbell* [19] can be successfully applied for the characterization of the bifilm and gas (hydrogen and entrained air) content of solid ingot materials. The method holds the potential to be applicable for the quality evaluation of any type of solid samples, such as sections of cast parts or running systems.
- Solidification simulations, thermal analysis, and microstructural investigations revealed that by using the proposed sample geometry and remelting technique, the differences in the solidification conditions of traditional and remelt RPT samples are too small to be uncovered by microstructural investigations.
- HDC cast ingots possess lower bifilm and gas concentrations, which can be traced back to the differences in the casting technologies of the ingots: gravity cast ingots are poured turbulently, which results in more severe air and oxide film entrainment. Shrinkage cavities in gravity cast ingots also contribute to lower metal quality.
- There is a strong linear correlation between the normalized values of Bifilm-Index and the total pore perimeter, which indicates that Bifilm-Index can be used for the prediction of total pore surface area.

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Raziskave in prenos tehnologije na področju litega železa – študije primerov iz CMRDI

Cast Iron Research and Technology Transfer – Case Studies from CMRDI

Povzetek

V tem poročilu so opisani nekateri projekti prenosa tehnologije in razvoja zlitin, ki jih je Centralni inštitut za raziskave in razvoj na področju metalurgije (CMRDI) izvedel za čim večjo lokalno proizvodnjo rezervnih delov strateškega pomena.

V prvem delu so predstavljene izkušnje s prenosom tehnologije proizvodnje valjev iz nodularne litine v livarsko industrijo v Egiptu. Valjarna je daleč najpomembnejši obrat za vroče in hladno preoblikovanje v kovinski industriji. Metalurške zahteve za valje v valjarnah so precej kompleksne, saj vključujejo visoko odpornost proti obrabi in lomljenju ter neobčutljivost na toplotne razpoke in luščenje. Doseganje ustrezne kombinacije lastnosti je za izdelovalca valjev nenehno velik izziv, saj so si rešitve med seboj nasprotujoče. Obravnavani so primeri projektov raziskav in razvoja, ki so bili izvedeni za povečanje konkurenčnosti valjev, proizvedenih v Egiptu na lokalnih in mednarodnih trgih.

V drugem delu tega poročila so obravnavana prizadevanja inštituta CMRDI za razvoj razmeroma novega materialaaustemprane litine s kroglastim grafitom (ADI), z izjemno kombinacijo lastnosti in izrazitimi potenciali za številne nove vrste uporabe. Poseben poudarek je namenjen nedavnemu delu, ki se ukvarja s termomehansko obdelavo in dinamičnim strjevanjem v ultrazvočnem polju.

Abstract

This report outlines some technology transfer and alloy development projects conducted at CMRDI, aiming to maximize the local production of spare parts of strategic importance.

In the first part of this report, the Egyptian experience with the technology transfer of ductile iron roll production to the Egyptian foundry industry is outlined. The rolling mill is by far the most important means of hot and cold forming in the metal industry. The metallurgical demands placed on rolling mill rolls are quite complex, as they include high resistance to wear and fracture, as well as insensitivity to fire cracking and spalling. The achievement of the proper combination of properties constantly presents serious challenges to the roll maker, as the solutions are mutually contradictory. Examples of R&D projects conducted to increase the competitiveness of Egyptian rolls in local as well as international markets are discussed.

In the second part of this report, CMRDI’s efforts to develop the relatively new material, austempered ductile iron (ADI), with an exceptional combination of properties and marked potential for numerous novel applications are discussed. Special emphasis is placed on recent work dealing with thermo-mechanical treatments, as well as dynamic solidification in the ultrasonic field.

1 Uvod

Tehnologija in metalurgija litega železa sta v zadnjih nekaj desetletjih zelo napredovali. Napredek pri nadzoru procesov, tako v livarnah kot v obratih za toplotno obdelavo, omogoča, da se načela fizikalne metalurgije iz teoretičnega vidika prenesejo v prakso. Zato se pričakuje, da se bo uporaba litega železa kot »novega« in najbolj uporabnega razreda materialov zelo povečala.

V tem poročilu so na podlagi rezultatov, pridobljenih na inštitutu CMRDI v zadnjih treh desetletjih, pregledani nekateri glavni dosežki na področju litega železa in njihov vpliv na zmogljivost tega materiala. Prva študija primera je povezana z uvedbo valjev iz litine s kroglastim grafitom v egiptovsko industrijo, druga pa z razvojem novih tehnologij za izboljšanje lastnosti austemprane litine s kroglastim grafitom (ADI) in iskanjem novih možnosti uporabe tega materiala z velikim potencialom.

2 Valji iz sive litine s kroglastim grafitom– metalurški izziv:

Valjarna je daleč najpomembnejši obrat za vroče in hladno preoblikovanje v kovinskopredelovalni industriji. Valji so orodje v valjarni in hitrost njihove degradacije med obratovanjem pomembno vpliva na kakovost valjanih izdelkov in stroške njihove proizvodnje. Obraba valjev se običajno meri s tonažo valjane mase na enoto premera. To zmanjšanje premera temelji na količini, ki jo je treba z valja odstraniti, da se ponovno vzpostavi zadovoljiva delovna plast valja, tako da se v tem smislu vsak dejavnik, ki vpliva na količino, ki jo je treba odstraniti, lahko šteje za obrabo.

Degradacija površine valja v valjarni ni enostaven proces, saj je vključenih več mehanizmov, katerih relativni vpliv je

1 Introduction

Cast iron technology and metallurgy have made great progress in the last few decades. Advances in process control, both in the foundry and in the heat treatment shops, make it possible to take physical metallurgy principles from the realm of theoretical interest to the arena of practical reality. As a result, the application of cast irons as a “new” and most useful class of materials is expected to grow remarkably.

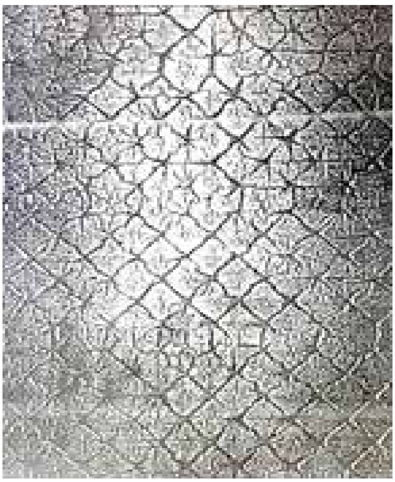
This report reviews some of the main developments of cast iron based on results obtained at CMRDI for the past three decades and their impact on cast iron performance. The first case study is related to the introduction of ductile iron rolls to the Egyptian industry, while the second case deals with the development of new technologies aiming at enhancing the properties of austempered ductile iron (ADI) and searching for novel applications of this very promising material.

2. Ductile Iron Rolls – The Metallurgical Challenge:

The rolling mill is by far the most important means of hot and cold forming in the metalworking industry. Rolls are the tools of the mill, and the rate at which they deteriorate in service has a significant impact on the quality of a rolled product and the cost of its production. Roll wear is normally measured by the tonnage of stock rolled per unit of diameter. This reduction in diameter is based on the amount which has to be dressed off the roll to restore the barrel of the roll to a satisfactory working condition, so that in this sense every factor which influences the amount to be dressed can be considered as wear.

odvisen od izvedenega načina valjanja. Najpomembnejši dejavniki, ki jih je treba upoštevati, so:

- *Abrazija:* je v veliki meri posledica relativnega gibanja materiala in valja. Stopnja abrazije je odvisna od hitrosti valjanja, sile ločevanja valjev in koeficienta trenja. Med vročim valjanjem je običajno prisotna abrazivna oksidna obloga, ki pospešuje obrabo površine valja. Višji oksidi – Fe_3O_4 in Fe_2O_3 – so izjemno trdi na vmesniku in ustvarjajo najzahtevnejše pogoje abrazije.
- *Termični učinki:* Termična utrujenost delovne površine valjev lahko povzroči nastanek razpok oziroma pokanje (crazing). Ta težava je najbolj pereča v primarnih valjarnah in obratih za grobo obdelavo, kjer so zaradi relativno nizke hitrosti valjanja in visoke temperature materiala termične napetosti največje (slika 1).
- *Mehanske napetosti:* Zaradi tlačne obremenitve med valjem in materialom pride do radialnega odklona valjev, katerega velikost je odvisna od



Slika 1. Pokanje na valju

Fig. 1. Fire cracking on roll

The deterioration of a roll surface in the mill is not a simple process as there are a number of mechanisms involved, the relative influence of which depends upon the type of rolling being carried out. The most important factors to consider are:

- *Abrasion:* is largely due to the relative movement between the stock and the roll. The rate of abrasion depends on the speed of rolling, the roll-separating force, and the coefficient of friction. During hot rolling, abrasive oxide scale is normally present, which accelerates the rate at which the roll surface is worn away. The higher oxides – Fe_3O_4 and Fe_2O_3 – are extremely hard on the interface, create the most severe abrasion conditions.
- *Thermal Effects:* The thermal fatigue experienced by the working surface of rolls may lead to the formation of fire cracking (crazing). This problem is most acute in primary and roughing mills, where, due to relatively slow roll speeds and high stock temperatures, thermal stresses are greatest (Fig. 1).
- *Mechanical Stresses:* The compressive loading between the roll and stock causes radial deflection of the rolls, the extent of which depends upon the level of the applied force and the roll diameter. The resulting radial flexing can cause fine surface pitting if the stress fluctuates in the range of the fatigue limit of the roll material. A more serious consequence of these compression forces is the formation of severe cracks and spalls, which require large reductions to remove the damage and, in many cases, can lead to scrapping of the rolls.

Metallurgical demands placed on rolling mills are therefore quite complex, and the main requirements of the roll material should cover:

velikosti uporabljene sile in premera valja. Posledično radialno upogibanje lahko povzroči drobne površinske izjede, če napetost niha v območju meje utrujenosti materiala valja. Resnejša posledica teh tlačnih sil je nastanek hudih razpok in drobcev, kar zahteva obsežno obdelavo valjev, da se odstranijo poškodbe, in v mnogih primerih lahko privede do izločitve valjev.

Metalurške zahteve za valjarne so zato precej zapletene, glavne zahteve materiala za valje pa morajo vključevati:
- visoko odpornost proti obrabi
- visoko odpornost proti zlomu
- neobčutljivost na pokanje in luščenje
- dobro kakovost površine in ustrezno režo za vstop valjanega materiala.

Doseganje visoke kakovosti valjanih izdelkov je kumulativno pri celotnem postopku valjanja in je odvisno od pravilne vrste in kakovosti valja, ki je nameščen na vsakem zaporednem stojalu valjarskega sklopa. Metalurške, mehanske in fizikalne zahteve za valje so precej kompleksne, zlasti v sodobnih valjarnah. S sedanjim metalurškim znanjem in poznavanjem materialov ne bi bilo posebej težko izpolniti nobene od zahtev glede materiala valjev, vendar pa je kombinacija tista, ki proizvajalcem valjev nenehno povzroča resne težave, saj se rešitve medsebojno izključujejo. Na primer, visoke odpornosti proti lomljenju ni enostavno združiti z zahtevo po dobri odpornosti proti obrabi, zato mora proizvajalec skrbno določiti pravilno ravnovesje lastnosti, če želi doseči želene rezultate.

Metalurgijo valjev lahko pravzaprav označimo kot metalurgijo kompromisov. Glavna lastnost valja je odpornost proti obrabi, medtem ko morajo biti vratovi valja dovolj odporni proti lomu, kar preprosto pomeni, da oblikovalec valjev želi doseči

- high wear resistance
- high resistance to fracture
- insensitivity to fire cracking and spalling
- good surface quality and adequate bite with the rolled stock.

The attainment of a high-quality rolled product is cumulative throughout the entire rolling operation and depends on the correct type and quality of roll being located in each successive stand of the rolling train. The metallurgical, mechanical, and physical demands placed on rolling mill rolls are quite complex, particularly in modern mills. With our current metallurgical and material knowledge, it would not be particularly difficult to meet any one of the roll material requirements; the combination, however, constantly presents serious problems to roll makers because the solutions are mutually contradictory. For example, a high resistance to breakage is not easily combined with a requirement for good wear resistance, and achieving the correct balance of properties requires careful specification by the manufacturer to ensure successful results.

Actually, roll metallurgy can be considered the metallurgy of compromise. The primary property of concern in the roll barrel is wear resistance, whereas the roll necks should acquire sufficient resistance to fracture. In contrast, the roll necks should acquire the resistance necessary to fracture, which implies that the roll designer is targeting two contradictory properties in the same roll cast from the same melt. Cast iron microstructures mainly depend on the alloy composition as well as the cooling rate, and the data shown in Table 1 illustrates the contribution of microstructural constituents of the ductile iron to achieve the different metallurgical demands and properties of roll material.

The “mix” of these phases used for any particular application will obviously depend dve nasprotujoči si lastnosti pri istem valju, ulitem iz iste taline. Mikrostruktura litega železa je odvisna predvsem od sestave zlitine in hitrosti ohlajanja, podatki v preglednici (1) pa prikazujejo vpliv mikrostrukturnih sestavin sive litine s kroglastim grafitom pri doseganju različnih metalurških zahtev in lastnosti materiala valja.

»Mešanica« teh faz, ki se uporablja za določeno uporabo, je seveda odvisna od zahtev valjarne, proizvajalec valjev pa določi strukturo, ki zagotavlja najboljšo odpornost proti slabšanju lastnosti površine. Kot primer lahko navedemo dva skrajna primera:

- Valjarniška ogrodja in proge za grobo valjanje blokov morajo vzdržati ekstremne udarne in velike toplotne obremenitve, zato je treba uporabiti trpežen in močan material za valje z dobro odpornostjo proti pokanju. Običajno velja, da je jekleni valj ali valj iz sive litine s kroglastim grafitom s strukturo iz ferita in perlita ali sferoidiziranega perlita najboljša kombinacija lastnosti. Površinska plast valja ima lahko tudi zgornjo bainitno strukturo z dobrimi rezultati, vendar morata imeti sredina in čep strukturo iz sferoidiziranega perlita z največjo žilavostjo.
- Drug primer skrajnega delovanja valjarne so zaključna ogrodja sodobne valjarne za kontinuirano valjanje palic. Pri tem so mehanske in termične obremenitve zanemarljive, zato se lahko izdelovalec valjev osredotoči na doseganje največje odpornosti proti obrabi za natančnejše dimenzije končnega izdelka. Uporabljajo se valji iz bele litine z zelo visoko vsebnostjo karbida (40 %) v martenzitni matrici.

Pri valjarskih nalogah med tema skrajnostma je potrebna večja pozornost on the mill requirements, and the roll maker will specify a structure that gives the best resistance to surface deterioration. Two extreme cases may be taken as examples:

- Blooming and slabing mill rolls must withstand extreme shock loads and severe thermal stresses so it is essential to use a tough, strong roll material with good fire crack resistance. Typically, a steel or ductile iron roll with a structure of ferrite and pearlite, or spheroidized pearlite, is considered to offer the best combination of properties. The barrel surface layer may also have upper bainite structure with good results, but the center and neck should have spheroidized pearlite structure of maximum toughness.
- The other extreme of mill duty is the finishing stands of a modern continuous rod mill. Here, mechanical and thermal stresses are negligible, and thus the roll maker can concentrate on achieving the maximum wear resistance for more precise dimensions of the finished product. Chilled iron rolls with a very high carbide content (40%) in a martensite matrix are used.

