ISSN 0024-5135

LIVARSKI VESTNIK

67/2020
3

DRUŠTVO LIVARJEV SLOVENIJE
SLOVENIAN FOUNDRYMEN SOCIETY

LIVARSKI VESTNIK

Izdajatelj / Publisher:
Društvo livarjev Slovenije
Lepi pot 6, P.P. 424, SI-1001 Ljubljana
Tel.: + 386 1 252 24 88
Fax: + 386 1 426 99 34
E-mail: drustvo.livarjev@siol.net
Spletna stran: www.drustvo-livarjev.si

Glavni in odgovorni urednik / Chief and responsible editor:
prof. dr. Alojz Križman
E-mail: probatus@triera.net

Tehnično urejanje / Technical editoring:
mag. Mirjam Jan-Blažić

Prevod v angleški jezik / Translation into English:
Marvelingua, Aljaž Seničar s.p.

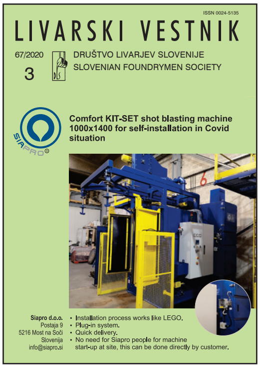
Lektorji / Lectors:
Angleški jezik / English:
Yvonne Rosteck, Düsseldorf
Slovenski jezik / Slovene: prof. Janina Šifrer

Tisk / Print:
Fleks d.o.o.

Naklada / Circulation:
4 številke na leto / issues per year
800 izvodov / copies

Letna naročnina: 35 EUR z DDV
Year subscription: 35 EUR (included PP)

Dano v tisk: september 2020



VSEBINA / CONTENTS

Stran / Page:

Izdajanje Livarskega vestnika sofinancira Javna agencija za raziskovalno dejavnost Republike Slovenije
Publishing supported by Slovenian Research Agency
Livarski vestnik je vpisan v razvid medijev Ministrstva za kulturo pod zaporedno številko 588

DIPL.-ING. P. GRÖNING,
Hüttenes-Albertus Chemische Werke GmbH (GER)

Trajnostni sistemi Coldbox

Sustainable Cold Box Systems

Povzetek

Livarska industrija se je morala vedno prilagajati spreminjajočim se gospodarskim in političnim razmeram. Vse večja specializacija in vse večja kompleksnost skupaj s strožjimi okoljskimi zahtevami vodijo tudi do potrebe po uporabe posebnih veziv. Zaradi široke palete aplikacij in nalog je potrebno zagotoviti tudi ustrezno obširen obseg izdelkov. Sistemi z organskimi vezivi, zlasti proces coldbox, še vedno prednjačijo v proizvodnji jeder, zlasti pri serijskem ulivanju.

Summary

The foundry industry has always had to adapt to changing economic and political conditions. Increasing specialization and growing complexity in combination with increased environmental requirements also demand the use of specialized binders. Due to the wide variety of applications and tasks, it is necessary to provide a correspondingly extensive product range. The organic binder systems and above all the Cold Box process are still the dominant core production processes, especially in serial casting.

Trajnostna kemija v livarstvu?

Ali je trajnostna kemija v livarstvu sploh mogoča? Če boste odgovorili po pravici, se bo vaš odgovor verjetno glasil »ne«. Ne glede na postopek ali sistem, ki se uporablja v livarni, livarske kemikalije bodo vedno pustile odtis. Namen kemije v livarstvu je torej zagotavljanje kar najmanjšega odtisa skozi obvladovanje širokega nabora zahtev in potreb.

Razvoj modernih in trajnostnih veziv za proces coldbox

Sodobni sistemi coldbox morajo izpolnjevati zahteve strank. Med osnovne lastnosti spadata visoka raven trdnosti in močna reaktivnost za zagotavljanje največje možne storilnosti. Med druge pomembne lastnosti spadata toplotna obstojnost (odziv na deformacijo) ter odziv na plin in emisije

Sustainable foundry chemistry?

Is there even such a thing as sustainable foundry chemistry? If you are being honest, the answer is likely “no”. No matter which process or system the foundry uses, there is always a “footprint” left by foundry chemicals. Therefore, the task of foundry chemistry is to keep this footprint as small as possible, which involves addressing a wide range of requirements and demands.

Development of modern sustainable Cold Box binders

Modern Cold Box systems must meet the customer’s requirements. Standard properties include a high strength level and high reactivity to ensure maximum productivity. Other important properties are thermal stability (deformation behaviour) gas and emission behaviour (pollutants, (onesnaževalci, dim, vonj, kondenzati). V zadnjih letih je veliko vprašanj vezanih na odstranjevanje livarskih ostankov na odlagališčih. Po eni strani se prostor na odlagališčih vse bolj omejuje, po drugi pa so stroški zaradi strožjih zakonskih zahtev vse višji. Posledično prihajajo v ospredje parametri odpadnega peska, kot so fenolni indeks, BTEX, TOC in DOC.

Viri livarskih emisij v postopku coldbox

Vezivni sistemi coldbox morajo izpolnjevati niz tako tehnoloških kot okoljskih lastnosti. Z vidika odpadnega peska so najpomembnejši parametri BTEX, fenolni indeks, TOC in DOC (Sl. 1, 2).

Okoljevarstveni vidiki

Opažamo dva glavna načina, na katera livarski industriji ponuditi trajnostne rešitve s sistemi coldbox:

- zmanjšanje vsebnosti organskih snovi;
- zmanjšanje vsebnosti monomerov v sistemu coldbox.

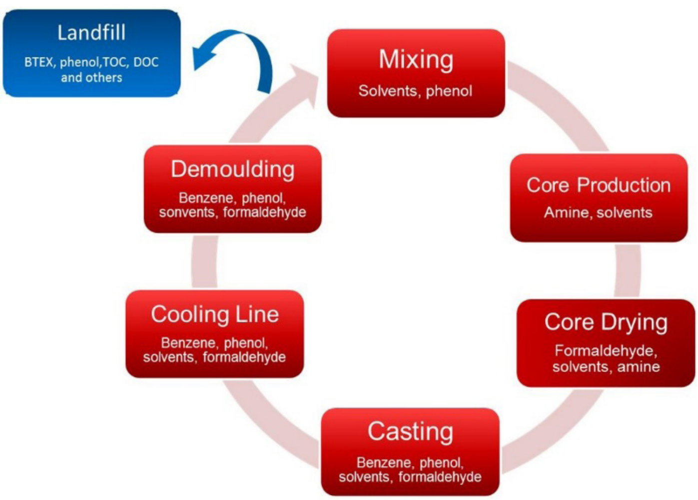
smoke, odour, condensates). In recent years, the demands placed on foundry residues to be dumped in landfills have also increased significantly. On the one hand, landfill space is becoming increasingly difficult, and on the other hand, the costs of dumping are increasing due to stricter legal requirements. As a result, the focus is increasingly on waste sand parameters such as the Phenol index, BTEX, TOC and DOC.

Sources of femissions from the Cold Box process

Cold Box binder systems must meet a wide range of technological, but also environmentally relevant characteristics. In terms of waste sand, the most relevant parameters are BTEX, Phenol index, TOC and DOC (Fig. 1,2).

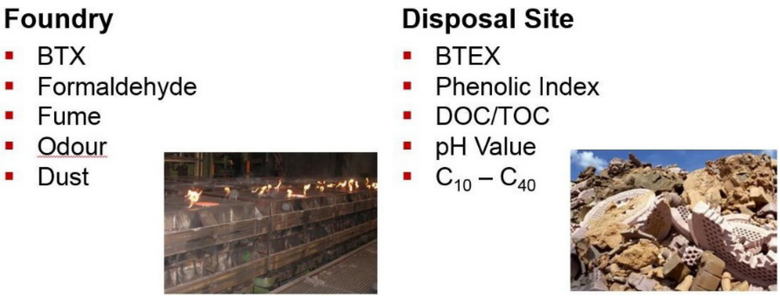
Environmental behaviour

We can see two main ways to offer sustainable Cold Box solutions to the foundry industry:



Sl. 1. Viri livarskih emisij – postopek coldbox

Fig. 1. Sources of foundry emissions – Cold Box process



Sl. 2. Pomembne livarske emisije

Fig. 2. Important foundry emissions

Zmanjšanje vsebnosti organskih snovi

»28. novembra 2018 je Komisija EU predstavila svojo dolgoročno strateško vizijo za uspešno, moderno, konkurenčno in podnebno nevtralno gospodarstvo do leta 2050. Strategija prikazuje, kako lahko Evropa utre pot do podnebne nevtralnosti z naložbami v realne tehnološke rešitve, s krepitvijo vloge državljanov in usklajevanjem ukrepov na ključnih področjih, kot so industrijska politika, financiranje ali raziskave – ter sočasno zagotavlja socialno pravičnost za pravičen prehod. Po pozivu Evropskega parlamenta in Sveta pokriva vizija Komisije EU o podnebno nevtralni prihodnosti skoraj vse politike EU in je skladna s ciljem Pariškega sporazuma o ohranitvi povečanja globalne temperature krepko pod 2 °C ter prizadevanji za njeno ohranitev pod 1,5 °C.« (*Vir: dolgoročna strategija Evropske komisije za leto 2050*)

Družba Hüttenes-Albertus se že vrsto let ukvarja z zmanjševanjem organske vsebnosti v sistemih coldbox. Na začetku so klasična aromatska ali alifatna topila v smoli in aktivatorske komponente zamenjala topila s silikatnimi oziroma anorganskimi sestavinami.

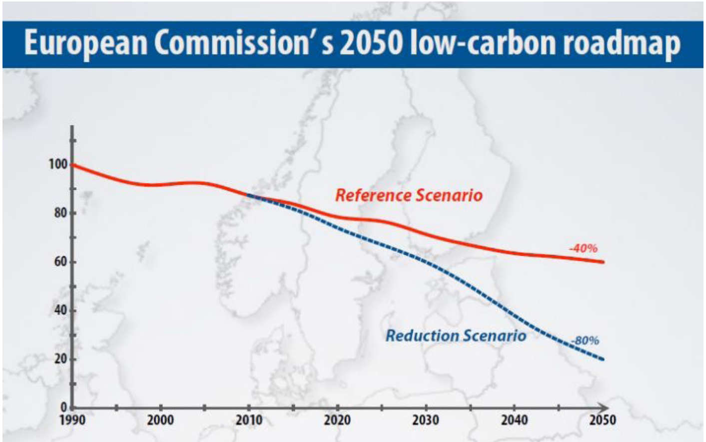
V nadaljevanju je bila smola coldbox delno modificirana s silikati (Sl. 4). V tej generaciji veziv – sistem SIPURID – so enote silicija vsebovane ne samo v topilu smole coldbox, ampak so integrirane

- the reduction of the organic content
- the reduction of the monomeric content of the Cold Box system.