For mill duties between these extremes, the choice of the correct structure requires more care from the roll mill maker due to the influence of other factors such as grip, hardness penetration, and spall resistance. Generally, the trend is to use a progressively harder structure with increasing carbide contents as the thermal and mechanical stresses cease and the need for good stock shape becomes more important. However, in many cases, the choice of role still involves an element of compromise. The efforts of the roll makers in recent years have been directed towards eliminating this need for a compromise as far as possible for many applications. Figure 2 shows some of the rolls produced during izdelovalca valjev pri izbiri pravilne strukture zaradi vpliva drugih dejavnikov, kot so oprijem, globina trdote in odpornost proti luščenju. Na splošno je trend usmerjen v uporabo vedno trše strukture z naraščajočo vsebnostjo karbida, saj se termične in mehanske napetosti zmanjšujejo, potreba po dobri obliki materiala pa postaja vse pomembnejša. Vendar je izbira valja v številnih primerih še vedno povezana s

the early stages of production with sizes up to 4 tons in EGYPTALUM, whereas Figure 3 shows some of the recently produced rolls at Helwan Iron Foundries.

To enhance the competitiveness of the locally produced rolls, several R&D projects have been conducted aiming at either improving the performance of rolls or lowering the production cost. Examples

Preglednica 1. Vpliv sestavin mikrostrukture sive litine s kroglastim grafitom na lastnosti valja.

Table 1. The influence of ductile iron microstructure constituents on the roll properties.

Faza / Phase	Lastnosti valja / Roll Properties	Faza / Phase	Lastnosti valja
Ferit / Ferrite	• odpornost proti poškodbam. • dobra odpornost proti pokanju. • visoka žilavost. • Dober oprijem (reža). • Nizka obraba in visoka trdota.	Martenzit / Martensite	• zelo visoka trdota, dobra površinska obdelava. • zelo dobra odpornost proti obrabi. • slaba odpornost proti pokanju. • nizka žilavost
	• resistance to breakage. • good fire crack resistance. • high toughness. • Good grip (bite). • Poor wear and high hardness.		• very high hardness, good surface finish. • very good wear resistance. • poor fire crack resistance. • low toughness
Lamelarni perlit / Lamellar Pearlite	• dobra trdnost in odpornost na pokanje. • primerna odpornost proti obrabi. • finejši perlit izboljša trdnost in obrabo, vendar na račun duktilnosti in odpornosti proti pokanju. • dober oprijem.	Karbidi / Carbides	• izredno dobra odpornost proti obrabi. • Visoke vsebnosti ogljika povzročajo krhkost. Ta učinek pa je mogoče ublažiti z ustrezno toplotno obdelavo z vsebnostjo C do 1,4 %.
	• good strength and fire crack resistance. • reasonable wear resistance. • finer pearlite improves strength and wear, but at the expense of ductility and fire crack resistance. • good grip.		• extremely good wear resistance. • High C-contents cause embrittlement. But this effect can be alleviated by suitable heat treatment with C-contents up to 1.4%.
Sferoidizirani perlit	• združuje visoko žilavost in primerno odpornost proti obrabi. • dobra odpornost proti pokanju. • relativno mehek. • dober oprijem.	Grafit / Graphite	• izboljša odpornost proti pokanju in drobljenju. • grafit v obliki lističev zmanjša trdnost zaradi učinka notranje zareze, temu učinku pa se v veliki meri izognemo s sferoidizacijo grafita. • izboljša oprijem.
	• combine high toughness with reasonable wear resistance. • good fire crack resistance. • relatively soft. • good grip.		
Bainit / Bainite	• visoka trdnost in trdota ter dobra odpornost proti obrabi. • zgornje bainitne strukture imajo dobro odpornost proti pokanju.		• improves fire crack and spalling resistance. • flake graphite lowers strength due to internal notch effect, this effect is largely avoided by graphite spheroidization. • improves grip.
	• high strength and hardness, together with good wear resistance. • upper bainite structures have good fire crack resistance.		

Slika 2. Valji, izdelani v družbi EGYPTALUM ob koncu prejšnjega stoletja

Figure 2. Rolls produced at EGYPTALUM in the end of the last century

Slika 3. Valji, izdelani v livarni Helwan leta 2021.

Figure 3. Rolls produced at Helwan Iron Foundries in 2021.

sprejemanjem kompromisa. Prizadevanja proizvajalcev valjev so bila v zadnjih letih usmerjena v čim večjo odpravo kompromisov pri številnih aplikacijah. Slika (2) prikazuje nekatere valje, izdelane v zgodnjih fazah proizvodnje, velikosti do 4 tone v podjetju EGYPTALUM, medtem ko Slika (3) prikazuje nekaj nedavno izdelanih valjev v družbi Helwan Iron Foundries.

Za povečanje konkurenčnosti lokalno proizvedenih valjev je bilo izvedenih več projektov raziskav in razvoja, katerih cilj je bil bodisi izboljšati zmogljivost valjev bodisi znižati stroške proizvodnje. Primeri teh programov raziskav in razvoja so prikazani na Sliki (4).

of those R&D programs are illustrated in Figure 4.

The final result of these R&D projects was the replacement of a good part of imported rolls with locally produced ones in all Egyptian steel mills. Moreover, two foundries have exported rolls to European as well as Arab steel mills.

Roll Casting Techniques Adopted in Egyptian Foundries

Rolls can be cast either through static casting or centrifugal casting. All attempts carried out in the five Egyptian foundries have been limited to static casting, and the

Končni rezultat teh projektov raziskav in razvoja je bila zamenjava velikega dela uvoženih valjev z lokalno proizvedenimi v vseh egiptovskih jeklarnah. Poleg tega sta dve livarni izvažali valje v evropske in arabske jeklarne.

Prevzete tehnike litja valjev v egiptovskih livarnah

Valje je mogoče liti s statičnim ali centrifugalnim litjem. Vsi poskusi v petih egiptovskih livarnah so bili omejeni na statično litje, statično uliti valji pa so bili bodisi enojno bodisi dvojno uliti.

Enojno uliti valji

Trdota enojno ulitih železnih valjev je omejena na manj kot 70 Shore C, ker zaradi uravnovešanja trdote valja postaneta struktura jedra in čepa prešibka zaradi razmeroma bele ali trde mikrostrukture, ki se razvije.

Tako mora en sam ulit valj, tj. ena sama talina in sestava, zagotavljati tako odpornost proti obrabi delovne plasti valja kot tudi trdnost, da vzdrži obremenitve valjanja na čepih**.**

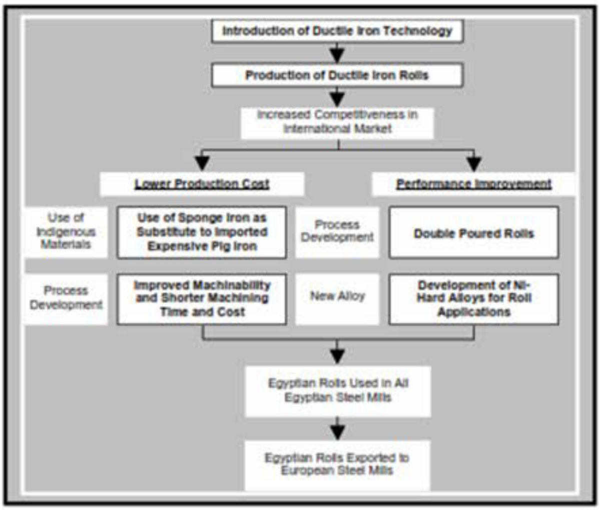
statically cast rolls were either single or double poured.

Single Poured Rolls

Single-poured iron rolls are limited to less than 70 shore C hardness because to balance this barrel hardness, the core and neck structures become too weak due to the relatively white or hard microstructure that develops.

Thus, a single poured roll, that is, a single melt and composition, must provide both wear resistance of the working barrel and strength to withstand rolling loads in the necks**.**

This type of iron roll is characterized by the gradual change in properties through the barrel cross section due to the same composition solidifying in various microstructures under the influence of a changing rate of cooling, when the roll barrel solidifies in a cast iron mold or "chill" whereas the necks solidifying in sand molds (Figure 5). An exception to this characteristic is the "clear chill" roll which solidifies as a true white iron at the barrel surface, but via a narrow "mottled" or eutectic zone, suddenly solidifies as a true gray iron.



Slika 4. Projekti raziskav in razvoja inštituta, ki so privedli do proizvodnje visokokakovostnih in poceni valjev

Figure 4. CMRDI R&D projects leading to production of high quality, low-cost rolls

Za to vrsto železnega valja je značilno postopno spreminjanje lastnosti skozi prerez valja zaradi strjevanja iste sestave v različne mikrostrukture pod vplivom spreminjajoče se hitrosti ohlajanja, ko se jedro valja strjuje v litoželezni formi (kokila), medtem ko se čepi strjujejo v peščenih formah (Slika 5). Izjema pri tej lastnosti je valj, ki se na površini valja strdi kot bela litina, vendar se prek ozke melirane ali evtektične cone nenadoma strdi kot siva litina.

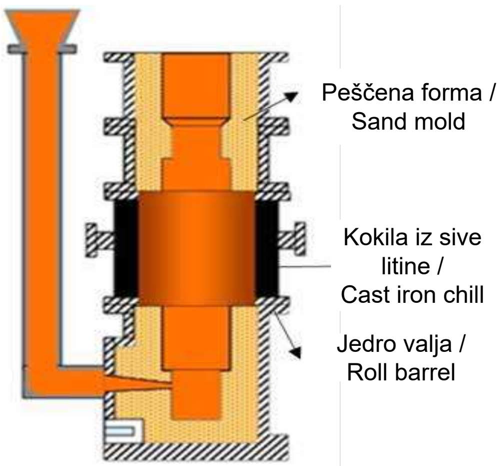
Vendar je profil trdote odvisen od različnih hitrosti ohlajanja med jedrom valja inšepi, tj. od debeline in toplotne prevodnosti litoželezne forme (kokile). Poleg tega ima pravilna izbira legirnih elementov, dodanih v sivo litino s kroglastim grafitom, ki se ulije v formo, predvsem Cr, Ni in Mo, ključno vlogo pri določanju profila trdote valja (slika 6). Opozoriti je treba, da se valji z enojnim litjem uporabljajo le, če zahtevana trdota v valju ni za več kot 50 % višja od trdote v čepih.

Dvojno uliti valji

Kadar je trdota valja za več kot 50 % večja od trdote čepov, je valj ulit iz dveh različnih litin; iz visoko legirane litine z večjo trdoto in odpornostjo proti obrabi v zunanji lupini – delovni plasti valja ter iz bolj žilave litine v jedru valja in čepih. Statično dvojno uliti valji se izdelajo s premikanjem in/ali redčenjem tekoče kovine v orodju z drugo tekočo kovino drugačne sestave. Litoželezni valji z dvojnim litjem se navadno proizvajajo z dodajanjem druge taline skozi dno forme prek istega ulivnega sistema kot prva kovina. Izpodrinjeni in razredčeni presežek se zbira med izlivanjem iz orodja in je nato na voljo kot legirana surovina za naslednje taline.

V orodje se najprej ulije kovina, iz katere se na koncu oblikujejo delovne plasti, lupina ali jedro, pri čemer je raven, do katere napolni orodje, delno na zgornjem čepu.

However, the hardness profile depends on the differential cooling rates between the barrel and the necks, i.e., the thickness as well as the thermal conductivities of the cast iron mold (chill). Moreover, the proper selection of the alloying elements added to the ductile iron poured in the mold; which are mainly Cr, Ni and Mo play a crucial role in determining the hardness profile of the barrel (Figure 6). It should be noted that the single- poured rolls are applicable only when the hardness required in the barrel is not more than 50% higher than the hardness in the necks.



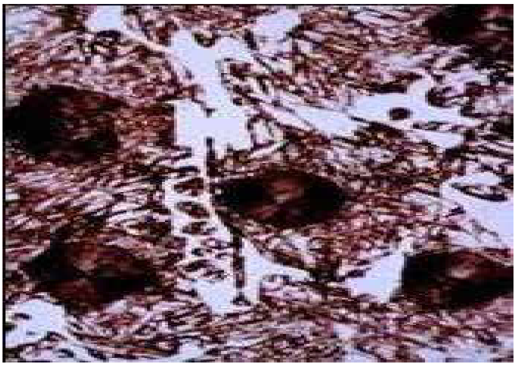
Slika 5. Tehnologija litja enojno ulitih valjev

Figure 5. Casting technology of single poured rolls.

Double Poured Rolls

Whenever the hardness of the barrel is more than 50% harder than that of the necks, the roll is cast from two different irons a highly alloyed iron with higher hardness and wear resistance in the outer shell and a tougher iron in the barrel core and the necks. Static cast double-poured rolls are produced by displacing and/or diluting the

Strjevanje prve kovinske lupine – delovne plasti se začne v kokili takoj po litju. Hitrost strjevanja in s tem globina delovne plasti je odvisna od časa in velikosti ulitka in kokile. Potrebno globino strjevanja delovne plasti določa valjarski obrat, kar pomeni, da je odvisna od najmanjšega premera valja preden se ga zavrže. Po ustreznem času za strjevanje delovne plasti se druga talina ali kovinsko jedro ulije skozi isti ulivni sistem, vendar z nadzorovano in enakomerno hitrostjo ulivanja. Hitrost ulivanja omogoča mešanje, redčenje in premikanje tekoče delovne plasti z mešanjem in nastajanjem sive litine na meji strjene delovne plasti in jedra valja. Uspešnost dvojnega ulivanja je v veliki meri odvisna od temperature in časa ulivanja obeh talin.

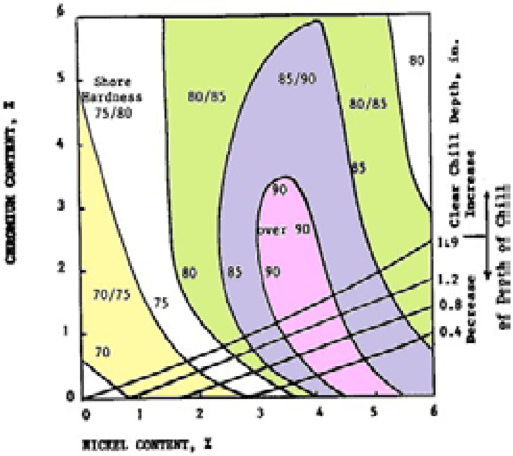


Slika 7. Mikrostruktura SG-Ni Hard z martenzitno karbidno matrico

Figure 7. Microstructure of SG-Ni Hard with martensitic carbidic matrix

Ni-hard, ki je bela litina, legiranega s Cr in Ni, tj. brez grafitnih tvorb v strukturi, se je močno uveljavila pri litju delovne plasti dvojno ulitih valjev, ki se uporabljajo v zadnjih ogrodjih valjarn za vroče trakove. V prejšnjih raziskavah na inštitutu CMRDI je bilo mogoče pridobiti kroglasti grafit (SG) v mikrostrukturi zlitineNi-Hard IV z matrico,

liquid metal inside the mold with a second liquid metal of different composition. Cast iron double-poured rolls are generally produced by adding the second liquid through the bottom of the mold via the same running system as the first metal. The displaced and diluted excess is collected as it pours from the mold and is then available as an alloyed raw material for the next melts.