Reduction of the organic content

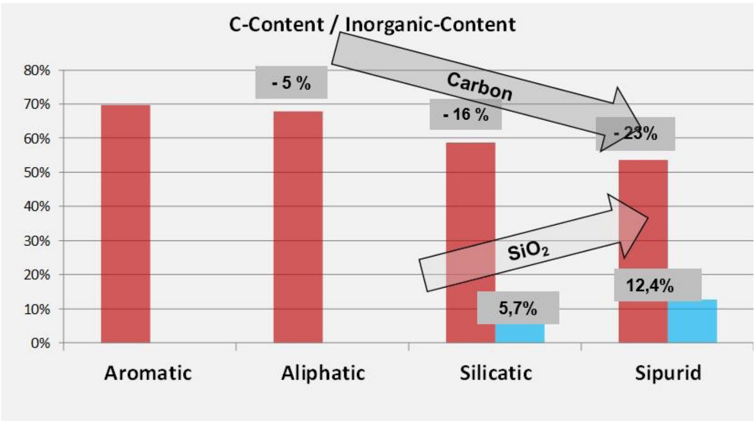
“On 28 November 2018, the EU Commission presented its strategic long-term vision for a prosperous, modern, competitive and climate-neutral economy by 2050. The strategy shows how Europe can lead the way to climate neutrality by investing into realistic technological solutions, empowering citizens, and aligning action in key areas such as industrial policy, finance, or research – while ensuring social fairness for a just transition. Following the invitations by the European Parliament and the European Council, the Commission’s vision for a climate-neutral future covers nearly all EU policies and is in line with the Paris Agreement objective to keep the global temperature increase to well below 2°C and pursue efforts to keep it to 1.5°C.” (*Source: European Commission 2050 Long term strategy*)

Hüttenes-Albertus has been practicing the reduction of the organic content in Cold Boxsystems for many years. Initially, the conventional aromatic or aliphatic solvents of the resin and activator components were substituted by solvents with silicatic, i.e. inorganic components.



Sl. 3. Načrt EU o karbonskih emisijah, *vir: CCAP Europe Th.Wyns*

Fig. 3. EU Carbon Road Map, *Source: CCAP Europe Th.Wyns*



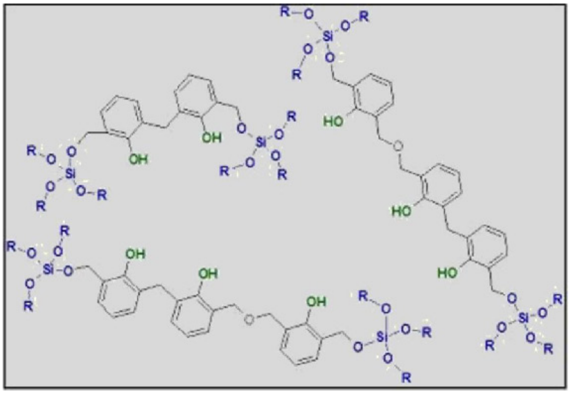
Sl. 4. Koraki razvoja HA – zmanjšanje vsebnosti ogljika v sistemih coldbox

Fig. 4. HA Development Steps – Reduction of Carbon in Cold Box Systems

tudi v molekularne strukture smole (Sl. 5). Patentirana rešitev družbe Hüttenes-Albertus predstavlja mejnik v razvoju novih sistemov coldbox. Prvič v zgodovini ti sistemi združujejo prednosti tako procesov coldbox kot tudi določene lastnosti anorganskih veziv. Integracija anorganskih enot se izvede skozi substitucijo, v okviru katere hidroksilne skupine molekul smole reagirajo z etil silikati.

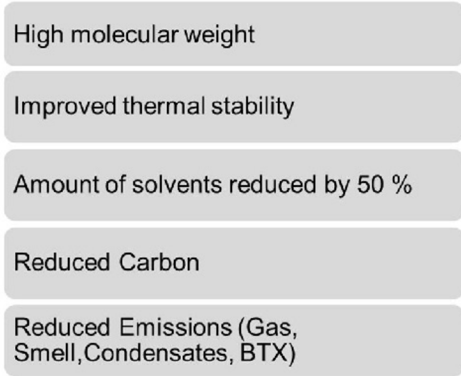
Med postopkom se velikost smolnatih molekul poveča, zato je mogoče količino aktivatorja v primerjavi z vsebnostjo smole zmanjšati. Viskoznost osnovne smole se zmanjša kljub večji molekularni teži.

In further development steps, the Cold Box base resin was also partially silicatically modified (Fig.4) In this generation of binder – SIPURID system - the silicium units are not only contained in the solvent of the Cold Box resin but are also integrated in the molecular structure of the resin (Fig.5) Hüttenes-Albertus patented solution is a milestone in the development of novel Cold Box systems. For the first time, it combines the advantages of both the Cold Box process and certain properties of inorganic cores. The integration of inorganic units is achieved through a substitution reaction during which the hydroxyl groups of the



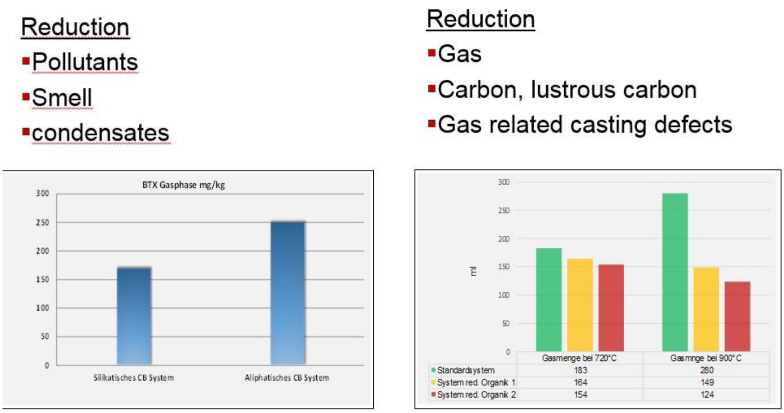
Sl. 5. Struktura smole SIPURID

Fig. 5. Structure of SIPURID Resin



Sl. 6. Lastnosti smole SIPURID

Fig. 6. Properties of SIPURID Resin



Sl. 7. Prednosti organskih reduciranih sistemov coldbox

Fig. 7. Advantages of organic reduced Cold Box systems

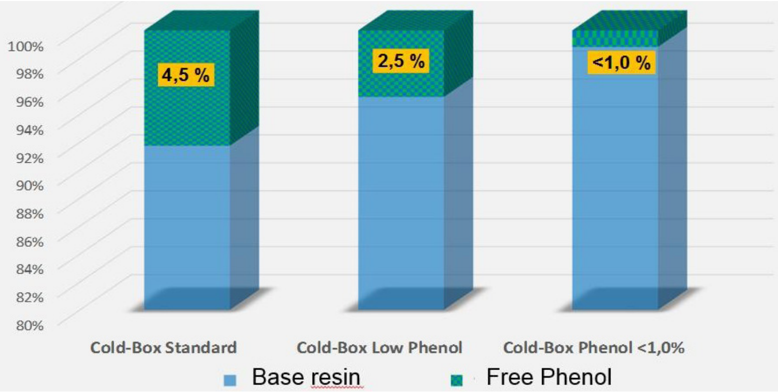
Posledično je potrebnega bistveno manj topila kot v predhodnih smolah coldbox. Prednosti teh silikatnih sistemov coldbox ne zajemajo samo manj izrazitega vonja, manj kondenzata in plinov, temveč tudi manj emisij onesnaževal, kot so BTX, BTeX, TOC in DOC (Sl. 7).

Zmanjšanje vsebnosti monomerov

Zmanjšanje vsebnosti monomerov v vezivu coldbox, tj. odsotnost fenola in zmanjšana vsebnost formaldehida, lahko še posebej pozitivno vpliva na primernost odpadnega

resin molecules are made to react with ethyl silicates.

In the process, the size of the resin molecules increases, so that the amount of activator can be reduced in relation to the resin content. The viscosity of the base resin is reduced despite the higher molecular weight. As a result, significantly less solvent is required than in the Cold Box resins previously. The advantages of these silicatic Cold Box systems not only include the reduction of odour, condensate and gas, but also the reduction of pollutant emissions such as BTX, BTeX, TOC and DOC (Fig 7).



Sl. 8. Koraki v razvoju tehnike coldbox za zmanjšanje prostega fenola

Fig. 8. Cold Box developments steps reducing free Phenol

peska za odlaganje na odlagališčih. Standardne smole imajo vsebnost monomerov <5,0 %, običajno okoli 4,5 %, smole z majhno vsebnostjo fenolov pa imajo vsebnost monomerov 2,5 % in se že dolgo uporabljajo v livarnah. Nova generacija smol vsebuje delež prostih monomerov (fenol+formaldehid) v vsebnosti < 1,0 % (Sl. 8). Tako je mogoče še posebej močno zmanjšati fenolni indeks odpadnega peska (Sl. 9). Zmanjšanje vsebnosti monomerov na < 1,0 % zagotavlja tudi prednosti za okoljsko pomembno označevanje. Glede na njihovo sestavo za te smole praktično niso več potrebne oznake v varnostnih listih. Žal pa samo z zmanjšanjem vsebnosti fenola v livarstvu ni mogoče zmanjšati vseh pomembnih parametrov emisij. Parametrov, kot so emisije BTX, TOC in DOC ter količine plina in kondenzata, ni mogoče zadosti zmanjšati samo z zmanjšanjem vsebnosti monomera.

Kombinacija prednosti

Po našem mnenju je za zmanjšanje obremenitev z emisijami treba nujno združiti prednosti obeh pomembnih načinov.