Slika 6. Vpliv vsebnosti Ni in Cr na trdoto soda in globino ohlajanja

Figure 6. Effect of Ni and Cr contents on the hardness of the barrel and depth of chill

The first metal to be poured into the mold is that which eventually forms of the working layers or shell of the barrel, the level to which it fills the mold is partway up the top neck. Solidification of the first shell metal commences immediately at the casing or permanent mold chiller. Speed of solidification, hence the depth of the shell, is dependent upon time and casting size. The depth of the shell solidification required is determined by the mill, that is, it is dependent upon the reject diameter of the roll under consideration. After due ki vsebuje karbide in martenzit (slika 7), uporabljeni za delovno plast dvojno ulitega valja. To je bilo mogoče z uporabo močnega inokulanta na osnovi bizmuta, kar je omogočilo uporabo razvitega materiala Ni-Hard IV v začetnih valjalnih ogrodjih, kjer je žilavost bolj pomembna. Poleg tega bi lahko strjevanje kroglastega grafita prineslo naslednje koristi:

- Povečana odpornost proti pokanju zaradi večje toplotne prevodnosti, ki zmanjšuje toplotne napetosti.
- Izboljšana obdelovalnost.
- Izboljšano mazanje valjev in boljši oprijem valjev.

ADI – nov revolucionarni material:

V zadnjih treh desetletjih je skupina livarn inštituta CMRDI v veliki meri prispevala k svetovnemu razmahu raziskav in razvoja, ki je sledil napovedi prve proizvodnje novega referenčnega materiala – poboljšane sive litine s kroglastim grafitom (ADI) – v osemdesetih letih prejšnjega stoletja. Odlična kombinacija lastnosti tega materiala je odprla nove možnosti za litino, ki lahko nadomesti jeklene ulitke in kovane elemente v številnih inženirskih aplikacijah z znatnimi stroškovnimi ugodnostmi. Poleg tega so vztrajna prizadevanja avtomobilske industrije po vsem svetu za uporabo lahkih materialov zmanjšala trg težjih železnih ulitkov. Trenutno ADI s svojo izjemno trdnostjo uspešno konkurira lahkim zlitinam, česar pa se številni inženirji še niso v celoti zavedali.

Mehanske lastnosti sive litine s kroglastim grafitom v litem stanju se lahko bistveno izboljšajo s toplotno obdelavo s kaljenjem (slika 8). To je privedlo do novega člana družine litega železa, sive litine s kroglastim grafitom (ADI) z edinstveno mikrostrukturo kroglastega grafita v ausferitni matrici [1].

time for solidification of the shell, the second liquid or core metal is poured through the same running system, but at a controlled and even pouring rate. The rate of pour allows mixing, dilution and displacement of the liquid shell metal with mixing and gray iron formation immediately at the solidified shell boundary. The success of the double pouring depends to a large degree on the pouring temperature and timing of both metals.

Ni-hard, which is Cr, Ni alloyed white iron, i.e., without graphite formations in the structure, has been firmly established for casting of the outer shell of double-poured rolls used in the last stands of hot strip mills. In a previous research at CMRDI, spheroidal graphite (SG) could be precipitated in the Ni-hard IV structure (Figure 7) microstructure of SG-Ni-hard IV shell layer of a double poured roll with a matrix comprising carbides as well as martensite, using a Bi-containing potent inoculant which permitted the developed Ni-hard IV to be used in the earlier stands, where toughness is of higher concern. Moreover, the precipitation of SG could lead to the following benefits:

- Increased resistance to fire cracking by increasing thermal conductivity, which alleviates thermal stresses.
- Improved machinability.
- Improved rolling lubrication and roll bite.

ADI – The Novel Revolutionary Material:

Over the past three decades CMRDI foundry group has been largely contributing to the worldwide explosion of research and development that followed the announcement of the first production of the new benchmark material, the austempered ductile iron (ADI) in the 1980s of the past century. The excellent property combination of this material has opened new horizons for cast iron to replace steel castings and

Transformacijo s kaljenjem v litini ADI lahko opišemo kot dvostopenjsko reakcijo [2]:

Reakcija 1. stopnje (povečanje žilavosti): avstenit (γc) → ferit (α) + visokoogljični stabilizirani avstenit (γHC)

Reakcija 2. stopnje (pojav krhkosti): visokoogljični avstenit (γHC) → ferit (α) + karbidi (ε)

Mehanske lastnosti litine ADI so odvisne od številnih medsebojno povezanih dejavnikov, med katerimi so predvsem temperature in časi avstenitizacije in austempranja ter mikrostruktura, sestava in velikost sklopa. Med njimi je najpomembnejša temperatura austempranja [1]. Te spremembe lastnosti so lahko povezane s spremembami mikrostrukture. Pri nizkih temperaturah austempranja nastane acikularni ferit (igličasti) z le majhno količino zaostalega avstenita. Pri najnižjih temperaturah austempranja lahko struktura vsebuje tudi nekaj martenzita. Ta vrsta mikrostrukture lahko zagotavlja visoko natezno trdnost in trdoto, vendar le ob omejeni duktilnosti in slabi obdelovalnosti. Pri višjih temperaturah austempranja postane ferit bolj grob z

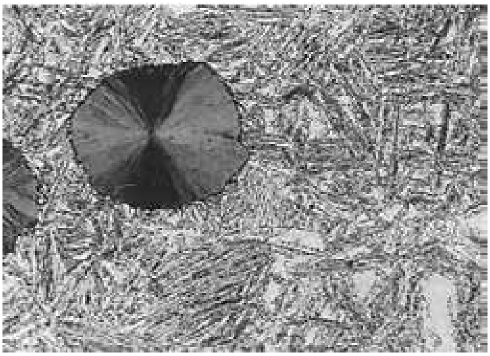
forgings in many engineering applications with considerable cost benefits. Moreover, the sustained efforts worldwide of the automotive industry to use lightweight materials have eroded the market for the heavier iron castings. Currently, ADI, with its super strength, is successfully competing with the lightweight alloys, a point which has yet to be fully realized by many design engineers.

The as-cast mechanical properties of ductile iron can be significantly improved through an austempering heat treatment (Figure 8). This has led to the birth of a new member of the cast iron family; the austempered ductile iron (ADI), with its unique microstructure, spheroidal graphite in an ausferritic matrix [1].

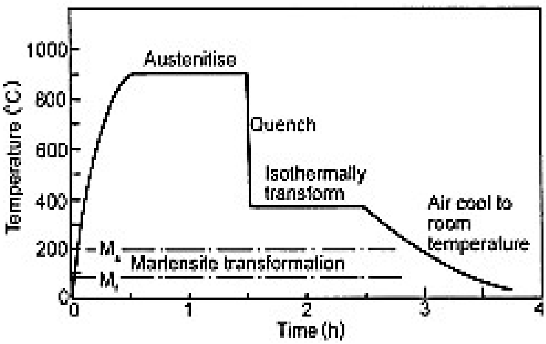
The austempering transformation in ADI can be described as a two-stage reaction [2]:

Stage I Reaction (toughening): austenite (γc) → ferrite (α) + high carbon stabilized austenite (γHC)

Stage II Reaction (embrittlement): high carbon austenite (γHC) → ferrite (α)+ carbides (ε)



a)



b)

Slika 8. (a) Tipična mikrostruktura litine ADI, (b) postopek austmpranja

Figure 8. (a) Typical microstructure of ADI, (b) the Austempering process

večjimi količinami zadržanega avstenita (do40 %) z značilno »ausferitno strukturo. S tem se bistveno poveča duktilnost in obdelovalnost pri manjši trdoti. Slika 9 prikazuje konkurenčno prednost litine ADI v primerjavi z drugimi inženirskimi materiali, saj je ta najlažja in hkrati najcenejša, če primerjamo težo in stroške materiala, potrebnega za zagotovitev ene enote trdnosti [3].

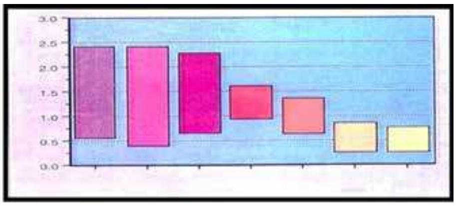
V nadaljevanju so predstavljeni nekateri raziskovalni in razvojni programi, ki jih inštitut CMRDI izvaja samostojno ali v sodelovanju z mednarodnimi partnerji in so namenjeni izboljšanju trdnostnih in triboloških lastnosti litine ADI ter raziskovanju možnosti za nove aplikacije tega dinamičnega in perspektivnega materiala.

Prispevek inštituta CMRDI k razvoju litine razvoju litine ADI:

1. Hladno valjanje litine ADI

Kot pove že ime, se je litina dolga leta proizvajala le z »litjem«. V smeri valjanja

The mechanical properties of ADI depend on a number of interlinked factors, including primarily the austenitizing and austempering temperatures and times, together with the as-cast microstructure, the composition, and the section size. Of these, the austempering temperature is the most important [1]. These variations in properties can be related to the changes in microstructure. At low austempering temperatures, an acicular (needle-like) ferritic phase is formed with only a small amount of retained austenite. At the very lowest austempering temperatures, the structure may also contain some martensite. This type of microstructure can provide high tensile strength and hardness, but only limited ductility and poor machinability. With increased austempering temperatures, the ferrite becomes coarser with increased amounts of retained austenite (up to -40%), with a typical “ausferrite structure. This results in a substantial increase in ductility and machinability with lower hardness. Figure 9 demonstrates the competitive edge of ADI compared with other engineering

a)


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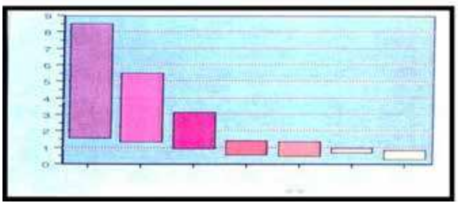

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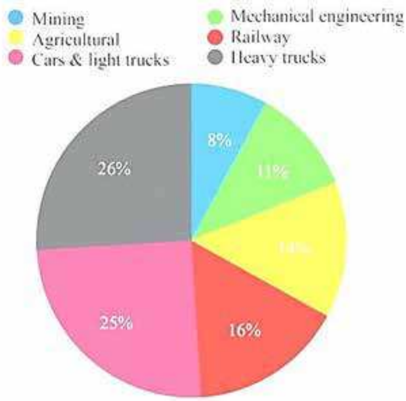


Slika 9. Konkurenčna prednost litine ADI: (a) relativna masa na enoto trdnosti, (b) relativni stroški na enoto moči in (c) tržni delež glavnih aplikacij za ADI

Figure 9. The competitive edge of ADI [3]; (a) relative weight per unit of strength, (b) relative cost per unit of strength, c) market share of major applications for ADI

so bili pripravljeni hladno valjani ploščati natezni vzorci ADI, na katerih je bil opravljen natezni preskus [4–6]. Slika 10 prikazuje, da se je z večanjem redukcij pri hladnem valjanju (CR) količina ohranjenega avstenita (ɣr) zmanjšala zaradi delne transformacije ɣr v martenzit. Slika 10a prikazuje, da se količina mehansko ustvarjenega martenzita povečuje s povečevanjem redukcije hladnega valjanja [4]. Kot je razvidno iz slik (10b,c) se raztezek in udarna žilavost zmanjšata, medtem ko se natezna trdnost in trdota povečujeta s povečevanjem redukcij hladnega valjanja. To pripisujemo povečanju utrjevanja zadevne litine ADI s procesi hladne deformacije (deformacijski trakovi in dvojčki) in deformacijsko induciranim martenzitom. Omeniti je treba, da so opažene spremembe mehanskih lastnosti pri lahki hladni deformaciji (7-odstotno zmanjšanje) v glavnem posledica utrjevanja te litine s plastično deformacijo, koncentrirano v ɣr. Pri tej lahki deformaciji je količina mehansko oblikovanega martenzita zelo majhna (Slika 10).

Dobro odpornost proti obrabi pri vsakem materialu običajno dosežemo z zagotavljanjem visoke trdote. Pri nizkih temperaturah austempranja (235–250 °C)

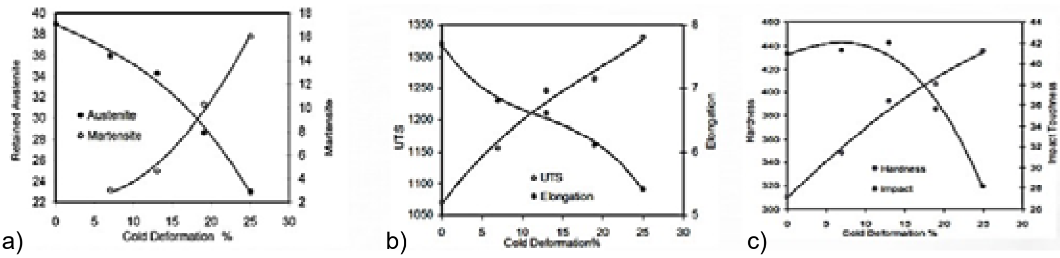
materials. When we compare the weight and cost of material required to give one-unit yield strength, ADI is the lightest and at the same time, the cheapest [3].

The following sections outline some of the research and development programs conducted by CMRDI, either solely or in cooperation with international partners, aiming at the enhancement of strength and tribological properties of ADI and exploring potentials for novel applications of this dynamic and prospective material.

CMRDI Contribution to ADI Development:

1. Cold Rolling of ADI

As its name implies, cast iron has been over years produced only by “casting” process. Cold-rolled ADI flat tensile specimens were prepared along the rolling direction and the specimens were subjected to tensile test [4 - 6]. Figure 10 shows that increasing the cold rolling (CR) reductions, the amount of retained austenite (ɣr) was decreased due to partial transformation of ɣr to martensite. Figure 10a indicates that the amount of mechanically generated martensite increases with increasing CR reduction [4]. As can be seen from Figures



Slika 10. Učinek odstotka hladne redukcije na: a) prostorninske deleže zadržanega avstenita in mehansko inducirane tvorbe martenzita, b) raztezek in natezno trdnost, c) Trdoto po Vickersu in udarno žilavost [4]

Figure 10. Effect of cold reduction percent on: a) volume fractions of retained austenite and mechanically induced martensite formation, b) elongation and ultimate tensile strength, c) Vickers hardness and impact toughness [4]

nastajajo trdi ADI (~480–550 BHN) in takšne vrste se izberejo, kadar je glavna zahteva dobra odpornost proti obrabi. Z višanjem temperature austempranja se trdota zmanjšuje, kar povzroča večjo obrabo. Vendar mehkejše vrste ADI (navadno 280–320 BHN) vsebujejo velike količine avstenita, ki se lahko ob mehanski obremenitvi na površini deformacijsko utrdi in/ali spremeni v martenzit, pri čemer je odpornost proti obrabi bistveno boljša, kot bi pričakovali. Čeprav ta učinek pri strojni obdelavi ni ugoden, je lahko zelo koristen za nekatere komponente ADI, saj se površina obrablja in jo nenehno nadomešča sveže oblikovana utrjena plast [5, 6].