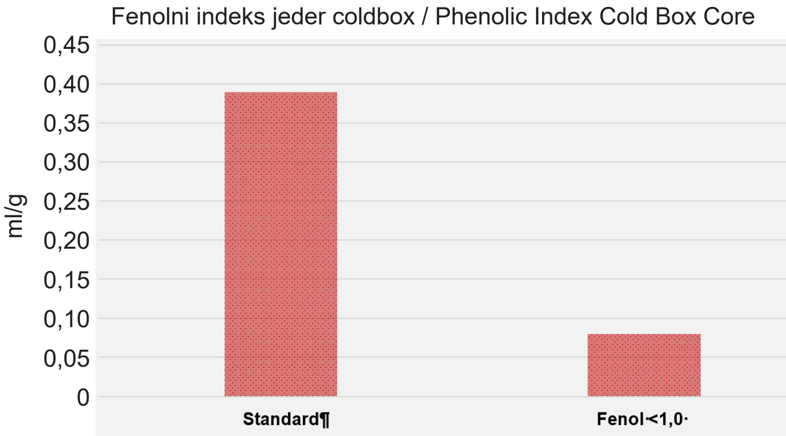
Uspelo nam je razviti sistem veziv z manjšo vsebnostjo organskih snovi z vsebnostjo monomerov <1,0 %. Da bi lahko

Reduction of the monomer content

The reduction of the monomer content in the Cold Box Binder, i.e. the free phenol + formaldehyde content, can have a further positive effect especially on the dumping capability of the waste sand. Standard resins have a monomer level of < 5.0%, usually around 4.5%., the so-called low-phenol resins with a monomer content of 2.5% have long been used in foundries. The new generation of resins have a share of free monomers (Phenol+Formaldehyde) <1,0% (Fig. 8). In particular, the phenol index in waste sand can be significantly reduced here (Fig. 9). Reducing the monomer content to < 1.0 % also offers advantages for environmentally relevant labelling. Depending on their composition, these resins are then virtually label-free in the MSDS. Unfortunately, it is not possible to reduce all important foundry emissions by reducing the phenol content alone. Parameters such as BTX emissions, TOC, DOC and the amount of gas and condensate cannot be reduced sufficiently only by reducing the monomer content.

Combination of advantages

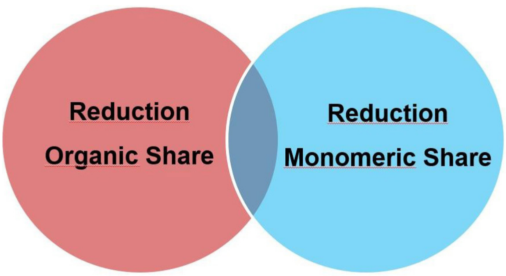
From our point of view, it is necessary to combine the advantages of the two major ways to reduce the emission load.



Sl. 9. Primerjava fenolnega indeksa jeder coldbox

Fig. 9. Phenolic Index Cold Box Core comparison

ponudili silikatno smolo coldbox popolnoma brez oznak, smo storili še korak naprej. Do sedaj na trgu ni bilo smole coldbox brez oznak. Z novo inovativno rešitvijo pa lahko zdaj predstavimo prvo silikatno smolo coldbox popolnoma brez oznak. Sistem sestavlja edinstvena kombinacija topil, zagotavlja prednosti silikatnih izdelkov coldbox in je brez oznake.



Sl. 10. Kombinacija lastnosti/prednosti

Fig. 10. Combination of Properties/Advantages

Emisije formaldehida

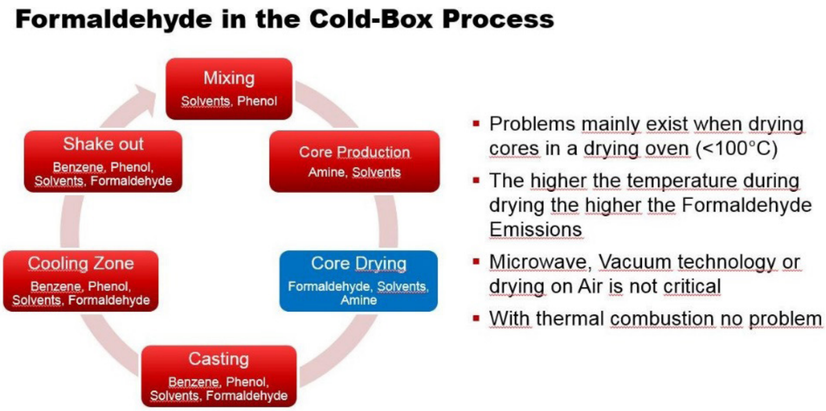
Mejne vrednosti izpostavljenosti za emisije formaldehida so se leta 2020 zaostrile. Prejšnja dovoljena mejna vrednost je bila 20 mg/m³, v letu 2020 pa se je omejitev znižala na 5 mg/m³. Izpostavljenost formaldehidu je največja predvsem v bližini sušilnih peči (Sl. 11).

We have succeeded in developing an organic-reduced binder system with a monomer content of <1.0 %. In order to be able to offer a label-free silicatic Cold Box resin, we have gone one step further. Until now there was no label free silicatic Cold Box resin in the market. With the new innovative solution, we can now present the first label-free silicatic Cold Box resin. This system has a unique new solvent combination, offers the advantages of the silicatic Cold Box product family and is label-free.

Formaldehyde Emissions

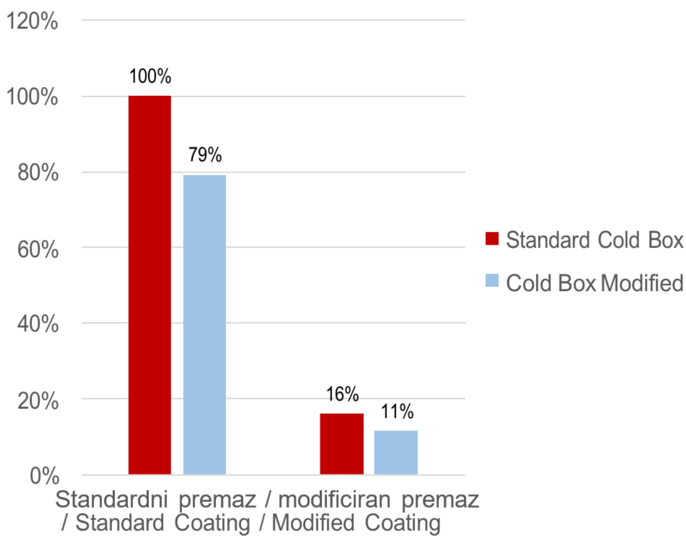
The exposure limit values for Formaldehyde Emissions will be tightened in 2020. At the moment, the limit value is 20 mg/m³ but will be only 5 mg/m³ in 2020. The Formaldehyde exposure is mainly affecting the area of the drying oven (Fig 11).

We have developed special Formaldehyde reduced Cold Box systems with an built-in substance to actively catch Formaldehyde during the complete production process in the foundry. If the reduction of Formaldehyde is not sufficient from the CB system alone, we also have developed a special additive and a special



Sl. 11. Viri formaldehida v postopku coldbox

Fig. 11. Sources of Formaldehyde in the Cold Box process



Sl. 12. Primerjava emisij formaldehida za modificiran postopek coldbox in modificiran premaz

Fig. 12. Comparison Formaldehyde emissions modified Cold Box + modified coating

Razvili smo poseben sistem coldbox z zmanjšano vsebnostjo formaldehida in z vdelanimi snovmi, ki aktivno ulovijo formaldehid med celotnim proizvodnim postopkom v livarni. Če zmanjšanje formaldehida v sistemu coldbox samo po sebi ne zadostuje, smo razvili tudi poseben aditiv kot tudi poseben premaz na vodni osnovi, ki še dodatno zmanjšajo emisije (Sl. 12).

water based coating to tackle the emissions successfully (Fig.12).

Viri / References:

Fig. 3 EU Carbon Road Map, Source: CCAP Europe Th.Wyns

D. Franzen, P. Martin, B. Pustal, A. Bührig-Polaczek,
Foundry Institute RWTH Aachen (Nemčija/Germany)

Ocena statističnih in dinamičnih mehanskih lastnosti pod vplivom zasnove legiranja pri duktilni litini

Evaluation of Static and Dynamic Mechanical Properties under the Influence of Alloying Design in Ductile Cast Iron

Povzetek

Za kompleksne komponente litega železa so značilne njihove raznolike mikrostrukture. Zaradi njihove mikrostrukturne različnosti zagotavlja duktilna litina (DL) široko paleto mehanskih lastnosti. Visoka vsebnost perlita pomeni visoko odpornost materiala proti obrabi, popolnoma feritna in malolegirana matrica pa zagotavlja zlasti dobro duktilnost in žilavost tudi pri nizkih temperaturah. Zlasti za razrede ojačene DL s trdno raztopino in večjo vsebnostjo silicija (Si) v količini od 3,2 do 4,3 mas. % je značilna precej višja duktilnost v primerjavi z razredi feritno-perlitnih DL pri enaki trdnosti. Vendar pa je žilavost ključni dejavnik pri teh materialih, saj z večanjem vsebnosti silicija močno upada.

Žilavost materiala je po eni strani odvisna od mikrostrukture, torej zasnove zlitine, po drugi strani pa od uporabljene zunanje obremenitve. Obremenitev predstavljajo temperatura preskusa, hitrost deformacije in stanje lokalne obremenitve, za mikrostrukturo pa so značilni tvorba grafitne faze, velikost zrna in lokalna kemična sestava matrice.

Za lokalno kemično sestavo matrice je značilna zlasti tvorba mikrosegregacijskih profilov, ki nastajajo med evtektičnim strjevanjem in so posebej izraziti v primeru ojačene DL s trdno raztopino tako zaradi nevezane rasti evtektične faze kot višje vsebnosti Si. Ključne obogatitve s Si v bližini grafitnih modulov spodbujajo tvorbo superstruktur FeSi, ki so privedle do krhkosti materiala. Zatorej tvorba superstruktur FeSi predvidoma povzroči dodatno krhkost lege, ki privede do hitrejšega nastajanja razpok v teh območjih. Nadalje tvorba superstruktur predvidoma povzroči slabše lastnosti žilavosti na makroskopski ravni.

Nedavne številske in eksperimentalne raziskave kažejo, da je na silicijev profil mikrosegregacije mogoče vplivati s prilagoditvijo zasnove legiranja. Z legiranjem aluminija z 0,3 do 1,2 mas. % je mogoče invertirati in natančno spremeniti silicijev profil mikrosegregacije. Podobno vedenje je mogoče opaziti tudi pri legiranju niklja. Na podlagi predstavljenih rezultatov prilagoditev zasnove zlitine predvidoma predstavlja primerno metalurško okolje za selektivno prilagoditev silicijevih mikrosegregacij in posledično za nadaljnje izboljšanje statičnih in dinamičnih lastnosti sodobnih duktilnih zlitin.

Ključne besede: lito železo, duktilna litina z visoko vsebnostjo silicija, strjevanje trdne raztopine, udarna žilavost, zasnova litine

Summary

Complex cast iron components are characterized by their various microstructures. Due to their microstructural diversity, ductile iron (DI) offers a wide range of mechanical properties. A high pearlite content leads to a highly wear-resistant material, while a fully ferritic, low-alloyed matrix enables a particularly good ductility and toughness even at low temperatures. In particular, solid solution strengthened DI grades with elevated silicon

(Si) contents ranging from 3.2 wt.% to 4.3 wt.% Si are characterized by a significantly higher ductility compared to ferritic-pearlitic DI grades at the same strength. However, toughness properties are a critical factor for these materials, which significantly decrease with increasing silicon content.