Zaradi vse pogostejše uporabe litine ADI kot nadomestka za kovana jekla v predelovalnih industrijah je deformacijsko utrjevanje litine ADI deležno vse večje pozornosti, zato je za boljše razumevanje tega pojava potrebnih več raziskav. To je mogoče pripisati naslednjim dejavnikom:

- Sestavni deli iz litine ADI, kot so zobniki menjalnikov, ročične gredi in kolesa železniških vagonov, so med proizvodnjo podvrženi obsežni strojni obdelavi, obnašanje litine ADI zaradi deformacijskega utrjevanja pa močno vpliva na življenjsko dobo orodja za strojno obdelavo in kakovost površine dela.
- V številnih aplikacijah so sestavni deli iz litine ADI izpostavljeni velikim plastičnim obremenitvam (npr. utrujenost, obraba). Na celotno življenjsko dobo teh sestavnih delov torej vplivajo značilnosti deformacijskega utrjevanja materiala.
- Deformacijsko utrjevanje matrice ADI povzroči nastanek martenzita zaradi deformacije, kar prispeva k visoki odpornosti litine ADI proti obrabi.

10b and 10c The elongation and impact toughness decrease, while the ultimate tensile strength and hardness increase with increasing CR reduction. This is attributed to increase of the hardening of the investigated ADI with cold deformation processes (deformation bands and twins) and deformation–induced martensite. It must be mentioned that the observed changes in the mechanical properties at light cold deformation (7% reduction) are mainly attributed to the hardening of this alloy by plastic deformation concentrated in γr. At this light deformation, the amount of mechanically formed martensite is very small (Figure 10).

Good wear resistance is usually obtained in any material by ensuring a high hardness. Low austempering temperatures (235-250 °C) produce hard ADI (~480-550 BHN), and such grades would be selected when good wear resistance is the main requirement. As the austempering temperature increases, the hardness decreases, resulting in more wear. However, the softer grades of ADI (typically 280-320 BHN) contain large amounts of austenite, and this can work harden and/ or transform to martensite when subjected to mechanical strain at the surface, with wear resistance significantly better than would be expected. Although this effect is disadvantageous when machining, it can be very beneficial for certain ADI components, since as the surface is worn away, it is continuously replaced by a freshly formed hardened layer [5, 6].

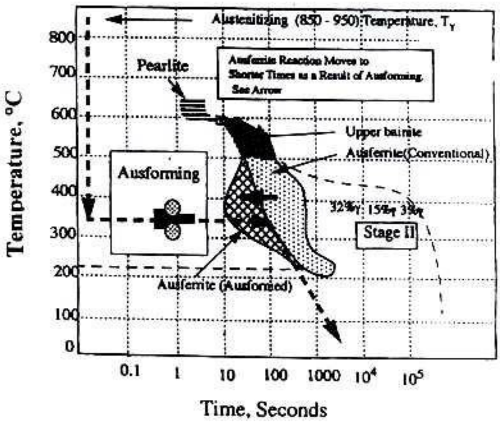
With increasing applications of ADI as a substitute for forged steels in manufacturing industries, strain hardening of ADI is attracting more attention, and more research is required for a better understanding of this phenomenon. This may be attributed to the following factors:

2. Poboljšana siva litina s kroglastim grafitom z ausformingom (AADI)

Izkazalo se je [7,8], da lahko hitrost nastajanja ferita med austempranjem na prvi stopnji nadzorujemo z naslednjimi spremenljivkami obdelave:

- **Kemijsko** – vključno z izbiro vsebnosti zlitine zaradi kaljivosti in izbiro temperature avstenitizacije, ki nadzoruje vsebnost ogljika v matrici.
- **Termično** – vključno s temperaturo in časom austempranja.
- **Mehansko** – vključno z mehansko deformacijo, ki se v načrt austempranja vključi takoj po gašenju, vendar pred kakršno koli bistveno transformacijo avstenita (ausforming) (Slika 11).

Seveda bi lahko optimalno končno mikrostrukturo dosegli z vključitvijo elementov vseh treh spremenljivk obdelave. Pokazalo se je [9–11], da lahko mehanska obdelava ADI deluje kot krmilni ventil za reakcijo austempranja na prvi stopnji. Pri poboljšani sivi litini s kroglastim grafitom z ausformingom (AADI) mehanska deformacija vpliva na mikrostrukturo



Slika 11. Shematski prikaz postopka kaljenja v vroči kopeli [7]

Figure 11. Schematic representation of the austempering process [7]

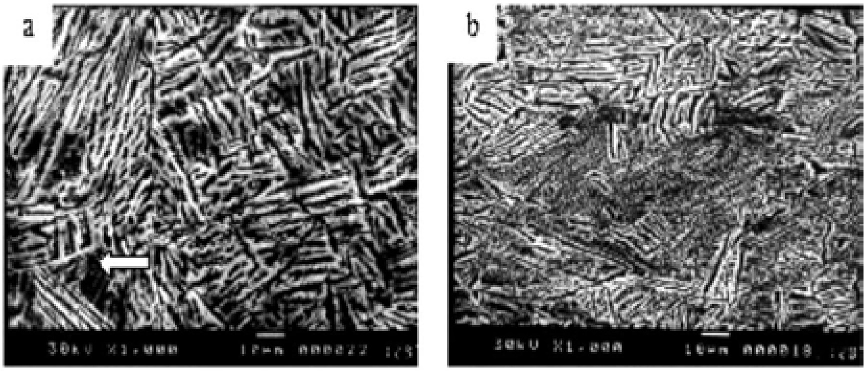
- ADI components such as transmission gears, crankshafts, and train car wheels are subjected to extensive machining during manufacturing, and the strain-hardening behavior of ADI has a profound influence on machining tool life and part surface finish.
- In many applications, ADI components undergo substantial plastic strains (e.g., fatigue, wear). The total life cycle of those components is, therefore, influenced by the strain-hardening characteristics of the material.
- Strain-hardening of the ADI matrix causes strain-induced martensite formation, and this contributes to the high wear resistance of ADI.

2. Ausformed Austempered Ductile Iron (AADI)

It has been shown [7,8] that the rate of ferrite formation during stage I austempering may be controlled by the following processing variables:

- **Chemical** – including alloy content selection for hardenability purposes, together with the austenitization temperature selection, which controls the matrix carbon content.
- **Thermal** – including austempering temperature and time.
- **Mechanical** – including mechanical deformation introduced into the austempering schedule just after quenching, but before any substantial transformation of austenite (ausforming) (Figure 11).

Naturally, an optimum final microstructure could be produced by including elements of all three processing variables. It has been shown [9 - 11] that mechanical processing of ADI can act as a control valve for the stage I austempering reaction. In ausformed austempered ductile



Slika 12. Mikrografije z vrstično elektronsko mikroskopijo za litine ADI, legirane z 2 % Ni, ki je bil 1 minuto kaljen pri 375 °C. (a) Običajno obdelan, (b) ausformiran na 25 %, puščice kažejo na krhek martenzit, ki je nastal v številnih conah v običajno obdelani litini ADI. [8]

Figure 12. SEM micrographs of ADI alloyed with 2% Ni austempered at 375 °C for 1 minute. (a) Conventionally processed; (b) Ausformed to 25% reduction arrows indicate the brittle martensite formed in many zones in the conventionally processed ADI. [8]

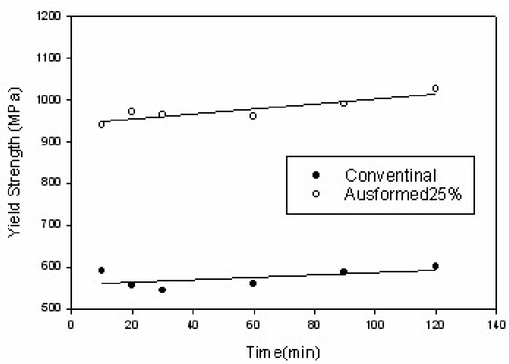
in posledično na mehanske lastnosti sive litine s kroglastim grafitmolitine zaradi pospeševanja ausferitne reakcije, izboljšanja mikrostrukture in povečanja strukturne homogenosti.

Izkazalo se je [9], da je ausforming do 25-odstotnega zmanjšanja višine med valjanjem prispeval k dodajanju komponente mehanske obdelave konvencionalni toplotni obdelavi litine ADI, kar je povečalo hitrost nastajanja ausferita in privedlo do veliko bolj finega in homogenega ausferitnega izdelka **(Slika 12)**. Vpliv ausforminga na vrednosti trdnosti je bil precej dramatičen **(Slika 13)** (do 70- oziroma 50-odstotno povečanje meje plastičnosti in meje trdnosti). Predlagamo lahko mehanizem, ki vključuje izboljšano mikrostrukturno raven zaradi okrepljene nukleacije feritov in povečane gostote dislokacij. Za povečanje možnosti utrjevanja ulitkov debelih profilov se običajno dodajo elementi za utrjevanje, kot sta Ni in Mo, pri čemer je bilo ugotovljeno, da je za ublažitev škodljivih učinkov segregacije litine na duktilnost potrebno oblikovanje do višjih stopenj deformacije [9].

iron (AADI), mechanical deformation is utilized to affect the microstructure and, consequently, the mechanical properties of ductile iron due to acceleration of ausferrite reaction, refining the microstructure, and increase of the structural homogeneity.

It has been has shown [9] that ausforming up to 25% reduction in height during a rolling operation contributed to add a mechanical processing component to the conventional ADI heat treatment, thus increasing the rate of ausferrite formation and leading to a much finer and more homogeneous ausferrite product **(Figure 12)**. The effect of ausforming on the strength values was quite dramatic **(Figure 13)** (up to 70 and 50% increase in the yield and ultimate strength respectively). A mechanism involving both a refined microstructural scale as a result of enhanced ferrite nucleation, together with an elevated dislocation density, may be suggested. Hardenability elements such as Ni and Mo are usually added to increase the hardenability of thick-section castings, and ausforming to higher degrees of deformation was found necessary to

Bolj praktično je, da se prednosti ausformiranja izkoristijo s kovanjem kot z valjanjem. Postopek kovanja se lahko izvede na ulitih predhodnih formah, ki se avstenitizirajo in gasijo na temperaturo austempranja, vstavijo v kokilo, stisnejo ali kujejo v končno obliko in nato vrnejo nazaj v kopel za austempranje, da se zaključi pospešena transformacija. Minimalne stopnje deformacije po običajnih standardih kovanja, tj. povprečna deformacija 25 %, bi zadostovala za oblikovni del postopka obdelave. Poročali so [10], da v primerih, ko pride do zelo močne deformacije, obdelovanca morda ne bo treba vrniti v kopel za kaljenje za dokončanje pretvorbe v ausferit, saj bo ta končana, ko bo obdelovanec izvlečen iz kokile.



Slika 13. Trdnost v odvisnosti od časa kaljenja in zmanjšanja ausformiranja za ADI, legirane z 2 % Ni [8]

Figure 13. Yield strength vs austempering time and ausforming reduction for ADI's alloyed with 2% Ni [8]

Zamisel o izdelavi predhodnih form iz sive litine s kroglastim grafitom in njihovem oblikovanju do končne oblike bi bila lahko precej učinkovita za relativno preproste oblikovane ulitke, ki morajo izpolnjevati visoke zahteve glede trdnosti in duktilnosti, alleviate the deleterious effects of alloy segregation on ductility [9].

It is more practical that the advantages of ausforming would be taken by forging rather than by rolling. The forging process may be performed on cast preforms, austenitized and quenched to the austempering temperature, inserted into a die, pressed or forged to the final shape, and then returned back into the austempering bath to complete the accelerated transformation. Minimal deformation degrees by conventional forging standards, i.e., an average strain of 25 % would be sufficient for the forming part of the processing sequence. It has been reported [10] that in situations where very severe deformation occurs, the workpiece may not need to be returned to the austempering bath to complete the transformation to ausferrite, as the latter will have been completed by the time the workpiece is extracted from the die.

The idea of creating preforms in ductile iron and then ausforming them to the final shape could be quite effective for relatively simple-shaped castings that must meet high-demanding strength and ductility requirements, e.g., connecting rods for automotive applications. It is understood that certain deviations in design elements of both the preform as well as the die set should be involved compared to the design of the conventional ADI process. The abovementioned concept has been utilized to produce tank track center guides [11] using a finite element simulation technique to match both the preform design and the die design so that a uniform equivalent strain throughout the casting averaged ~20%. No inclination to fracture or cracking has been reported.

npr. ojnice za avtomobilsko industrijo. Razume se, da je treba v primerjavi z načrtovanjem konvencionalnega postopka ADI upoštevati določena odstopanja pri konstrukcijskih elementih tako predhodne forme in kokile. Zgoraj omenjeni koncept je bil uporabljen za izdelavo središčnih vodil za rezervoarje [11] z uporabo tehnike simulacije končnih elementov, ki je ustrezala zasnovi predoblike in zasnovi kokil, tako da je bil enakomeren delež dodatkov v celotnem ulitku v povprečju ~20 %. Nagnjenosti k lomljenju ali razpokam ni bila zaznana.

Termomehanska obdelava sive litine s kroglastim grafitom in ADI

Ta raziskovalni program je potekal v sodelovanju z Inštitutom za metalurgijo Tehnološke univerze Clausthal v Nemčiji v obdobju 2011–2022, rezultati pa so bili objavljeni v različnih mednarodnih revijah in na konferencah [12–22].

V naslednjem kratkem primeru sta bili izvedeni termomehanska obdelava in dilatometrična študija z uporabo termomehanskega simulatorja Baehr Dil 805D (Slika 14), da bi potrdili učinek izpopolnjevanja ausforminga na mikrostrukturo litine ADI.

Za termomehansko obdelavo in dilatometrično študijo je bil uporabljen termomehanski simulator Baehr Dil 805D. Termomehanska simulacija je bila izvedena na valjastih vzorcih s premerom 5 mm in dolžino 10 mm. Na površino vzorcev so bili v osrednjem položaju posamično točkovno privarjeni termočleni tipa S »Pt/Pt-10 % Rh« z nazivnim premerom 0,2 mm. Vzorci so izpostavljeni dvema termomehanskima razporedoma (Slika 15). Pri teh načrtih so bili vzorci segreti na 960 °C in izpostavljeni dvema deformacijskima stopnjama pri 960 °C ter 940 °C. Glavni cilj teh deformacijskih korakov je izboljšati strukturo

Thermomechanical Treatment of Ductile Iron and ADI

This research program has been conducted in collaboration with the Institute of Metallurgy- Clausthal University of Technology-Germany over the time period of 2011-2022, and the results have been published in different international periodicals and conferences [12 - 22].

In the next short discussion, the thermomechanical processing and dilatometric study were performed using a Baehr Dil 805D thermomechanical simulator (Fig. 14) to confirm the refining effect of ausforming on the ADI microstructure.

For thermo-mechanical processing and dilatometric study, a Baehr Dil 805D thermo-mechanical simulator was used. The thermo-mechanical simulation was performed on cylindrical samples of

5 mm diameter and 10 mm length. Sheathed type S “Pt/Pt-10% Rh” thermocouples with a nominal diameter of 0.2 mm were individually spot-welded to the specimens’ surface in a central position. The specimens are subjected to two thermo-mechanical schedules (Fig. 15). In these schedules, the specimens were heated up to 960°C and subjected to two deformation steps at 960°C and 940°C. The main objective of these deformation steps is to refine the structure through work hardening, recovery and recrystallization effects in austenite.

This work highlights transformation kinetics, microstructure evolution and mechanical behavior of thermo-mechanically processed ductile irons. Two types of matrices were produced in the ductile iron, namely ausferritic and ferritic-ausferritic matrices.

Furthermore, the ductile iron is deformed applying a total true strain of 0.3 in the austenite region one time and 0.2 in the austenite region and 0.1 during s postopkom utrjevanja, obnavljanja in rekristalizacije v avstenitu.

To delo poudarja kinetiko preoblikovanja, razvoj mikrostrukture in mehansko obnašanje termomehansko obdelanih sivih litin s kroglastim grafitom. V sivi litini s kroglastim grafitom sta nastali dve vrsti matric, in sicer ausferitna in feritno-ausferitna matrica.

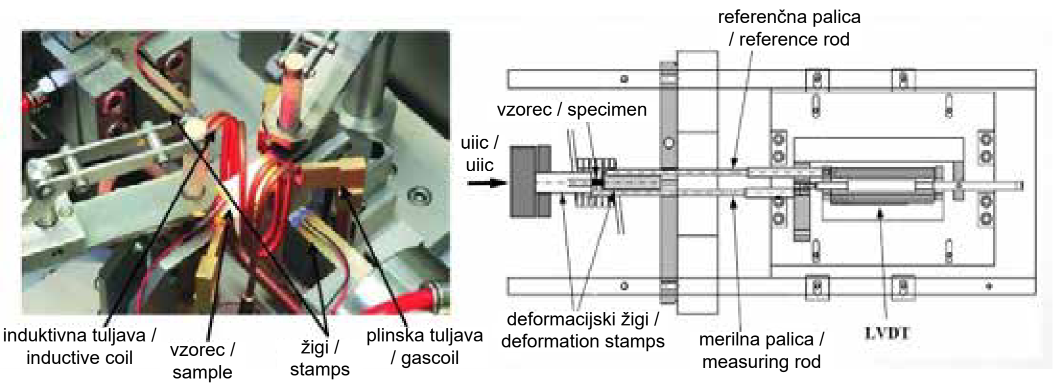
Poleg tega se siva litina s kroglastim grafitom enkrat deformira s skupno pravo deformacijo 0,3 v območju avstenita, drugič z 0,2 v območju avstenita in 0,1 med ustempranjem (ausforming) **(Slika 15).** Tako ausforming kot vnos ferita v matrico pospešita kinetiko pretvorbe ausferita (Slika 16). Postopek ausforminga vpliva na povečanje enakomernosti mikrostrukture in izpopolnjevanje ausferitnih ploščic. Zaradi takšnih mikrostrukturnih sprememb se trdota, trdnost in duktilnost tako oblikovane sive litine s kroglastim grafitom znatno povečajo.

Primerjava morfologije ausformiranega ausferita z neausformiranim pri obeh uporabljenih shemah kaže na vpliv ausformiranja na povečanje mikrostrukturne enotnosti in izboljšanje ausferitnih ploščic (slika 17). Opažena izpopolnitev je austempering (ausforming) other time (Fig. 15). Both ausforming and ferrite-introduction to the matrix accelerate the ausferrite transformation kinetics (Figure 16). The ausforming process has its impact on enhancing the microstructural uniformity and refining the ausferrite platelets. Such microstructural variations result in a remarkable increase in hardness, strength and ductility of the ausformed ductile iron.

The comparison of the ausformed ausferrite morphology with the non-ausformed one for both of the applied schedules indicate the impact of ausforming on enhancing the microstructural uniformity and refining the ausferrite platelets (Figure 17). The observed refinement is mainly a consequence of the increased nucleation sites of the ausferrite-platelets.

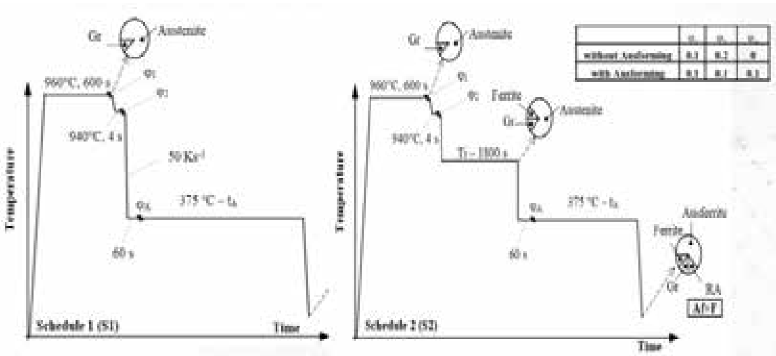
3 Machinability of ADI

When ADI first started to be used for engineering applications, there were many difficulties experienced in trying to machine it, and some of these doubtlessly persist to this day. The hardest grades of ADI reach a hardness of ~ 50 HRC, which would pose a challenge for any high-volume machining



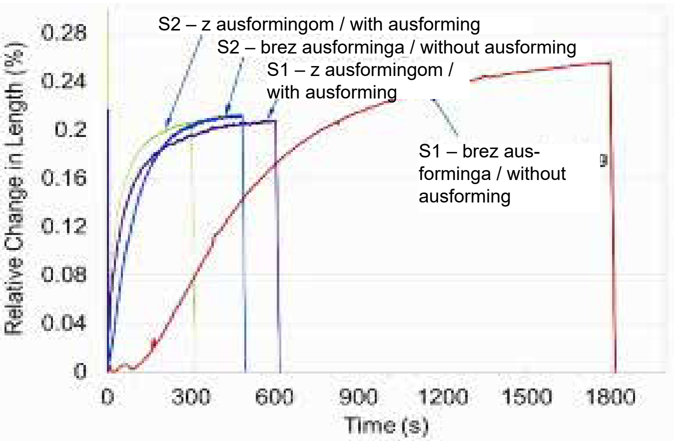
Slika 14. Termomehanski simulator Baehr Dil 805D

Figure 14. Baehr Dil 805D thermomechanical simulator



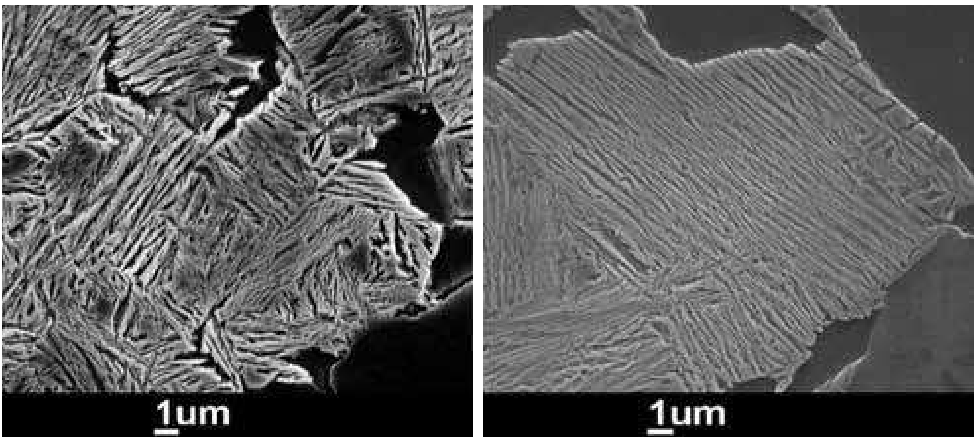
Slika 15. Termomehanski razporedi

Figure 15. The thermomechanical schedules



Slika 16. Vpliv ausforminga na pospešitev ausferitne transformacije

Figure 16. Effect of ausforming on acceleration of the ausferritic transformation



Slika 17. Vpliv ausforminga na strukturno izpopolnjevanje

Figure 17. Effect of ausforming on structural refinement

predvsem posledica povečanega števila mest nukleacije ausferitnih ploščic.

3 Obdelovalnost litine ADI

Ko se je litina ADI prvič začela uporabljati za inženirske aplikacije, so se pojavile številne težave pri njeni strojni obdelavi, in nekatere od njih nedvomno še danes niso odpravljene. Najtrše vrste ADI dosegajo trdoto ~50 HRC, kar bi predstavljalo izziv za vsako obsežno strojno obdelavo. Čeprav imajo mehkejše vrste ADI tipično trdoto 300–350 BHN, njihova matrična struktura vsebuje do 40 % zadržanega avstenita. Ko je ta faza podvržena obremenitvam med obratovanjem, se hitro strdi in se lahko spremeni v martenzit; to lahko zmanjša obdelovalnost v primerjavi z jeklom z enako trdoto.

Sestavni deli iz litine ADI se zdaj uporabljajo v zelo širokem polju uporabe z enako širokim razponom zahtev glede natančnosti in kakovosti površine. Slika 18 povzema možnosti glede vključitve postopkov strojne obdelave v proizvodno pot litine ADI. Na enem koncu lestvice velikega števila sestavnih delov iz litine ADI ni treba strojno obdelati; primeri vključujejo kmetijska orodja in orodja za zemeljska dela. Vendar je treba večino avtomobilskih sestavnih delov strojno obdelati. Večino izdelkov iz mehkejših vrst litine ADI je mogoče strojno obdelovati po toplotni obdelavi z uporabo ustreznih strojnih orodij in vložkov. To je z naraščanjem trdote vedno težje, zato je pogosto bolje, da se jih pred toplotno obdelavo strojno obdela z upoštevanjem povečevanja dimenzij, če je to predvidljivo in če ne pride do večjih deformacij. Če povečevanje dimenzij ni dovolj dosledno, je edina možnost, da se večino strojne obdelave opravi pred austempranjem in se vse kritične dimenzije dokončno obdela po kaljenju. Ta način se

operation. Although the softer grades of ADI have a typical hardness of 300–350 BHN, their matrix structure contains up to 40% retained austenite. When subjected to strains in service, this phase rapidly work hardens and can transform to martensite; this can thereby reduce the machinability compared with a steel of equivalent hardness.

ADI components are now used in a very wide range of applications, having an equally wide range of requirements regarding accuracy and surface finish. Fig. 18 summarizes the options regarding the integration of the machining operations into the ADI production route. At one end of the scale, substantial numbers of ADI components do not require to be machined; examples include ground- engaging agricultural and earth-moving tools. However, most automotive components will need to be machined. Most of those made in the softer grades of ADI can be machined after heat treatment using appropriate machine tools and inserts. This becomes progressively more difficult as the hardness increases and it is often preferable to machine before heat treatment by making an allowance for the dimensional growth, assuming that this is predictable and that there is no significant distortion. If the dimensional growth is not sufficiently consistent, the only option is to do most of the machining before austempering, and to finish machining any critical dimensions after austempering. This route has been widely used for ADI gears, which must be extremely accurate for them to operate quietly and have a long life.

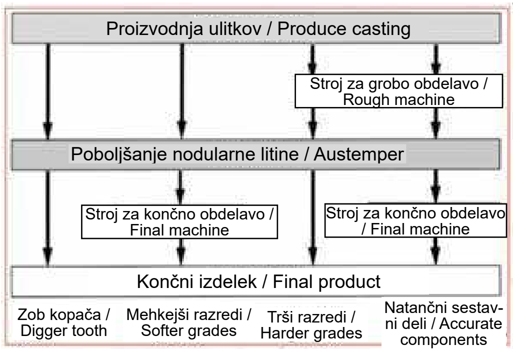
In a recent research at CMRDI [23, 24], the machinability of the different ADI-grades was determined as a function of the cutting force experienced during machining. The effect of different parameters of machining, like cutting speed as well as cutting depth, pogosto uporablja za zobnike iz litine ADI, ki morajo biti zelo natančni za tiho delovanje in dolgo življenjsko dobo.

V nedavni raziskavi na inštitutu CMRDI [23, 24] je bila obdelovalnost različnih razredov litine ADI določena v odvisnosti od rezalne sile med obdelavo. Preučen je bil vpliv različnih parametrov obdelave, kot sta hitrost in globina rezanja, na silo rezanja, ki so bili povezani z deformacijsko inducirano martenzitno pretvorbo iz ohranjenega avstenita med obdelavo. Ugotovljeno je bilo, da ima ohranjena transformacija avstenita v martenzit z učinkom TRIP pomembno vlogo pri določanju rezalne sile in obdelovalnosti vrst litin ADI.

Debelina plasti, utrjene z nastankom martenzita, je odvisna od različnih dejavnikov, med katerimi sta globina in hitrost rezanja, ter od količine in stabilnosti zadržanega avstenita v različnih litinah ADI. Očitno je, da je povečanje rezalne sile vedno povezano z ustreznim povečanjem vsebnosti martenzita pri povečanju globine rezanja od 0,5 do 2,0 mm (Slika 19). Zlitini ADI-375 in ADI-275, ki sta bili podvrženi rezanju globine 2,0 mm, sta imeli enak skupni delež martenzita (ki je vsota prvotne vsebnosti pred strojno obdelavo + martenzit, ki je nastal zaradi deformacijske pretvorbe iz ohranjenega avstenita). Dejstvo, da sta zlitini ADI-375 in ADI-275 pri globini reza 2,0 mm dosegli enako rezalno silo, je dober pokazatelj, da je martenzitna transformacija zaradi induciranih deformacij

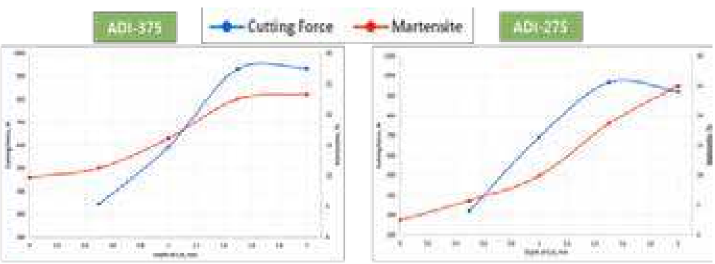
on the force of cutting was investigated and correlated to the strain-induced martensitic transformation from retained austenite during machining. Retained austenite transformation to martensite through the TRIP effect was found to play a profound role in determining the cutting force and machinability behavior of ADI grades.

The thickness of the layer hardened by martensite formation is a function of different factors, among them are the cutting depth and cutting speed, added to the amount and stability of the retained austenite in the different alloys of ADI. It is evident that the increase in cutting force is always associated with a corresponding



Slika 18. Možnosti integracije litja, strojne obdelave in toplotne obdelave komponent iz litine ADI [2]

Figure 18. Options for integrating casting, machining and heat treatment of ADI Components [2]



Slika 19. Rezalna sila kot funkcija deformacije, ki jo povzroči nastanek martenzita med strojno obdelavo vzorcev ADI, kaljenih pri 275 in 375 °C.

Figure 19. The cutting force as a function of deformation-induced martensite formation during machining os ADI specimens austempered at 275 & 375 °C

tesno povezana z možnostjo obdelave zlitin ADI.

4 Ultrafina litina ADI, strjena v ultrazvočnem polju

Ta raziskava je bila nedavno opravljena na inštitutu CMRDI v sodelovanju z inštitutom FTI v Minsku, Belorusija. V tem delu je bila uporabljena ultrazvočna obdelava taline (UST) za proizvodnjo nove ultrafine kakovosti sive litine s kroglastim grafitom (SG) in litino ADI. Shematski prikaz eksperimentalnega sistema je prikazan na Sliki 20. Ultrazvočni sistem z močjo 0,7–1,0 kW in frekvenco 20 kHz je bil uporabljen za obdelavo taline sive litine s kroglastim grafitom (SG), ki se strjuje.