The toughness of a material is on the one hand dependent on the microstructure and thus by the alloy design, and on the other hand on the external load applied. While the load case is represented by testing temperature, the strain rate and local stress state, the microstructure is characterized by the formation of the graphite phase, the grain size and the local chemical composition of the matrix.

The local chemical composition of the matrix is represented in particular by the formation of microsegregation profiles, which build up during eutectic solidification and are especially prominent in the case of solid solution strengthened DI due to both the decoupled growth of the eutectic phase and elevated Si contents. Critical Si enrichments in the vicinity of the graphite nodules promote the formation of FeSi superstructures that lead to an embrittlement of the material. It is therefore assumed that the formation of FeSi superstructures provoke additional notch sensitivity that lead to a promotion of crack initiation in these areas. It is further assumed that the formation of superstructures results in the decrease in toughness properties on a macroscopic level.

Recent numerical and experimental investigations show that the silicon microsegregation profile can be influenced by the adjustment of the alloying design. By alloying with 0.3 to 1.2 wt.% aluminum it is possible to invert and precisely modify the microsegregation profile of silicon. Similar tendencies can also be observed when nickel is alloyed. On the basis of the present results, it is assumed that the adaptation of the alloy design represents a suitable metallurgical tool for the selective adjustment of silicon microsegregations and thus for further improving the static and dynamic mechanical properties of modern ductile cast irons.

Keywords: Cast iron, high silicon ductile iron, solid solution strengthening, impact toughness, microsegregation, alloy design

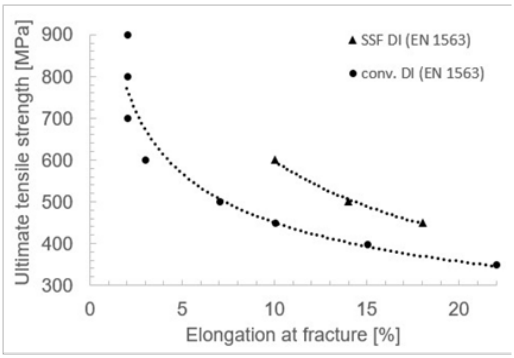
1 Uvod

Zaradi odlične livnosti in izvrstne kombinacije mehanskih lastnosti, kot sta visoka trdnost in dobra duktilnost, imajo duktilne litine visok za uporabo tako v livarstvu kot na področju dizajna [1]. Duktilnim litinam z veliko vsebnostjo silicija se zaradi vključitve v evropski standard DIN EN 1563 v letu 2012 na področju raziskav ter v industriji posveča veliko pozornosti [2–6]. Zaradi ojačanja trdne raztopine imajo ti materiali še posebej ugodno razmerje med natezno trdnostjo in duktilnostjo. Enofazna popolnoma feritna matrica zagotavlja homogeno distribucijo s trdoto povezanih lastnosti ter izvrstno

1 Introduction

Due to their very good castability and excellent combinations of mechanical properties such as high strength and very good ductility, ductile cast irons offer a high application potential for both foundrymen and designers [1]. With their inclusion in the European standard DIN EN 1563 in 2012, high silicon grades of ductile iron receive great attention in research and industry [2-6]. Due to solid solution strengthening, these materials show especially favorable ratios of tensile strength and ductility. Furthermore, the single-phase fully ferritic matrix offers a homogeneous distribution strojno obdelavo [7]. Kot je prikazano na Sl. 1, se takšni materiali zaradi kombinacije visoke trdnosti in dobrega raztezka do razpoke uporabljajo na jeklarskem področju zaradi njihove konkurenčnosti, in sicer kot varnostne komponente in za uporabo, kjer so v različnih vejah industrije potrebni deli nize teže, npr. v avtomobilski industriji, proizvodnji vetrne energije, v ladjedelništvu in na področju strojegradništva [8; 9].

Vendar pa se zaradi povečane vsebnosti silicija močno poveča prehodna temperatura žilavosti (DBTT – ductile-to-brittle transition temperature) v preizkusu udarne žilavosti, kot je prikazano na Sl. 2. Vendar pa številne oblikovalske smernice narekujejo določene minimalne lastnosti v povezavi s trdnostjo. Še posebej pomembne so certifikacije v aplikacijah, kjer je zahtevana dobra trdnost. Posledično obsežna uporaba teh litih železni mogoča. V livarski industriji je za preizkušanje udarne žilavosti zaradi svoje preprostosti najpriljubljenejši Charpyjev preizkus.



Sl. 1. Natezna trdnost in raztezek ob porušitvi duktilne litine, ojačane konvencionalno in s trdno raztopino skladno s standardom DIN EN 1563 [1]

Fig. 1. Ultimate tensile strength and elongation at fracture of conventional and solid solution strengthened DI according to DIN EN 1563 [1]

of the hardness properties and excellent mechanical machinability [7]. As illustrated in Fig. 1, the combination of high strength and good elongation at fracture ensures that these grades primarily serve as competitive products for steel applications, as safety components and for the use in lightweight applications in various branches of industry such as automotive engineering, wind energy technology, shipping industry and mechanical engineering [8; 9].

However, increased silicon contents result in a significant increase of the ductile-to-brittle transition temperature (DBTT) in the impact toughness test, as illustrated in Fig. 2. However, certain minimum toughness properties are required in many design guidelines. In particular, certifications for applications with requirements for good toughness properties are of special importance. A wide-ranging use of these cast iron materials is therefore significantly prevented. The Charpy impact test is the industrially preferred test method for toughness properties due to its low effort.

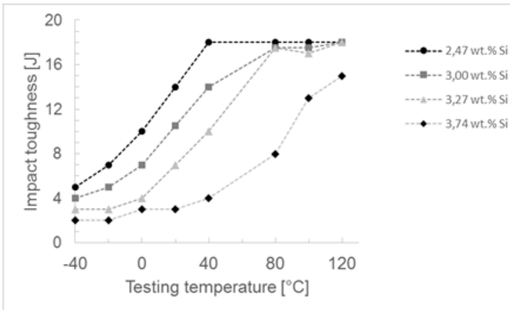
Besides the external load case, toughness properties of a material are essentially influenced by their microstructure. The microstructure of cast irons is mainly described by the formation of the grain size, graphite phase and the local chemical composition of the metallic matrix. While the global chemical composition is mainly influenced by the selection of the alloy, the local chemical composition is primarily determined by the formation of microsegregation profiles. The formation of distinct silicon microsegregations is promoted in particular by the decoupled growth of the eutectic phase as well as by increased silicon contents. Since silicon atoms are preferably embedded in the γ solid solution during eutectic solidification, negative microsegregation profiles with silicon accumulations in the first-to-freeze

Poleg zunanjih obremenitev na z žilavostjo povezane lastnosti materiala vplivajo pretežno njihove mikro strukture. Mikrostruktura litih železje opisana predvsem s formacijo velikosti zrn, grafitne faze in lokalne kemijske sestave kovinske matrice. Medtem ko na globalno kemijsko sestavo vpliva predvsem izbira zlitine, je lokalna kemijska sestava odvisna predvsem od nastanka profilov mikro segregacije. Nastanek izrazitih mikro segregacij silicija še pospešuje nevezana rast evtektične faze kot tudi povečana vsebnost silicija. Ker se silicijevi atomi vdelajo v trdno raztopino γ med evtektičnim strjevanjem, običajno nastanejo negativni profili mikro segregacije ob akumulaciji silicija v predelih FTF (First-To-Freeze) [13-15]. Vsi drugi elementi, ki povzročajo grafitiranje, se običajno izrazijo s particijskim koeficientom > 1. Nasprotno pa se elementi, ki stabilizirajo karbide in so torej pozitivni izcejalni elementi, nabirajo v predelih LTF (Last-To-Freeze) blizu meja zrn, kar vodi do particijskega koeficienta <1 [10].

Še posebej pri duktilnih litinah s povečano vsebnostjo silicija lahko pride do lokalnih presežkov vsebnosti silicija v bližini grafitnih nodul zaradi negativne mikro segregacije Si. Weiß in sod. so v preteklosti že dokazali, da obstaja jasna korelacija med globalno vsebnostjo Si in formacijo krhkih super struktur FeSi. Nastanek teh super struktur, kot je prikazano na Sl. 3, je fenomen, poznan v proizvodnji električnih jekel s povečano vsebnostjo Si. Pri vsebnosti pribl. 4 mas. % Si nastanejo ureditve dolgega reda FeSi, ki vodijo do zmanjšanja duktilnosti in oblikovalnosti [14; 15].

Na podlagi raziskav s TEM s strani Weiß in sod. je znano, da je ureditev dolgega reda FeSi formacije faze B2 pri globalni vsebnosti 3,96 mas. % [12], kot je razvidno na Sl. 4. Ko se vsebnost silicija dodatno poveča do 5,36

regions (FTF) are usually formed [13-15]. As for all other graphitizing elements, this is usually expressed in a partition coefficient > 1. In contrast, carbide stabilizing and thus positively segregating elements accumulate in last-to-freeze areas (LTF) near the grain boundaries resulting in a partition coefficient of <1 [10].

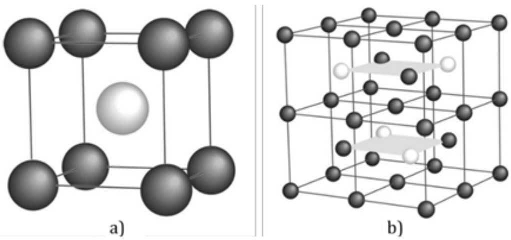


Sl. 2. Udarna žilavost pri različnih temperaturah duktilne litine z različnimi vsebnostmi silicija v skladu s [7]

Fig. 2. Impact toughness at different temperatures of DI with varying silicon content according to [7]

Particularly for DI with elevated silicon contents, local exceedings of the silicon content near the graphite nodules can occur due to negative microsegregation of Si. It was shown earlier by Weiß et al. that there is a distinct correlation between the global Si content and the formation of embrittling FeSi superstructures. The occurrence of these FeSi superstructures, as illustrated in Fig. 3, is a phenomenon known from the production of electrical steels with increased Si contents. At about 4 wt.% Si, FeSi long-range orderings are formed that lead to a reduction in ductility and formability [14; 15].

From TEM investigations by Weiß et al. it is known that FeSi long-range orderings of the phase formation B2 at global Si contents of about 3.96 wt.% [12], as can mas. %, se moč formacije faze B2 poveča. Prav tako se povečanje odraža v formaciji faze DO_3. Zato velja, da je jakost gradienta mikro segregacije Si odvisna od skupne vsebnosti Si. Prav tako se predpostavlja, da se formacija super struktur FeSi poveča zaradi močnejših mikro segregacij Si, še posebej v predelih FTF. Pri takšnih super strukturah se dislokacije nakopičijo, kav vodi do povečane lokalne trdnosti [11]. Tako je tendenca za nastanek razpok povečana, kar vodi v zmanjšano duktilnost in žilavost



Sl. 3. Modeli osnovnih celic a) formacije faze B2 in b) formacije faze DO_3; atomi Fe so označeni s črno, atomi Si pa z belo [11]

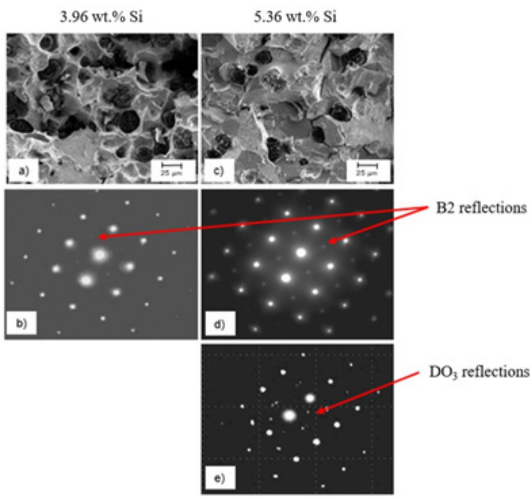
Fig. 3. Models of the unit cells of the a) B2 and b) DO_3 phase formation; Fe atoms are represented in black, Si atoms in white [11]

Na podlagi teh rezultatov predpostavljamo, da je nastajanje takšnih ureditev dolgega reda, ki povzročajo krhkost, glavni krivec za slabe statične in dinamične mehanske lastnosti duktilnih litin s povečanimi vsebnostmi silicija.

Da bi še dodatno izboljšali mehanske lastnosti tudi pri visokih vsebnostih silicija, je treba zmanjšati nastajanje super struktur FeSi, ki povzročajo krhkost. V ta namen je treba modificirati profil mikro segregacije Si in posledično zmanjšati kritične vsebnosti silicija v predelu grafitnih nodul. Homogenzacija gradienta mikro segregacije bi tako vodila v na splošno nižje

be observed from Fig. 4. When the silicon content is further increased up to 5.36 wt.%, the intensity of the B2 phase formation increases. Additionally, reflections of the phase formation DO_3 can be observed. It is therefore assumed that the intensity of the Si microsegregation gradient is dependent on the global Si content. It is further assumed that as a result of stronger Si microsegregations, especially in FTF areas, the formation of FeSi superstructures increases. At such superstructures, dislocations are concentrated which leads to an increase in the local strength [11]. In this way, the tendency for crack initiation in these areas is enhanced, resulting in decrease of ductility and toughness.

On the basis of these results, it is assumed that the formations of these embrittling long-range orders are mainly responsible for the low static and dynamic mechanical properties of DI alloys with increased silicon contents.



Sl. 4. Analiza površine razpoke in preiskave TEM super strukture vzorcev z vsebnostjo Si 3,96 mas. % in 5,36 mas. %

Fig. 4. Fracture surface analysis and TEM superstructure investigations of samples with 3.96 wt% and 5.36 wt.%

lokalne vsebnosti silicija iz predelov FTF v predele LTF.

Predhodne raziskave so razkrile, da dolgotrajna toplotna obdelava z avstenizacijo pri visokih temperaturah ni primerna metoda za vplivanje na profil mikro segregacije Si. V trenutnih raziskavah na Livarskem inštitutu univerze RWTH Aachen želijo spremeniti profil mikro segregacije silicija z ustreznimi metalurškimi metodami. Do sedaj ni bilo izvedenih raziskav o vplivanju na gradient segregacije silicija s prilagajanjem sestave duktilne litine. Zato predstavlja ta prispevek izhodišče, na podlagi katerega je mogoče spremeniti profil mikro segregacije silicija z namenom izogibanja kritični vsebnosti Si za nastanek super struktur FeSi. V ta namen smo preiskali elemente, ki so analogni s silicijem in se, če je le mogoče, vdelajo v avstenit med evtektičnim strjevanjem.

2 Metode in materiali

2.1 Zasnova poskusa

Da bi določili učinek različnih legirnih elementov na mikro segregacijo silicija v duktilni litini, sta bili izvedeni tako numerična kot eksperimentalna raziskava. Na numerični osnovi so bili posamezni učinki Al in Ni na profil mikro segregacije Si izračunani z uporabo mikro segregacijskega modela. Za potrditev numeričnega podatka smo izvedli različna poskusna litja z namenom preučitve samostojnih in kombiniranih učinkov aluminija in niklja. Različne vsebnosti Al v izmeri 0,3 do 1,2 mas. % in različne vsebnosti Ni med 1,0 in 2,0 mas. % so bile izbrane za preučevanje posameznega učinka vsakega elementa. Izdelali smo tudi drug ulitek z vsebnostjo Al 0,3 mas. % in vsebnostjo Ni 1 mas. %, ki smo ga uporabili za raziskavo kombiniranega učinka obeh elementov. Skupaj smo izdelali

In order to further improve the mechanical properties even at high silicon contents, the formation of embrittling FeSi superstructures has to be reduced. For this purpose, the Si microsegregation profile should be modified so that critical silicon contents in areas of the graphite nodules are reduced. A homogenization of the microsegregation gradient would thus result in an overall lower local silicon content from FTF to LTF areas.

Preliminary studies show that heat treatments based on long holding times at investigations of samples with 3.96 wt% and 5.36 wt.% S high austenitization temperatures are not suitable for influencing the Si microsegregation profile. Instead, current investigations at the Foundry Institute of RWTH Aachen University aim to modify the silicon microsegregation profile by suitable metallurgical methods. So far, no studies have been carried out to influence the segregation gradient of silicon by adapting thealloy design of ductile iron. Therefore, in the present work a possibility shall be created to modify the microsegregation profile of silicon to avoid locally critical Si contents for the formation of FeSi superstructures. For this purpose, elements will be investigated which, analogous to silicon, are preferably embedded into the austenite during eutectic solidification.

2 Methods and Materials

2.1 Design of experiments

In order to determine the effect of different alloying elements on the silicon microsegregation in ductile iron both numerical and experimental studies were conducted. On a numerical basis the single effects of Al and Ni on the Si

7 talin, imenovanih talina št. 1–7, s težo 250 kg, kot je navedeno v Preglednici 1. Iz vsake taline smo izdelali 5 ulitkov, kot je prikazano na Sl. 5; iz standardnih testnih blokov Y2 in Y4 smo s strojno obdelavo izdelali 2 vzorca za metalografske analize, 5 vzorcev za statično mehansko testiranje in 48 vzorcev za udarno testiranje. V Preglednici 1 je povzeto poskusno litje preiskovanih zlitin.

Preglednica 1. Pregled proizvedenih in toplotno obdelanih zlitin

Table 1. Overview of produced and heat-treated alloys

No.	Si [mas. %]	Al [mas. %]	Ni [mas. %]
1	3,8	0	0
2	3,8	1,2	0
3	3,8	0,3	0
4	3,8	0,6	0
5	3,8	0	1,0
6	3,8	0	2,0
7	3,8	0,3	1,0

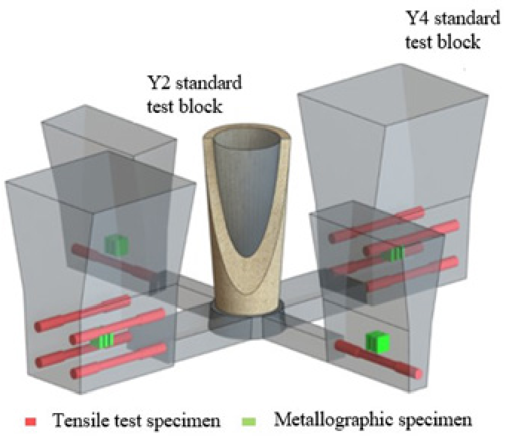
2.2 Simulacijski postopek

Da bi izračunali kinetiko strjevanja legirnih elementov med evtektično reakcijo v duktilni litini, smo uporabili model numerične mikro segregacije [13], vključno z zbirko termodinamičnih (TCFE6) in mobilnostnih (MOBFE2) podatkov. Združitev termodinamičnih in kinetičnih podatkov smo izvedli z uporabo knjižnice-tq programske opreme ThermoCalc. Termodinamični podatki so nujni za pridobitev mejnih pogojev na fazni meji grafit-avstenit in avstenit-teočina, da bi lahko simulirali difuzijo v avstenitu. To omogoča napovedovanje transformativne kinetike, npr. difuzijo ogljika iz tekočine skozi avstenit in v grafit. Na takšen način omogoča model mikro segregacije izračunavanje tako samostojnih kot navzkrižnih učinkov, povezanih z vzorci

microsegregation profile were calculated using a microsegregation model. To validate the numerical data different casting trials were conducted studying the single and combined effects of aluminum and nickel. Different Al contents of 0.3 to 1.2 wt.% and varying Ni contents of 1.0 and 2.0 wt.% were chosen to study the single effect of each element. Another casting with an Al content of 0.3 wt.% and a Ni content of 1 wt.% was produced to investigate the combined effect of both elements. Overall, a total of 7 melts, referred to as alloy No. 1-7, 250 kg according to Table 1 were produced. For each melt 5 castings were cast as shown in Fig. 5. 2 specimens for metallographic analysis, 5 specimens for static mechanical testing and 48 specimens for impact testing were machined from Y2 and Y4 standard test blocks. Table 1 summarizes the casting trials performed for the investigated alloys.

2.2 Simulation procedure

In order to calculate the solidification kinetics of alloying elements during the eutectic reaction in ductile iron, a numerical microsegregation model [13] including Thermodynamic (TCFE6) and mobility (MOBFE2) databases was used. The coupling to thermodynamic and kinetic information is realized by applying the tq-library of ThermoCalc. The thermodynamic data is required to obtain the boundary conditions at the graphite-austenite and the austenite-liquid interface in order to simulate diffusion in the austenite. This allows to predict the transformation kinetics such as the diffusion of carbon from the liquid through the austenite to the graphite. In this way, the microsegregation model allows the calculation of both single and cross-effect related microsegregation patterns. In this work, the gradients of Si, Al, Ni of a melt mikro segregacije. V tem prispevku so izračunani gradienti Si, Al, Ni taline, ki se ohlaja s 1500 °C s stopnjo ekstrakscije toplote 650 W/kg. Temeljna zlitina za te izračune je FeSi3.8C v skladu z razredom EN-GJS-500-14. Reprezentativni volumski element (RVE) je popolnoma sferičen in ima polmer 42 µm. Ti pogoji ustrezajo eksperimentalnim pogojem ohlajanja in številu nodul v bloku Y4.