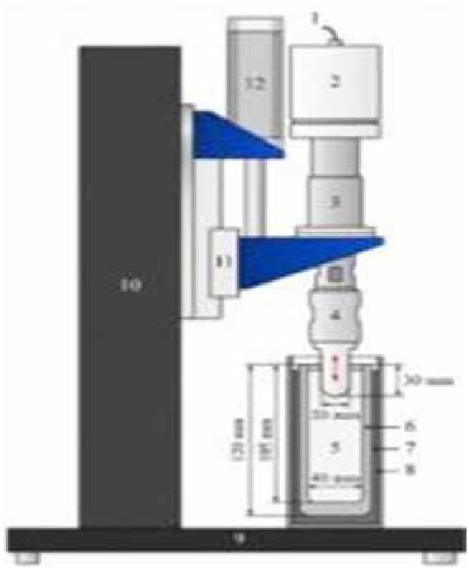
Metalografska analiza novo razvite železove zlitine SG je pokazala ultrafino strukturo grafita. Premer grafitnih krogel je bil od 6 do 19 µm, skupno število krogel pa od 900 do več kot 2000 na mm2 (Slika 21), kar v literaturi za ulitke enakega premera, tj. 40 mm, še ni bilo omenjeno. Poleg tega je bila pri vseh ultrazvočno obdelanih sivih litinah s kroglastim grafitom opažena popolnoma feritna matrica. Nadaljnja toplotna obdelava z austempranjem je bila izvedena za izdelavo različnih vrst poboljšane litine ADI z različnimi ausferitnimi morfologijami. Dilatometrične študije za razvite litine ADI so pokazale, da je bil čas, potreben za dokončanje tvorbe ausferita v ultrazvočno obdelanih litinah, štirikrat krajši od časa, potrebnega za statično strjene sive litine s kroglastim grafitom (Slika 22). mikroposnetki z vrstično elektronsko mikroskopijo za litine ADI so pokazale izjemno fino in kratko ausferitno strukturo skupaj z majhnimi avstenitnimi bloki v matrici (Slika 23). Z delno avstenitizacijsko toplotno obdelavo v interkritičnem temperaturnem območju, kjer soobstajajo faze avstenit + ferit + grafit, je bila izdelana

increase in the martensite content when the cutting depth was increased from 0.5 - 2.0 mm (Figure 19). The ADI-375 and ADI-275 alloys, being subjected to a cutting depth of 2.0 mm had the same total martensite (which is the sum of original content before machining + the martensite formed by deformation induced transformation from the retained austenite). The fact that the two alloys, ADI-375 and ADI-275, reached the same cutting force at 2.0 mm depth of cut gives a good indication that the martensitic transformation due to induced strains is closely related to the machinability behavior of the ADI-alloys.

4 Ultrafine ADI Solidified in Ultrasonic Field

This research was recently carried out at CMRDI in collaboration with the Physico-Technical Institute, Minsk, Belarus. In this work, ultrasonic melt treatment (UST) was used to produce a new ultrafine grade of spheroidal graphite (SG) cast iron as well as ADI. The schematic drawing of the experimental setup is shown in Figure 20. An ultrasonic system with 0.7-1.0 KW power and 20 kHz frequency was used for the treatment of solidifying ductile iron (SG) melt.

The metallographic analysis of the newly developed SG iron alloy showed an extremely ultrafine graphite structure. The graphite nodule’s diameter ranged between 6 to 19 µm with a total nodule count ranging between 900 to more than 2000 nodules per mm2 (Fig. 21), which has never been mentioned in the literature for castings of the same diameter, i.e., 40 mm. In addition, a fully ferritic matrix was observed in all UST SG irons. Further austempering heat treatments were performed to produce different austempered ductile iron (ADI) tudi dvofazna interkritično poboljšana siva litina s kroglastim grafitom (IADI). Pri dvofazni litini IADI je bilo ugotovljeno, da bi vnos prostega ferita v matrico zagotovil dodatno izpopolnitev ausferita [25].



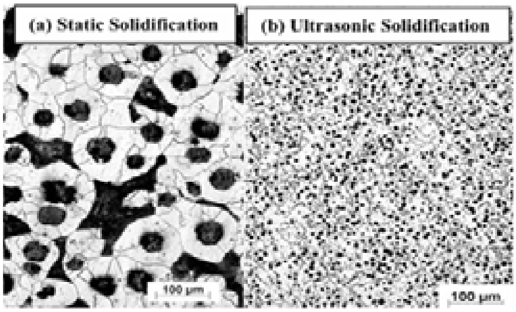
Slika 20. Eksperimentalna postavitev za ultrazvočno obdelavo sive litine s kroglastim grafitom. 1. Kabel za ultrazvočni generator, 2. Pretvornik, 3. Pospeševalnik, 4. Sonotroda, 5. Talina, 6. Grafitno orodje, 7. Polnilo, 8. Posodica, 9. Stojalo za podstavek, 10. Nosilec, 11. Mehanizem za odmik, 12. Pnevmatski cilinder.

Figure 20. The experimental setup for the ultrasonic treatment of SG iron. 1. Cable to ultrasonic generator, 2. Transducer, 3. Booster, 4. Sonotrode, 5. Molten metal, 6. Graphite mold, 7. Filling, 8. Cup, 9. Base stand, 10. Mount, 11. Displacement mechanism, 12. Pneumatic cylinder.

Očitno je, da bi 75-odstotno skrajšanje cikla toplotne obdelave litine ADI povzročilo znatno zmanjšanje proizvodnih stroškov, kar bi se zagotovo odrazilo v nadaljnjem povečanju konkurenčne prednosti materiala ADI.

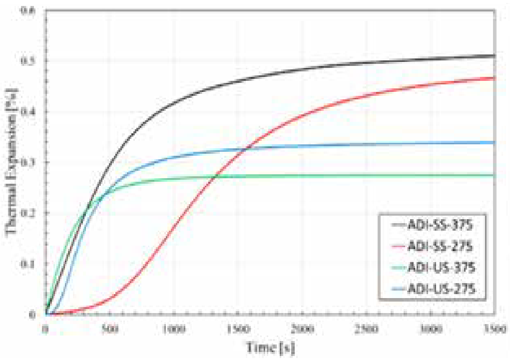
grades with different ausferrite morphologies. The dilatometry studies for the developed ADI alloys showed that the time required for the completion of the ausferrite formation in UST alloys was four times shorter than that required for statically solidified SG irons (Figure 22). SEM micrographs for the ADI alloys showed an extremely fine and short ausferrite structure together with small austenite blocks in the matrix (Figure 23). A dual-phase intercritically austempered ductile iron (IADI) alloy was also produced by applying partial austenitization heat treatment in the intercritical temperature range, where austenite + ferrite + graphite phases coexist. In a dual-phase IADI alloy, it was established that introducing free ferrite in the matrix would provide additional refinement for the ausferrite [25].

It is obvious that 75% shortening of the heat treatment cycle of ADI would result in a considerable reduction of production cost, which will certainly reflect on a further increase in the competitive edge of ADI material.



Slika 21. Mikrostruktura, pridobljena iz sive litine s kroglastim grafitom, (a) statično stanje in (b) stanje UST

Figure 21. Microstructure obtained from the SG iron, (a) static condition and (b) UST condition

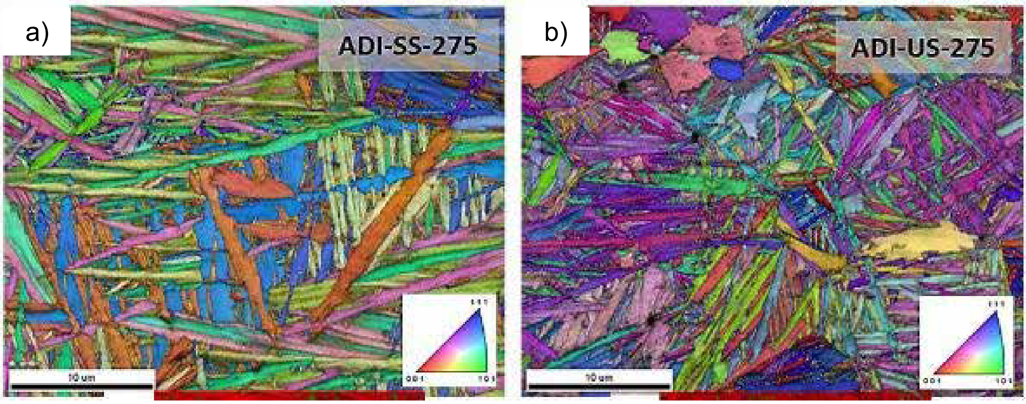


Slika 22. Dilatometrična krivulja različnih preiskovanih vzorcev, kaljenih pri 275 °C in 375 °C, SS: vzorec za konvencionalno strjevanje, US: vzorci, obdelani z ultrazvokom

Figure 22. The dilatometry curve of the different investigated samples austempered at 275°C and 375 °C, SS: conventional solidification sample, US: ultrasonically treated samples

Slika 23. Izboljšanje ausferitne matrice po ultrazvočni obdelavi

Figure 23. Refinement of ausferritic matrix after ultrasonic treatment



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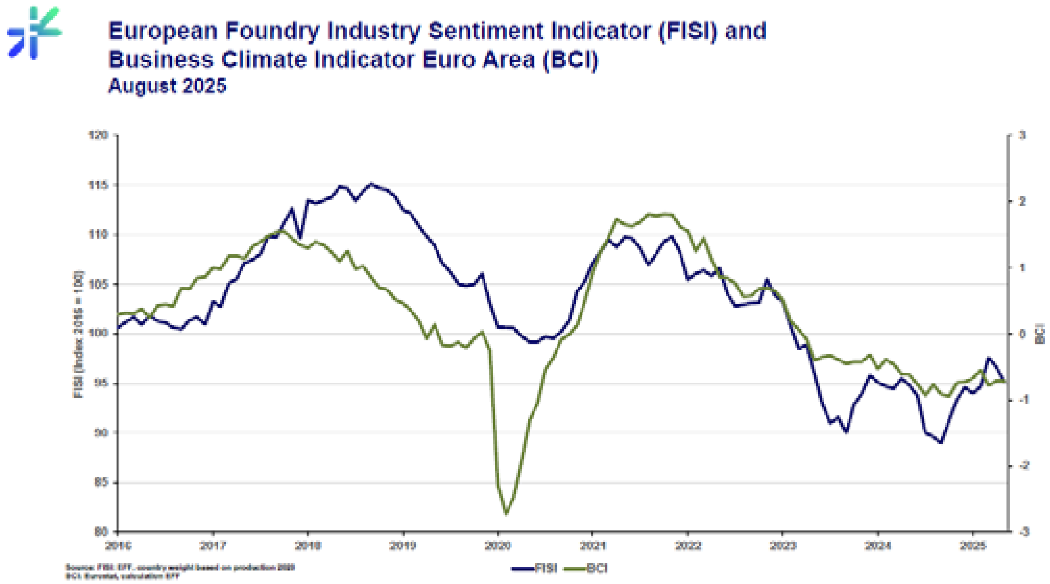
AKTUALNO / CURRENT

Evropski indeks razpoloženja v livarski industriji (FISI) avgusta 2025

Evropski indeks razpoloženja v livarski industriji (FISI), ki ga mesečno objavlja Evropska livarska federacija, se je avgusta 2025 znižal za 1,5 točke in dosegel raven 95,1 točke.

Zabeležen je bil upad proizvodnje ulitkov iz sive litine in ulitkov iz neželeznih kovin. Edini material, ki je v zadnjem mesecu beležil pozitiven trend, je bil segment jeklene litine. Glede pričakovanj za prihodnje mesece raziskava kaže na nadaljevanje tega trenda.



Vendar je stanje v evropski livarski industriji vedno odsev splošnega gospodarskega položaja v Evropi. To se včasih pokaže z rahlim zamikom, vendar nedavne raziskave kažejo, da je evrsko območje avgusta 2025 prvič po petnajstih mesecih zabeležilo rast novih naročil. Indeks poslovne klime (BCI), ki ga objavlja Evropska komisija, je avgusta 2025 dosegel –0,72, kar je nekoliko manj od predhodne vrednosti –0,71 iz julija 2025. Gospodarska aktivnost se povečuje že osmi mesec zapored. Proizvodni PMI evrskega območja se je avgusta 2025 pospešil in dosegel raven 50,5, kar pomeni povečanje za 0,7 točke v primerjavi z julijsko vrednostjo 49,8. To so lahko znaki počasnega okrevanja evropskih gospodarstev iz zahtevnih razmer.

Z upanjem na bolj pozitivne novice v prihodnje Evropska livarska federacija nenehno spremlja razmere na evropskem livarskem trgu.

EFF • Evropska livarska federacija
Alameda Urquijo 33, 1D, Abando 48008, Bilbao • Španija
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AKTUALNO / CURRENT

Livarski dogodek Deutscher Giessereitag 2025, v AAchnu

Kot gostja BDG – Zveznega združenja nemške livarske industrije sem 12. in 13. junija letos prisostvovala livarskemu dogodku pod naslovom »Deutscher Giessereitag 2025«. Vodilni odločevalci nemške livarske industrije so razpravljali o strateških usmeritvah za prihodnja leta. Izpostavili so ključne izzive in najbolj pereče teme panoge. Na dogodku se je zbralo skoraj 400 udeležencev. Poleg najvišjih odločevalcev iz livarn so bili prisotni tudi dobavitelji in predstavniki raziskovalno-razvojnih inštitucij kot tudi presenetljivo močno predstavniki vlade iz Berlina. Livarska panoga je ob imenovanju nove zvezne vlade za vlado pripravila nove okvirne pogoje za nemško livarsko industrijo. Ker je po imenovanju vlade preteklo že 100 dni, je le-ta že bila pozvana na podajanje prve ocene. Osrednja tema je bila, kaj vse je potrebno storiti in zagotoviti, da bo Nemčija kot industrijska lokacija ponovno postala konkurenčnejša.

Vsi poročevalci so si bili edini, da je sprejemanje odločitev danes za livarne zelo težavno. Na več ravneh – politično-ekonomskih, procesno-tehničnih in strateških – se kaže kompleksnost v panogi. Smernice tega livarskega dogodka so imele za cilj, da se podjetjem olajša spremljanje hitro nastajajočih sprememb s strokovnim znanjem.

V dveh dneh smo lahko sledili predstavitvam strokovnih predavanj in panelnim razpravam. Dogodek je spremljala tudi livarska razstava z 40 razstavljavci. V zadnjih letih se na dogodkih naše livarske panoge vidi bistveno manj rdečega žarečega kovinskega litja in strokovnih delavnic. BDG kot organizator je uspešno združil zahteven strokovni program svojega osrednjega dogodka s sodobno predstavitvijo, kjer je kar nekaj prostora bilo posvečeno vsebinski strategiji. Saj danes ne gre več le za aktualne izzive, temveč tudi za prihodnje priložnosti. Koncept je zato vključeval številne teme in govorce, ki so se poglobljeno ukvarjali s prihodnostjo od tržnih sprememb in transformacijskih poti in tudi digitalizacije. Predstavniki znanosti, industrije in politike so pokazali, kako se lahko panoga s pomočjo novih okvirnih pogojev, prebojnih tehnologij in strateškega preoblikovanja pripravi na prihajajoča desetletja. Pri tem je bilo jasno poudarjeno: prihodnost nastane tam, kjer se združijo znanje, izkušnje in vizija.