Sl. 5. Položaj preizkusa natezne trdnosti in metalografskega vzorca iz standardnih testnih blokov Y2 in Y2

Fig. 5. Positions of tensile test and metallographic specimen from Y2 and Y2 standard test blocks

2.3 Poskusni postopek

Taline smo pripravili iz surovin (recirkuliran material, čisto železo in ferosilicij (FeSi), čisti nikelj), ki smo jih stalili v srednje frekvenčni indukcijski peči z zmogljivostjo 250 kg. Vse surovine smo raztalili in segreli do 1400 °C. V primeru legiranja z Al, pri tej temperaturi, so bili na dno talilnega lonca postavljeni na 500 °C predogreti kosi aluminija skupaj s magnezijevo predzlitino in so bili nato prekriti z odpadnim železom tik pred izpustom. Vse

cooling down from 1500 °C with a heat extraction rate from 650 W/kg is calculated. The base alloy for these calculations is a FeSi3.8C according to the grade EN-GJS-500-14. The representative volume element (RVE) is considered to be ideally spherical with a radius of 42 µm. These conditions correspond to the experimental cooling conditions and the nodule count in the Y4 block.

2.3 Experimental procedure

The melts were prepared using raw materials (recirculation material, pure iron and ferrosilicon (FeSi), pure nickel) and melted in a medium-frequency induction furnace with a capacity of 250 kg. All raw materials were melted and heated up to 1400 °C. In the case of alloying with Al, at this temperature, to 500 °C preheated solid pieces of aluminum were placed at the bottom of the ladle together with the magnesium pre alloy and covered with steel scrap shortly before tapping. All melts were then superheated to 1500 °C for about 5 minutes in order to remove impurities from the melt. After deslagging and producing samples for thermal and spectrometric analysis, the magnesium treatment was performed following the sandwich method at a tapping temperature of 1450–1470 °C. Therefore 1.3 wt.% of a magnesium pre-alloy (6.5 wt.% Mg, 1.9 wt.% Ca, 45 wt.% Si, balance Fe) was placed at the bottom of a ladle with a capacity of 250 kg and covered with steel scrap (0.03 wt.% C, 0.02 wt.% Si, 0.25 wt.% Mn, 0.04 wt.% Cr, 0.02 wt.% Cu). The inoculation was conducted immersing 0.3 wt.% of an inoculant (68–73 wt.% Si, 3.2–4.5 wt.% Al, 0.3 – 1.5 wt.% Ca, traces of Mg and Ce, balance Fe) into the melt using a rod. After the melt treatment, final samples for thermal and spectrometric taline so bile nato pregrete na 1500 °C pribl. 5 minut, da bi iz njih odstranili nečistoče. Po odstranitvi žlindre in izdelavi vzorcev za toplotno in spektrometrično analizo je bila izvedena obdelava z magnezijem, in sicer skozi sendvič metodo pri temperaturi izpuščanja 1450-1470 °C. Posledično je bila na dno talilnega lonca s kapaciteto 250 kg postavljena magnezijeva predzlitina v količini 1,3 mas. % (6,5 mas. % Mg, 1,9 mas. % Ca, 45 mas. % Si, ostalo Fe) in prekrita z odpadnim jeklom (0,03 mas. % C, 0,02 mas. % Si, 0,25 mas. % Mn, 0,04 mas. % Cr, 0,02 mas. % Cu). Inokulacija je bila izvedena s potopitvijo 0,3 mas. % inokulanta (68–73 mas. % Si, 3,2–4,5 mas. % Al, 0,3–1,5 mas. % Ca, sledovi Mg in Ce, ostalo Fe) v talino z uporabo palice. Po obdelavi taline so bili iz livnega lonca zajeti končni vzorci za toplotno in spektrometrično analizo. Talino smo nato ulivali pri začetni livni temperaturi 1400 °C. Za vsako talino smo izdelali 5 ulitkov v 5 formah, kot je prikazano na Sl. 5. Livna temperatura je bila izmerjena v formah št. 1, 3 in 5. Vsaka forma je sestavljena iz livnih votlin za standardne testne bloke 2 Y2 in 2 Y4 skladno s standardom DIN EN 1563. Po hlajenju smo vse ulitke razkalupili in očistili. Iz livnega sistema smo nato izrezali standardne testne bloke Y2 in Y4. Za vsako zlitino smo nato strojno obdelali 3 vzorce za statične preizkuse natezne trdnosti, 24 vzorcev za preizkušanje udarne žilavosti in 3 vzorce za metalografske analize in za vrstično elektronsko mikroskopiranje.

2.4 Analize vzorcev

Mehanske lastnosti

Za vsako izmed zlitin je bilo izdelanih 9 (3×Y2, 6×Y4) vzorcev, ki so bili nato za namene mehanskega preizkušanja obdelani v preizkusne bloke z uporabo

analysis were taken from the ladle. The melt was then poured at an initial casting temperature of 1400 °C. Per melt overall five castings in five moulds as illustrated in Fig. 5 were produced. The casting temperature was measured at moulds No. 1, 3 and 5. Each mould contains cavities for 2 Y2 and2 Y4 standard test blocks according to the DIN EN 1563. After cooling, all castings were unpacked and cleaned. Y2 and Y4 standard test blocks were then cut from the casting system. For each alloy, a total of 3 samples for static tensile tests, 24 samples for impact tests and three samples for metallographic and scanning electron microscopic analyses were then machined.

2.4 Specimen analyses

Mechanical Properties

For each alloy a total of 9 (3×Y2, 6×Y4) samples in the as-cast state were machined formechanical testing from the test blocks using an 18 mm core drill. The position of the samples in the Y2 and Y4 test block corresponds to the positions A (Y2) and A, C (Y4) according to the DIN EN 1563, respectively. Corresponding to the DIN EN 50125 tensile test specimens of shape A with a test diameter of 8 mm and an overall length of 115 mm are turned. For evaluating static mechanical properties such as ultimate tensile strength (UTS), yield strength (YS) and elongation at fracture (A) quasi-static tensile tests are conducted on an *Instron Model 8033* using a main cross speed of 0.6 mm/min.

For alloys 3-7, 32 samples (16×Y2, 16×Y4) for impact testing in the as-cast state were produced per setting. Machining of the specimen Charpy with V-notch was carried out according to DIN EN ISO 148-1. The samples were then tested on a *Zwick/Roell model HIT50P* impact testing machine

18 mm jedrnega svedra. Položaj vzorcev v preizkusnih blokih Y2 in Y4 je skladen s položaji A (Y2) ter A, C (Y4) skladno s standardom DIN EN 1563. Skladno s standardom DIN EN 50125 smo za preizkus natezne trdnosti s stružnico izdelali vzorce oblike A s preizkusnim premerom 8 mm in skupno dolžino 115 mm. Za oceno statičnih mehanskih lastnosti, kot so natezna trdnost (UTS), meja plastičnosti (YS) in raztezek do razpoke (A), smo s pomočjo naprave *Instron Model 8033* izvedli kvazi statične natezne preizkuse pri hitrosti raztezanja 0,6 mm/min.

Pri zlitinah 3–7 smo izdelali 32 vzorcev (16×Y2, 16×Y4) za udarno preizkušanje. Strojna obdelava vzorca Charpy z V-zarezo je bila izvedena skladno s standardom DIN EN ISO 148-1. Vzorci so bili nato preizkušeni na udarnem stroju *Zwick/ Roell, model HIT50P,* z največjo udara 50 J v skladu s standardom DIN ISO 148-1. Položaj vzorcev za udarno testiranje ustreza položajema A in C standardnih geometrij Y2 in Y4.

Metalografske preiskave

Za oceno metalografskih parametrov, kot je nastanek grafitne faze, kot tudi lokalne kemijske sestave matrice smo iz testnih blokov Y2 in Y4 odvzeli 3 metalografske vzorce na zlitino (1×Y2, 2×Y4) iz neposredne bližine vzorca, in sicer za mehansko preizkušanje in z uporabo 18 mm jedrnega svedra. Po rezanju smo vdelali metalografske vzorce in jih nato štirikrat brusili z brusi grobosti 180, 320, 500, 1000 dve minuti pri kontaktnem tlaku 20 N in 150 vrtljajih na minuto z vodo kot tudi z mazivom. Vzorci so nato zloščenih v treh fazah loščenja v diamantnih suspenzijah z zrni velikosti 9 µm, 3 µm in 0,25 µm pri tlaku 25 N v času 3–4 minute. Jedkanje po Klemmu [22] smo izvedli z namenom vizualizacije profilov mikro segregacije

with a maximum impact energy of 50 J according to DIN ISO 148-1. The position of the impact test specimens corresponds to the positions A and C of the Y2 and Y4 standard geometries.

Metallographic Examinations

For evaluating the metallographic parameters such as the formation of the graphite phase as well as the local chemical composition of the matrix, per alloy 3 metallographic samples (1×Y2, 2×Y4,) from Y2 and Y4 test blocks are taken from the direct vicinity of the specimen for mechanical testing using an 18 mm core drill. After cutting, metallographic samples are embedded and then subjected to four successive grinding processes with grain sizes 180, 320, 500, 1000 for 2 minutes each at a contact pressure of 20 N and 150 rates per minute with water as lubricant. The samples are then each polished on three polishing stages with diamond suspensions of grain sizes 9 µm, 3 µm and 0.25 µm at a pressure of 25 N for 3–4 minutes. Etchings according to Klemm [22] are performed in order to visualize silicon microsegregation profiles by metallographic examinations. Microstructural analyses of both polished and etched specimens are carried out using an optical up-light microscope.

Spectrometric Analysis

In order to analyze the chemical composition of the alloys produced, spectrometer samples were prepared by pouring melt into a copper mould. The samples were then ground using 80-SiC abrasive paper and tested with a spectrometer. Table 2 summarizes the results comparatively.

silicija z metalografskimi preiskavami. Mikrostrukturne analize tako zloščenih kot jedkanih vzorcev smo izvedli s svetlobnim optičnim mikroskopom.

Spektrometrična analiza

Da bi analizirali kemijsko sestavo proizvedenih zlitin, smo pripravili vzorce za spektrometer, in sicer z litjem taljene zlitine v bakreno formo. Vzorce smo nato analizirali z brusnim papirjem 80-SiC in preizkusili s spektrometrom. V Preglednici 2 so povzeti rezultati primerjave.

Preglednica 2. Kemijska sestava preiskovanih zlitin, vsebnosti v wt.%

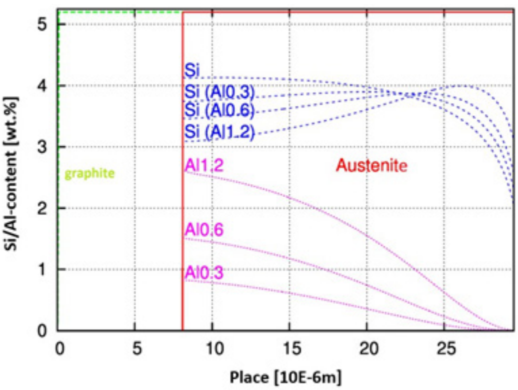
Table 2. Chemical composition of the investigated alloys, contents in wt.%

Zlitina/ Alloy	C	Si	Al	Ni	Mg	CE
1	2.99	4.24	0.01	0.03	0.042	4.23
2	3.03	3.86	1.14	0.03	0.048	4.45
3	3.08	3.63	0.31	0.03	0.048	4.29
4	3.05	3.81	0.67	0.02	0.053	4.32
5	3.05	4.19	0.04	0.97	0.051	4.42
6	3.01	3.75	0.02	1.92	0.052	4.22
7	3.5	3.89	0.23	0.97	0.042	4.83

3 Rezultati

3.1 Simulacija mikro segregacije

Pri evtektičnem strjevanju pri temperaturi 1138 °C prikazuje Sl. 6 izračunane profile mikro segregacije Si in Al pri globalni vsebnosti Si 3,8 mas. % in variabilni globalni vsebnosti Al 0,3 do 1,2 mas. % ob radiju evtektičnega zrna. Opazili smo, da se



Sl. 6. Formacija mikro segregacij silicija pri različnih skupnih vsebnostih Al v RVE med evtektično reakcijo pri temperaturi 1.138 °C

Fig. 6. Formation of silicon microsegregations at various global Al contents in an RVE during eutectic reaction at 1138 °C

3 Results

3.1 Microsegregation simulation

For the eutectic solidification at a temperature of 1138 °C, Fig. 6 shows the calculated microsegregation profiles of Si and Al at a global Si content of 3.8 wt.% and variable global Al contents of 0.3 to 1.2 wt.% along the radius of the eutectic grain. It can be observed that Al atoms are preferably embedded in the austenite during eutectic solidification and therefore segregated negatively [14]. When no Al is present, a negative microsegregation of Si is predicted by the model. If the global Al content in the alloy is increased to 1.2 wt.%, an inverted microsegregation profile of Si is predicted with Si enrichments forming in LTF areas. If the Al content is set to 0.3–0.6 wt.% a more homogenous distribution of Si throughout the eutectic grain is calculated.

However, considering the Si microsegregations when nickel is added, no effect on the distribution of the Si gradient can yet be determined by means of microsegregation simulations. In the following, this observation will be considered by experimental investigations.

atomi Al preferenčno vdelajo v avstenit med evtektičnim strjevanjem in tako negativno vplivajo na segregacijo [14]. Ko Al ni prisoten, model napove negativno mikro segregacijo Si. Če se skupna vsebnost Al v zlitini poveča na 1,2 mas. %, se napove obratni profil mikro segregacije Si s formacijo obogatitev s Si v področjih LTF. Če je vsebnost Al nastavljena na 0,3–0,6 mas. %, je izračunana bolj homogena distribucija Si po evtektičnih zrnih.

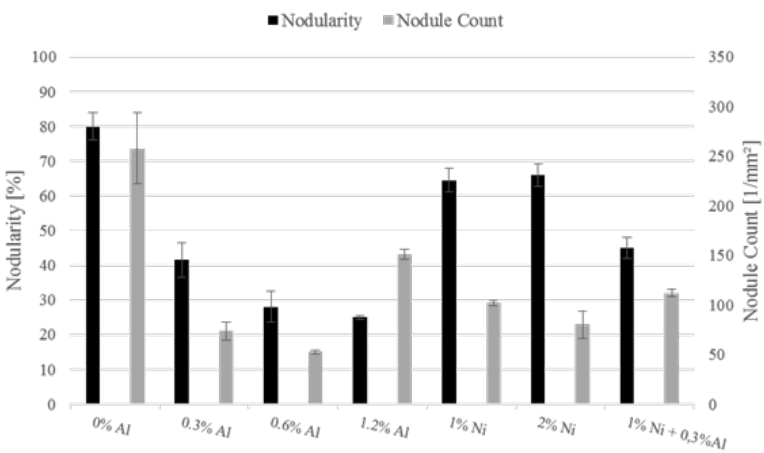
Z vidika mikro segregacij pa po dodatku niklja s simulacijo mikro segregacije še ni mogoče določiti učinka na distribucijo gradienta Si. V nadaljevanju bodo te ugotovitve podkrepljene z eksperimenti.

3.2 Analiza grafita

Da bi preiskali vpliv zasnove zlitine na mikro strukturo, smo nastajanje grafita in faze matrice ocenili z uporabo samodejne programske opreme za analiziranje posnetkov v skladu s standardom ISO 945-4. Na Sl. 7 so prikazane srednje vrednosti nodularnosti ter število nodul v preiskovanih zlitinah. Jasno je, da nodularnost močno upada zaradi legiranja z Al. Ta učinek je na splošno že poznan ter ga potrjujejo

3.2 Graphite Analysis

In order to investigate the influence of the alloy design on the microstructure, the formation of the graphite and matrix phase is evaluated using automated image analysis software according to ISO 945-4. Fig. 7 shows the mean values of nodularity and the nodule count for the investigated alloys. It becomes apparent that the nodularity decreases significantly due to alloying with Al. This effect is generally known and confirmed e.g. by investigations of Soinski et al. [15-17]. However, alloying with 1 and 2 wt.% Ni has only little effect on the nodularity. The nodule count decreases by about 200 1/mm² to 50 to 75 1/mm², when Al is alloyed. In alloys alloyed with 1 and 2 wt.% Ni, the nodule count is decreased by about 50 1/mm². Alloys 1-4 that are alloyed with Si and Al contain no pearlite. In alloy 5 with an Ni content of 1 wt.% a pearlite content of 2–5 % can be observed. Also, in alloy 7 the pearlite content is less than 5 %. If the Ni content is increased to 2 wt.% the pearlite content amounts to about 13 % in the Y2 test block.



Sl. 7. Nodularnost in število nodul v preiskovanih zlitinah

Fig. 7. Nodularity and nodule count of the investigated alloys

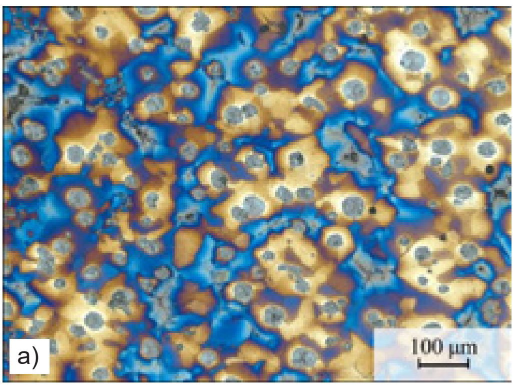
raziskave, ki so jih npr. izvedli Soinski in sod. [15-17]. Vendar pa ima legiranje z 1 in 2 mas. % Ni zgolj majhen vpliv na nodularnost. Število nodul se je pri legiranju z Al zmanjšalo za pribl. 200 1/mm² na 50 do 75 1/mm². Pri zlitinah, legiranih z 1 in 2 mas. % Ni, se je število nodul zmanjšalo za pribl. 50 1/mm². Zlitine 1–4, legirane s Si in Al, ne vsebujejo perlita. Pri zlitini 5 z vsebnostjo Ni 1 mas. % je bila izmerjena vsebnost perlita 2–5 %. Tudi v zlitini 7 je bila vsebnost perlita nižja od 5 %. Če se vsebnost Ni poveča na 2 mas. %, meri količina perlita v testnem bloku Y2 pribl. 13 %.

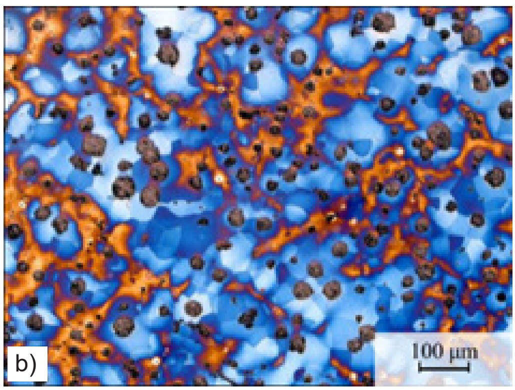
3.3 Analiza mikro segregacije

Da bi preiskali profile mikro segregacije Si in Al, ki se napovedujejo z numeričnim modelom, smo izvedli metalografske preiskave z namenom kvalitativne vizualizacije vedenja mikro segregacije Si. Dva vzorca z 0 mas. % in 1,17 mas. % Al smo obdelali s Klemmovim jedkalom in ju primerjali s svetlobno-optičnimi analizami (gl. Sl. 8). Rjavi do rumeni predeli označujejo

3.3 Microsegregation Analysis

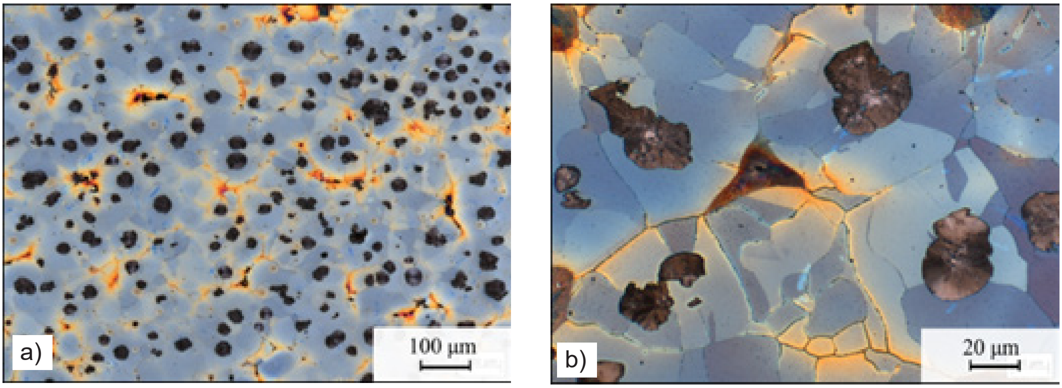
In order to investigate the microsegregation profiles of Si and Al, which are predicted by the numerical model, metallographic investigations are carried out with the aim of qualitatively visualizing the microsegregation behavior of Si. Two samples with 0 wt.% and 1.17 wt.% Al are subjected to Klemm etchings and compared using light-optical analyses (accord. to Fig. 8). Brown to light yellow areas indicate increased silicon contents, while bluish zones indicate silicon depletion. In Fig. 8a, FTF areas appear light yellow, while blue coloration can be observed in LTF zones. A contrasting pattern can be seen in analyses of samples with 1.17 wt.% Al (Fig. 8a). In these, FTF areas appear blue, indicating silicon depletion. However, zones that tend to be assigned as LTF areas appear in a brownish color. An analogous behavior can be seen when considering the alloy with 1 wt.% Ni (Fig. 9). Predominantly bluish appearing areas that can be found in the vicinity of the graphite nodules, indicate a silicon depletion. Light yellow areas in