Nemška livarska panoga se sooča z vse večjimi pritiski zaradi močne globalne konkurence, zahtevnih ciljev na podnebnem področju in vse večjega pomanjkanja strokovne delovne sile. To se občutno odraža na gospodarskih rezultatih. Proizvodnja in promet sta bila v preteklem letu nižja za 13 oz. 12 odstotkov. V vseh razpravah se je lahko občutila velika zaskrbljenost tudi glede prihodnosti, najbolj in predvsem pri vprašanju cene elektrike v industriji. Organizator je torej že na začetku dogodka opozoril na usmeritev razprav. Za livarska podjetja so stroški električne energije odločilni. BDG je zato oblikoval pragmatične predloge za industrijsko in energetsko politiko, da bi osvetlil najbolj pereče gospodarsko-politične ukrepe.

Med drugim je to izpostavil tudi prof. Jens Südekum, ki je bil v začetku junija imenovan za gospodarsko-političnega svetovalca zveznega ministra za gospodarstvo in

Predsednica Mirjam Jan-Blažić s g. Max Schumacherjem glavnim direktorjem BDG (levo) in g.Clemens Kuepperjem predsednikom BDG(desno)

podkanclerja Larsa Klingbeila. »Hitrost deindustrializacije na trgu dela se povečuje,« je dejal Südekum. Ustaviti to, je kot pravi, »ena največjih nalog za novo zvezno vlado.«

Prof. Jens Südekum je zagovarjal uvedbo industrijske cene elektrike, katere izvedba v Berlinu naj bi naletela na veliko pripravljenost. »Vseh 16 ministrskih predsednikov se je izreklo za industrijsko ceno elektrike,« je povedal Südekum. Zato obstaja »utemeljeno upanje, da bo mogoče pričakovati gospodarski zagon v nemškem gospodarstvu«. Industrijska cena elektrike se po njegovem mnenju ujema s podnebnim in transformacijskim skladom, ker meni, da je elektrifikacija enaka razogljičenju. Izrazil je tudi upanje, da bo tudi EU omogočila pomoč pri ceni elektrike za industrijo. Vendar pa je BGD bil kritičen do nekaterih določil Evropske komisije v zvezi s pogoji za industrijsko ceno elektrike.

V vseh drugih razpravah je bilo izraženo soglasje o nujni politični podpori panogi. »Potrebujemo partnerja, s katerim lahko sodelujemo,« je poudaril dr. Marc Mateika, direktor skupine Meierguss. Daniel Rinkert, poslanec SPD v nemškem Bundestagu, ki je imel plenarno predavanje je tudi izkazal pripravljenost za sodelovanje in ob tem izjavil: »Končno moramo odpraviti investicijsko zavoro države in uvesti industrijsko ceno elektrike, ki bo dosegla tudi mala in srednje velika podjetja.«

Dejansko se je že po prvem, politično usmerjenem panelu med udeleženci pojavil previden optimizem. Za organizatorje je bil to pomemben trenutek, da se navežejo na nadaljnji potek, ki se je osredotočal predvsem na procesno-tehnične izzive, s katerimi se podjetja srečujejo na poti do podnebne nevtralnosti. V središču je bilo tudi vprašanje, katere tehnologije in postopki dejansko upravičujejo nova vlaganja.

»Livarsko-tehnične inovacije nastajajo v povezovalnem polju med konstrukcijskimi zahtevami, proizvodnimi potrebami in sistemskimi omejitvami vzdolž celotne procesne verige,« pojasnjuje dr. Wolfram Volk, ki je v Aachnu predaval o nepričakovanih in zelo hitrih spremembah v industrijskem sektorju. Kot nosilec katedre za preoblikovalno tehnologijo in Livarskega raziskovalnega centra na Tehniški univerzi v Münchnu si prizadeva reševati tehnične konflikte in uveljavljati nove materiale ter koncepte razmišljanja. Kot primer je Volk izpostavil veliko uporabno vrednost lahkih konstrukcijskih delov iz recikliranih materialov (t. i. reo-casting), ki se v tej državi vse bolj ambiciozno raziskuje. Njegov poziv: »Kar zdaj potrebujemo, je pogum za izvedbo in pripravljenost za vlaganje.«

Da bi panogi ponudili smernice za ukrepanje, je BDG skupaj s Future Camp Climate pripravil načrt poti (roadmap), ki štiri transformacijske poti do podnebne nevtralnosti ocenjuje glede na dejstva. Elektrifikacija je pri tem osrednja in obetavna možnost, vendar še posebej za operaterje z visokimi toplotnimi zahtevami povezana z velikimi operativnimi spremembami. In: »Uspeh poti elektrifikacije je v veliki meri odvisen od dejavnikov, na katere je težko vplivati,« je pojasnil dr. Roland Geres, direktor Future Camp Climate, v svojem osrednjem predavanju – s čimer je pokazal, da politični okvirji tudi v tej posebni razpravi ne morejo biti izvzeti.

Pogled na konferenčno dvorano

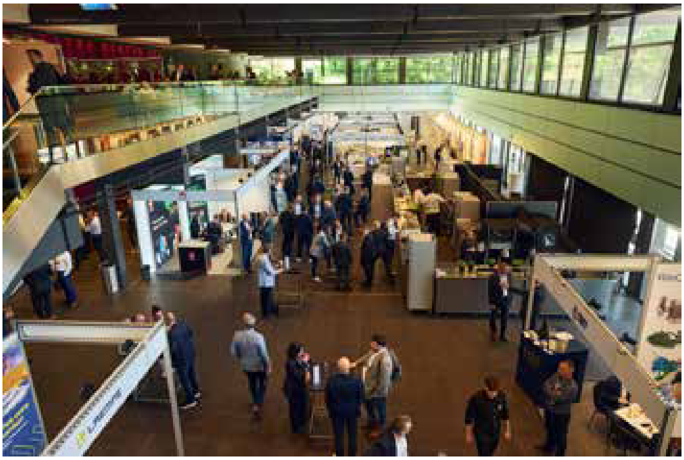
Cene elektrike bi morale biti konkurenčne za uspešno uvedbo tehnologije. Poleg tega bi moral biti za razogljičenje potreben energetski miks iz obnovljivih virov večinoma zagotovljen z zvezno in deželno politiko. Vodik, denimo v jeklarski industriji .

S parolo da „Digitalna transformacija ne čaka“ je podano pomembo sporočilo in opozorilo vsem, da je ta potencial potrebno nujno prepoznati, če želimo obstati in ostati v vrsti proizvajalcev.

Litje vemo, da je izjemno kompleksen proces, katerega je ustrezen rezultat odvisen od velikega števila parametrov. Predstavimo si obrat, ki bi lahko v realnem času nadzoroval vse relevantne podatke svoje proizvodnje: temperature, porabo energije, emisije in tokove materialov – vse bi bilo vidno, povezano in analizirano. Namesto da bi se zanašali na točkovne vzorčne preglede, izkušnje ali ročne posege, bi vsi pomembni procesni parametri tekli vzporedno v centralni sistem. Odstopanja bi bila zaznana, še preden bi nastala težava, predlagane bi bile optimizacije in brez vrzeli bi bila dokumentirana kakovost vsakega posameznega izdelka.

To ni znanstvena fantastika. Dr. Sebastian Tewes, ki pri BDG vodi področje Naprednih tehnologij in inovacij (srečali smo ga v Portorožu letos kot predavatelja na septembrskem seminarju za izračun ogljičnega odtisa in na 65. IFC) meni, da je digitalizacija osrednji vzvod za to, da postanejo procesi preglednejši, viri učinkoviteje uporabljeni in konkurenčnost trajnostno zagotovljena v vse bolj tehnološko usmerjenem okolju.

Modeli stopnje zrelosti, kot je BDG-Kompass Gießerei 4.0, kažejo, da digitalni pristopi v livarski industriji sicer obstajajo, a še niso široko uvedeni. Ključ je v sposobnosti



Pogled na livarsko razstavo

pravilnega in uspešnega komuniciranja med človekom in strojem. Potrebne so torej nove kvalifikacije na vseh ravneh hierarhije, je poudaril dr. Tewes. S projektom ReGAIN BDG podaja prvi impulz – in podpira svoje člane z učnimi gradivi, usposabljanji in svetovanji. »Na ta način se lahko strategije uresničijo v praksi, digitalne in trajnostne inovacije pa uspešno vključijo,« pravi Tewes.

Za Alberta Muellerja, vodjo digitalnih rešitev pri ABP Induction, je zdaj najpomembneje, da se začne – če je treba, tudi z majhnimi koraki. »Čas je, da zapustimo območje udobja. Medtem ko mi tukaj razpravljamo, drugi že delujejo,« je Mueller v svojem predavanju izpostavil neprijetno resnico. Kaj s tem konkretno misli, razkrije pogled na obseg investicij: po Muellerju je bilo v Nemčiji v zadnjem **času v ključne tehnologije vloženih okoli 7,3 milijarde evrov. Za primerjavo: na Kitajskem je ta znesek znašal približno 127 milijard evrov iz državnih sredstev.** Podobno intenzivno tehnološki velikani v ZDA pospešujejo digitalizacijo – in evropski sosedi, zlasti iz skandinavskih držav, že nekaj časa živijo v miselnosti „digital-first“.

Predavatelj Albert Mueller meni, da bi lahko nemška mala in srednja podjetja z umetno inteligenco in boljšim upravljanjem podatkov še bolje izkoristila svoje prednosti – natančnost, domensko znanje in temeljitost.

Kot ovire pri uvajanju digitalnih tehnologij Muellller vidi v tem, da je panoga preveč zaverovana vase in preveč in prepočasi razmišlja. Popolnost je napačen cilj,« je dejal Muellller. Ob tem bi lahko podjetja že kratkoročno veliko dosegla – na primer z digitalno predajo izmene ali nadzornimi ploščami namesto Excelovih tabel. Tudi Stefan Bredl, direktor podjetja Pinter Guss, ki je informatik, je v diskusiji svetoval, naj se ne čaka na subvencije. »V veliki sliki gre za veliko majhnih delčkov.

Podjetja morajo zbirati podatke in jih povezovati z znanjem zaposlenih,« je dejal Bredl.

BDG kot organizator tega dogodka si je zastavil cilj, da vsak od udeleženec ob koncu tega dogodka oddide z boljšim razumevanjem potrebnih ukrepov za ohranjanje konkurenčnosti gospodarskega okolja v Nemčiji. Skozi jedrnato izmenjavo mnenj usmerjeno v prihodnost, mislim da jim je to uspelo.

Strateške pogled s tega livarskega dogodka lahko strnemo še v naslednje usmeritve in vsebine: Krize premagovati ob izkoriščanju danih priložnosti. Potrebnega varstva podnebja pri tem ne bi smeli dojemati kot breme, temveč kot priložnost.

Sredi številnih kriz in vse večjih negotovosti ostaja za livarsko industrijo odločilno naslednje: volja, da se gre naprej.

Poročala: mag. Mirjam Jan-Blažić

AKTUALNO / CURRENT

Kratko okvirno poročilo o 65. IFC Portorož 2025

Brief Preliminary Report on the 65th IFC Portoroz 2025

V tem prispevku samo na kratko in samo okvirno poročamo o osrednjem livarskem dogodku Društva livarjev Slovenije, ki že tradicionalno 65 let poteka v Portorožu. Letos je to bilo v času od 17.–19. septembra. Soorganizatorja dogodka sta tudi to pot bila Katedra za livarstvo z Naravoslovnotehniške fakultete Univerze v Ljubljani in Fakulteta za strojništvo Univerze v Mariboru.

Prvega dne so se udeleženci konference in livarske razstave srečali v Piranu na spoznavnem srečanju na vrtu kulturnega centra Georgios pri stolni cerkvi sv. Jurija.

Udeleženci na srečanju v Piranu

V imenu organizatorja konference in razstave je dobrodošlico udeležencem iz 22 tujih držav in Slovenije uvodoma zaželela mag. Mirjam Jan-Blažič, predsednica Društva livarjev Slovenije in organizacijskega odbora konference, v imenu županstva občine Piran pa g. Matej Knep, vodja Družbenih dejavnosti.

In this contribution we provide only a brief and preliminary report on the central foundry event of the Slovenian Foundrymen Society, which has traditionally been held in Portoroz for 65 years. This year it took place from 17 to 19 September. The co-organisers of the event were once again the Chair of Foundry Engineering of the Faculty of Natural Sciences and Engineering, University of Ljubljana, and the Faculty of Mechanical Engineering, University of Maribor.

Udeleženci na srečanju v Piranu

On the first day, the participants of the conference and the foundry exhibition gathered in Piran for a get-together in the garden of the Georgios Cultural Centre next to St. George’s Cathedral. On behalf of the organisers of the conference and exhibition, a welcome address to the participants was given by **MSc. Mirjam Jan-Blažič**, President of the Slovenian Foundrymen Society and Chair of the Conference

Posebnega pozdrava je bila deležna tudi kitajska delegacija. To srečanje se je tudi to pot izkazalo kot pomemben del tega dogodka, ki je omogočil v sproščenem in prijetnem vzdušju nove kontakte in poslovna poznanstva ter utrjevanje že obstoječih.

Kitajska delegacija na srečanju v piranu

Konferenco je naslednji dan odprla mag. Mirjam Jan-Blažič, predsednica organizacijskega odbora. V otvoritvenem nagovoru je uvodoma pozdravila vse prisotne udeležence in razstave, ter med njimi še posebno avtorje in soavtorje predavanj, razstavljavce na livarski razstavi in še posebno naslednje goste:

- **Prof. dr. Rafal Danko,** podpredsednik WFO in predsednik Poljskega livarsko združenje
- **g. José Javier González**, generalni sekretar WFO- Svetovna livarska organizacija
- **g. Max Schumacher,** do nedavna glavni direktor BDG -Zvezno združenje Nemške livarske industrije
- **dr. PETER LIEPERT**, direktor ÖGI-Avstrijski livarski inštitut
- **ga. Yunxia Wang,** direktorica Oddelka za akademske zadeve FICMES-Livarska inštitucija Kitajskega društva za strojništvo
- **dr. Anna Szombatfalvy**, predsednica Mađarsko rudarsko in metalurško društvo

Organising Committee, and on behalf of the Municipality of Piran by Mr Matej Knep, Head of Social Activities. A special welcome was extended to the Chinese delegation. This gathering once again proved to be an important part of the event, providing an opportunity in a relaxed and pleasant atmosphere for establishing new contacts and business relations, as well as for strengthening existing ones.

Otvoritev konference

The following day, the conference was formally opened by **MSc. Mirjam Jan-Blažič**, President of the Conference and Exhibition Organising Committee. In her opening address, she first welcomed all the participants of the conference and exhibition, with special mention of the authors and co-authors of the lectures, the exhibitors at the foundry exhibition, and in particular the following distinguished guests:

- **Prof. Dr. Rafal Danko**, Vice-President WFO – World Foundry Organization and President of the Polish Foundry Association
- **Mr. José Javier González,** Secretary General WFO-World Foundry Organization/
- **Mr. Max Schumacher,** until recently Director General BDG-Bundesverband der Deutschen Gießerei-Industrie

- **g. Milorad Vasilić**, predsednik Hrvatskega združenja za livarstvo

Nato je predstavila programske vsebine konference. Prvega dne sklop desetih plenarnih predavanj, in predavanja drugega dne v sekcijah: Železove zlitine, livarske tehnike in tehnologije, Neželezne zlitine ter Mladi predavatelji in raziskovalci.

Pogled na konferenno dvorano

V nadaljevanju je poudarila, da se danes celotno evropsko livarstvo sooča z zelo zahtevnimi izzivi, ki se v prvi vrsti nanašajo na tako imenovani zeleni prehod. Ta zahteva investicije v tehnologije razogljičenja, zniževanja izpustov, uvedbo novih tehnologij in tehnik ter tudi projekte samooskrbe z električno energijo. Gre za procese, ki jih ni mogoče uresničiti kratkoročno, saj so pogojeni z zahtevnimi posegi in predvsem visokimi stroški, ki resno ogrožajo konkurenčnost livarn. Izpostavila je tudi problem nesprejemljivo visokih cen električne energije, s katerim se soočajo livarne v večini evropskih držav in tudi v Sloveniji, ki tudi resno ogrožajo njihovo konkurenčnost. Menila je, da so zato nujno potrebni vladni posegi znotraj posameznih držav kot tudi pomoč in ukrepi znotraj Evropske Unije.

To tematiko je zaključila s oceno, da današnji časi zahtevajo tudi meddržavno sodelovanje, da bomo lahko vsi skupaj

- **Dr. Peter Liepert,** Director ÖGI Österreichisches Gießerei-Institut
- **Ms. Yunxia Wang**, Director of Department of Academic Affairs/ FICMES-Foundry Institution of Chinese Mechanical Engineering Society
- **Dr. Anna Szombatfalvy,** President Hungarian Mining and Metallurgical Society
- **Mr. Milorad Vasilić,** President Croation Foundry Association

She then presented the programme contents of the conference. The first day included a set of ten plenary lectures, while the second day featured presentations in the following sections: ferrous alloys, foundry techniques and technologies, non-ferrous alloys, and young lecturers and researchers.

Pogled na konferenno dvorano

In her address, she emphasized that today the entire European foundry industry is facing very demanding challenges, which primarily relate to the so-called green transition. This requires investments in decarbonization technologies, emission reduction, the introduction of new technologies and techniques, as well as projects for self-sufficiency in electricity. These are processes that cannot be realized in the short term, as they depend on complex interventions and, above postali močnejši in kos tem izzivom. Prav zato je tudi mednarodna konferenca v Portorožu prizorišče, kjer si izmenjujemo izkušnje in iščemo rešitve za to zahtevno skupno pot zelenega prehoda, ki pomeni pospešen prehod in preobrazbo v bolj trajnostno ter krožno gospodarstvo.

Na konferenci je bilo predstavljenih 35 predavanj v rednem programu in 8 v plakatni obliki. V naslednji številki 4. številki Livarskega vestnika bomo predstavili vse glavne avtorje in njihove teme predavanj. Vsem predavateljem s plakatnimi predstavitvami je letos bilo omogočeno, da so po urniku plakatnih predstavitev lahko svoje prispevke predstavili interesentom na lokaciji pred panojem za plakatne predstavitve.

Pozdrav g. Jerneja Salecla, generalnega diektorata za industrijo, podjetništvo in internacionalizacijo v Hotelu Slovenija s strani predsednice M. Jan-Blažić

Organizatorji poseben poudarek vsako leto namenjamo uveljavljeni livarski razstavi, na kateri je letos sodelovalo 45 razstavljavcev, od tega 23 iz tujine in 22 iz Slovenije. Konferenca in razstava omogočata neposreden stik med industrijo in raziskovalno sfero, kar je ključnega pomena za prenos znanja in nadaljnji tehnološki razvoj. Vse razstavljavce bomo posamično predstavili v naslednji 4. številki Livarskega vestnika.

all, high costs that seriously threaten the competitiveness of foundries.

She also highlighted the problem of unacceptably high electricity prices faced by foundries in most European countries, including Slovenia, which also seriously jeopardize their competitiveness. She expressed the opinion that, therefore, government interventions within individual countries, as well as support and measures within the European Union, are urgently needed.

She concluded this topic with the assessment that today's times also call for interstate cooperation so that together we can become stronger and able to meet these challenges. This is precisely why the international conference in Portoroz is a venue where we exchange experiences and seek solutions for this demanding common path of the green transition, which means an accelerated shift and transformation towards a more sustainable and circular economy.

At the conference, 35 lectures were presented in the regular program and 8 in the form of posters. In the next, 4th issue of the Foundry Bulletin, we will present all the main authors and their lecture topics. This year, all presenters with poster contributions were given the opportunity to present their work to interested participants on-site at the poster panels during the scheduled poster sessions.

The organizers devote special attention each year to the established foundry exhibition, which this year hosted 45 exhibitors, 23 from abroad and 22 from Slovenia. The conference and the exhibition enable direct contact between industry and the research sphere, which is crucial for knowledge transfer and further technological development. All exhibitors will be individually presented in the upcoming 4th issue of the Foundry Bulletin.

Poseben prispevek k uspešni izvedbi konference in razstave so zagotovili naslednji pokrovitelji konference: **Laempe Moessner Sinto** kot zlati pokrovitelj, **LTH Castings d.o.o**. kot srebrni pokrovitelj ter **Difa d.o.o**., **HA Group** in **Talum d.d.** kot bronasti pokrovitelji. Talum d.d. je vsem udeležencem v konferenčne torbice dodal še reklamno posodico za vodo.

Društvo livarjev Slovenije tudi na ta način izreka iskreno zahvalo za sodelovanje in pomemben prispevek uspešnosti in razpoznavnosti konference vsem pokroviteljem konference in sponzorjem razstave kot tudi medijskim partnerjem: **Giesserei Medien, Casting Plant & Technology International, Foundry Planet, Giesserei Rundschau, Foundry Trade Journal, IRT3000 in China Foundry.** Nemški medijski pokrovitelj je vsem udeležencem zagotovil v konferenčnih torbicah izvoda revije Giesserei in Casting Plant & Technology International.

g. Jernej Salecl na ogledu livarske razstave s predsednico M. Jan-Blažić

V času prvega dne konference je Društvo livarjev Slovenije organiziralo tudi že tradicionalno delovno srečanje s vodstvi članov Društva na katerem je kot gost sodeloval g. Jernej Salecl, generalni direktor direktorata za industrijo, podjetništvo in internacionalizacijo. Pred

A special contribution to the successful implementation of the conference and exhibition was ensured by the following sponsors:

Laempe Moessner Sinto as the golden sponsor, **LTH Castings d.o.o.** as the silver sponsor, and **Difa d.o.o., HA Group, and Talum d.d.** as the bronze sponsors. Talum d.d. also added a promotional water container to the conference bags of all participants.

In this way, the Foundry Society of Slovenia expresses its sincere gratitude for the cooperation and significant contribution to the success and recognition of the conference to all conference sponsors and exhibition supporters, as well as to the media partners: **Giesserei Medien, Casting Plant & Technology International, Foundry Planet, Giesserei Rundschau, Foundry Trade Journal, IRT3000, and China Foundry**. The German media partner also provided every participant with copies of the magazines *Giesserei* and *Casting Plant & Technology International* in their conference bags.

On the first day of the conference, the Foundry Society of Slovenia also organized the traditional working meeting with the management of its member companies, attended as a guest by **Mr. Jernej Salecl**, Director-General of the Directorate for Industry, Entrepreneurship and Internationalization. Before the meeting, Mr. Salecl also toured the entire foundry exhibition.

At the request of the Chinese delegation, the Foundry Society of Slovenia arranged, prior to the conference in Portoroz on 17 September, two visits in Ljubljana: one to the **Jožef Stefan Institute** and another **to LTH Castings d.o.o**. During the conference, a networking and presentation meeting was also held, where we introduced the Foundry Society of Slovenia and exchanged

Na sredi Jose Javier Gonzales , generalni sekretar WFO, Mirjam Jan-Blažič , predsednica in ga. Yunxia Wang vodja kitajske delegacije (FICMES) s sodelavci

delovnim srečanjem je g. Salecl opravil tudi ogled celotne livarske razstave.

Na prošnjo kitajske delegacije je Društvo livarjev Slovenije pred konferenco v Portorožu, dne 17. septembra zagotovilo kitajski delegaciji organizacijo dva obiska v Ljubljani: prvega v Inštitutu Jožef Stefan in drugega v podjetju LTH Castings d.o.o. V času konference pa še spoznavno - predstavitveni sestanek na katerem smo predstavili Društvo livarjev Slovenije in obojestransko podali predstavitve livarstva v obeh državah.

Pisni in ustni odzivi na konferenco in razstavo so tudi letos bili zelo pozitivni in spodbudni. Eno od nalog oz. predlog za izboljšavo, ki smo ga prejeli s strani enega od razstavljavcev, ki se nanaša na večjo uradno udeležbe livarn iz držav nekdanje skupne jugoslovanske države bomo proučili skupaj s razstavljavci - predvsem dobavitelji za livarsko industrijo. Treba je vedeti, da je konferenca in razstava v Portorožu renomiran evropsko in svetovno presentations on the foundry industries of both countries.

Written and oral feedback on the conference and exhibition was again very positive and encouraging this year. One of the tasks or proposals for improvement, received from one of the exhibitors, concerns the greater official participation of foundries from the countries of the former common Yugoslavia. We will examine this issue together with the exhibitors – especially suppliers to the foundry industry. It must be recognized that the conference and exhibition in Portoroz are a renowned European and globally competitive foundry event, and that the Foundry Society of Slovenia, being a non-profit organization under Slovenian law, cannot offer special participation discounts to non-members. This would mean that Slovenian foundries would subsidize the participation of other foundries, and given our local circumstances and financial capabilities, such a proposal would not be acceptable to our members.

Predstavniki vodstva in članov Društva livarjev Slovenije s kitajsko delegacijo

konkurenčen livarski dogodek in da Društvo livarjev Slovenije, ki je po slovenskem zakonu neprofitna organizacija ne more ponujati udeležencem izven Društva posebne popuste pri kotizacij za udeležbo. To bi pomenilo, da bi slovenske livarne sofinancirale udeležbo drugih livarn, za kar poznavajoč naše lokalne razmere in finančne možnosti ne bo soglasja s strani naših članic. Nenazadnje kolegi iz okrožij nekdanje skupne države bodo morali spoznati, da bo nujno potrebno za svojo strokovno rast nekaj investirati in na poti internacionalizacije se tudi otresti dolgoletnih balkanizmov, da se pojavljajo na prizoriščih mednarodnih konferenc brez plačila kotizacije ali pa logistiko mednarodne konference koristijo za svoje paralelne aktivnosti na isti lokacji.

Poročala: *mag. Mirjam Jan-Blažić*

Finally, colleagues from the regions of the former common state must also recognize that it is essential to invest in their own professional growth and, along the path of internationalization, to move away from long-standing Balkan practices, such as appearing at international conferences without paying participation fees or using the logistics of an international conference for their own parallel activities at the same location.

Reported by: *MSc. Mirjam Jan-Blažić*

AKTUALNO / CURRENT

Izračun ogljičnega zapisa z orodjem Fred

V okviru prizadevanj za trajnostni razvoj in zmanjševanje okoljskega vpliva livarske industrije je Društvo livarjev Slovenije 17. septembra 2025 v Portorožu organiziralo seminar na temo izračuna ogljičnega zapisa z orodjem FRED. Dogodek je bil namenjen predstavitvi metodologije za izračun ogljičnega odtisa proizvodnih procesov v livarnah ter praktični uporabi orodja FRED, ki omogoča natančno analizo emisij toplogrednih plinov. Predavanje sta izvedla BDG – Zvezno združenje za nemško livarsko industrijo in podjetje Prosimalys GmbH in sicer: dr. Sebastian Tewes, vodja za tehniko in inovacije v BGD in g. Ralf Boehl.

Seminarja so se udeležili predstavniki šestih podjetij: Difa d.o.o., Exoterm-IT d.o.o., Hidria d.o.o., Iskra ISD d.o.o., LTH Castings d.o.o. in Talum d.d., kar kaže na širok interes slovenskih livarn za okoljsko odgovorno poslovanje. Predavanja so bila usmerjena v razumevanje osnov ogljičnega zapisa, zakonodajnega okvira ter v obravnavo pritiska kupcev na dobavitelje glede popisa ogljičnega odtisa izdelkov.

Orodje FRED (Footprint REDuction Tool) omogoča izračun *Product Carbon Footprint* (PCF) za ulitke in *Corporate Carbon Footprint* (CCF) za livarne. Temelji na mednarodnih standardih ISO 14064, ISO 14067 ter Greenhouse Gas Protocol (GHG), kar zagotavlja njegovo zanesljivost in primerljivost. FRED omogoča simulacijo ukrepov za zmanjšanje emisij, analizo t. i. »hotspotov« ter uporabo industrijskih primarnih podatkov, kar je še posebej koristno za podjetja, ki nimajo lastnih podatkovnih baz. Orodje je vključeno tudi v mrežo Catena-X Automotive Network, kar dodatno potrjuje njegovo relevantnost v avtomobilski industriji.

Poseben poudarek je bil namenjen praktičnemu delu, kjer so udeleženci pod vodstvom strokovnjakov preizkusili orodje FRED na podlagi podatkov iz primera celotnega procesa v livarni. S tem so pridobili vpogled v možnosti optimizacije porabe energije, surovin in logistike, kar neposredno vpliva na zmanjšanje emisij CO_2.

Za naše podjetje je bila udeležba na seminarju izjemno koristna, saj smo pridobili konkretna orodja in znanja, ki jih bomo lahko uporabili pri nadaljnjem razvoju trajnostnih strategij. Poleg tega je dogodek omogočil izmenjavo izkušenj med podjetji, kar je pomemben korak k skupnemu cilju – bolj zeleni livarski industriji.

Zahvaljujemo se Društvu livarjev Slovenije za odlično organizacijo seminarja ter za priložnost, da prispevamo k razvoju okoljsko odgovornega livarstva.

Poročal: Jaka Trček, Hidria d.o.o.

AKTUALNO / CURRENT

Livarske prireditve 2025/26

Datum dogodka	Ime dogodka	Mesto in država
2. - 3. 10. 2025	World Foundry Summit	Pariz, Francija
24. - 25. 10. 2025	Ledebur-Kolloquium	Freiberg, Nemčija
25. - 28. 10. 2025	The 17th Asian Foundry Congress	Xi'an, Kitajska
29. 10. 2025	Seminar Bewertung von Simulationsergebnissen - Schwerpunkt Druckguss	Aachen, Nemčija
12. - 13. 11. 2025	Parts Finishing	Karlsruhe, Nemčija
12. - 13. 11. 2025	FORUM EISENGUSS - Optimierung & Wandel	Aachen, Nemčija
26. - 27. 11. 2025	Forum: Bauteil-, Prozess- und Wirtschaftlichkeitsoptimierung durch effiziente Werkzeugtemperierung	Aachen, Nemčija
12. 12. 2025	Polish Foundry Day	Krakov, Poljska
13. - 15. 01. 2026	Euroguss 2026	Nürnberg, Nemčija
09. - 11. 06. 2026	CastForge 2026	Stuttgart, Nemčija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