Sl. 8. Porazdelitev silicija v vzorcih s 3,8 mas. % Si in a) 0 % Al ter b) 1,2 mas. % Al, vizualizirana s Klemmovim jedkalom

Fig. 8. Distribution of silicon in samples with 3.8 wt.% Si and a) 0 % Al and b) 1.2 wt% Al visualized by Klemm-etchings



Sl. 9. Porazdelitev silicija v vzorcih s 3,8 mas .% Si 1,0 mas .% Ni pri a) 100-kratni in b) 500-kratni povečavi

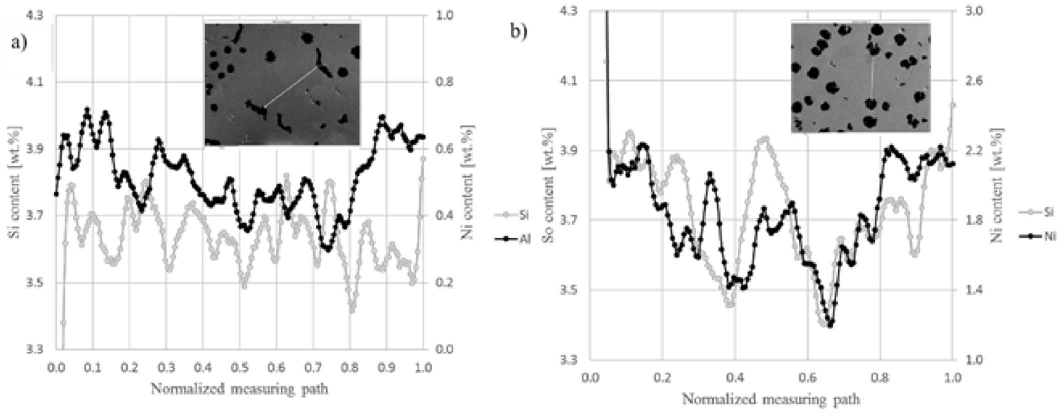
Fig. 9. Distribution of silicon in samples with 3.8 wt.% Si and 1.0 wt.% Ni at a) 100x and b) 500x magnification

povečano vsebnost silicija, modri predeli pa predele, kjer je bil silicij izčrpan. Na Sl. 8a so predeli FTF obarvani svetlo rumeno, modro pa so obarvani predeli LTF. Nasprotni vzorec je mogoče opaziti v analizah vzorcev z Al 1,17 mas. % (Sl. 8a). Tukaj so predeli FTF obarvani modro, kar označuje izčrpanost silicija. Vendar pa so predeli, ki so najpogosteje označeni kot predeli LTF, označeni z rjavkasto barvo. Analogno vedenje je mogoče opaziti tudi pri zlitini z vsebnostjo Ni 1 mas. % (Sl. 9). Pretežno modro so obarvani predeli v bližini grafitnih nodul ter označujejo izčrpanost silicija. Svetlo rumena območja v predelih LTF, v katerih je občasno prisoten perlit, so znak legiranja s Si.

Da bi lahko kvantitativno potrdili kvalitativne trditve o distribuciji Si, so bile meritve EDX, natančneje skeniranje linij, izvedene na izbranih mikro strukturnih mestih. Sl. 10 na reprezentativen način prikazuje profile mikro segregacije Si, Al in Ni med dvema precipitatoma grafita v zlitinah z Al 0,3 mas. % in Ni 2,0 mas. %. Na podlagi Sl. 10a postane jasno, da vodi lokalna vsebnost Si do zgolj majhnih variacij, ko vsebuje zlitina 0,3 mas. % Al. Po drugi

LTF zones, in which additionally pearlite is occasionally present, serve as a sign for an enrichment of Si.

In order to quantitatively validate the qualitative statements on the Si distribution, EDX measurements in terms of line scans were performed at selected locations of the microstructure. Fig. 10 shows the microsegregation profiles of Si, Al and Ni between two graphite precipitates in alloys with 0.3 wt.% Al and 2.0 wt.% Ni in a representative manner. It becomes obvious from Fig. 10a that the local Si content shows only slight variations when the alloy contains 0.3 wt.% Al. On the other hand, alloy 6 with a Ni content of 2 wt.% shows more intensive fluctuations (Fig. 10b). Furthermore, a higher silicon content can be observed in LTF zones, which indicates an effect of alloying with Ni. If the Ni content is set to 1 wt.% more variations in the silicon distribution can be observed as well. When both Al and Ni are added the microsegregation profile these variations tend to be smaller compared to alloys that contain only Ni.



Sl. 10. Reprezentativne meritve EDX porazdelitve elementov a) Si in Al ter b) Si in Ni med dvema precipitatoma grafita v 3.8Si0.3Al (zlitina 3) in 3.8Si2.0Ni (zlitina 6)

Fig. 10. Representative EDX-measurements of element distribution of a) Si and Al and b) Si and Ni between two graphite precipitates in 3.8Si0.3Al (alloy 3) and 3.8Si2.0Ni (alloy 6)

strani pa so nihanja pri zlitini 6 z vsebnostjo Ni 2 mas. % bolj intenzivna (Sl. 10b). Prav tako je v predelih LTF opaziti večjo vsebnost silicija, ki je znak legiranja z Ni. Če je vsebnost Ni nastavljena na 1 mas. %, je mogoče prav tako opaziti več raznolikosti v distribuciji silicija. Ob sočasnem dodatku Al in Ni je profil mikro segregacije manjši v primerjavi z zlitinami, ki vsebujejo samo Ni.

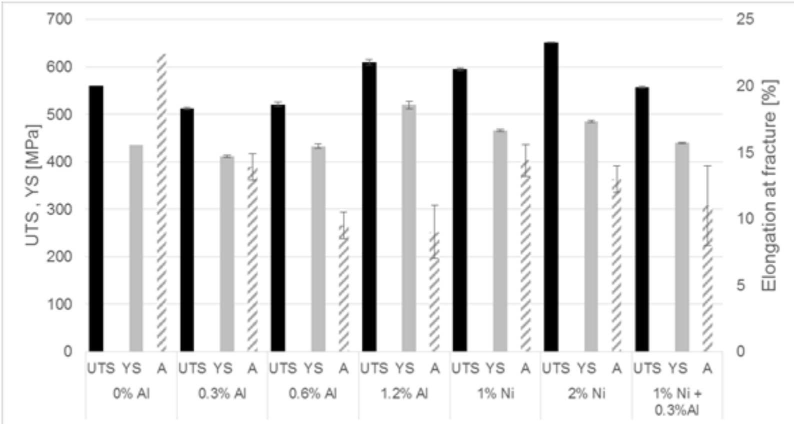
3.4 Mehanske lastnosti

Sl. 11 prikazuje statične mehanske lastnosti preiskovanih zlitin. Bistveno povečanje natezne trdnost (UTS) in meje plastičnosti (YS) je mogoče doseči z legiranjem z Al in Ni. Pri vsebnostih Al 0,3 do 0,6 mas. % je mogoče opaziti majhno zmanjšanje UTS. Pri vsebnosti Al 1,2 mas. % Al je UTS pribl. 50 MPa višja kot brez Al. Dodatno ojačanje trdne raztopine je bolj izrazito pri legiranju z Ni kot z Al. UTS se poveča za pribl. 90 Mpa v primeru legiranja z 2 mas. % Ni. YS se poveča pri legiranju

3.4 Mechanical properties

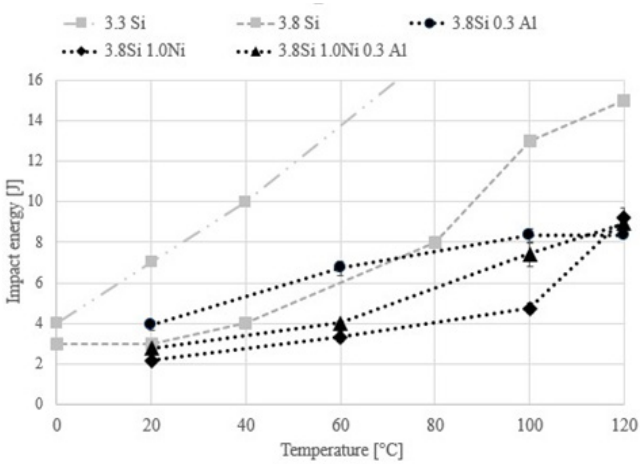
Fig. 11 shows the static mechanical properties of the investigated alloys. A significant increase in ultimate tensile strength (UTS) and yield strength (YS) can be achieved by alloying both Al and Ni. At Al contents of 0.3 to 0.6 wt.% a slight loss of UTS can be observed. At 1.2 wt.% Al the UTS is about 50 MPa higher than without Al. The additional solid solution strengthening is more prominent in the case of Ni than in the case of Al. The UTS is increased by about 90 MPa when alloyed with 2 wt.% Ni. The YS is increased when both Al and Ni are alloyed. At an Al content of 1.2 wt.% the YS is about 510 MPa, which is an increase of about 90 MPa compared to alloy 1. The elongation at fracture (A) decreases significantly due to the addition of Al, which is attributed to the negative effect of Al on the nodularity. The negative effect of Ni on A is thus about 50 % lower than that of Al.

Fig. 12 illustrates the impact energy of SGI-500-14 with 3.8 wt.% Si and that of



Sl. 11. Statistične mehanske lastnosti preiskovanih zlitin v standardnih testnih blokih Y2

Fig. 11. Static mechanical properties of the investigated alloys in Y2 standard test blocks



Sl. 12. Energija udara zlitine 3.8Si0.3Al (zlitina 3), 3.8Si1.0Ni (zlitina 5) in 3.8Si1.0Ni0,3Al (zlitina 7) v standardnih testnih blokih Y2 pri različnih temperaturah

Fig. 12. Impact energy of the alloys 3.8Si0.3Al (alloy 3), 3.8Si1.0Ni (alloy 5) and 3.8Si1.0Ni0,3Al (alloy 7) in Y2 standard test blocks at different temperatures

z Al in z Ni. Pri vsebnosti Al 1,2 mas. % meri YS pribl. 510 MPa, kar predstavlja povečanje za pribl. 90 MPa v primerjavi z zlitino 1. Raztezek do razpoke (A) se močno zmanjša zaradi dodatka Al, kar velja za negativen učinek Al na nodularnost. Negativni učinek Ni na A je torej pribl. 50 % nižji kot pri Al.

the adjusted alloys. Only alloy 3 with 0.3 wt.% aluminum tends to improve the impact energy in the considered temperature range of 0-120 °C. However, alloys with Ni and a combination of Ni and Al show no improvement in the notched bar impact energy.

Sl. 12 prikazuje udara vpliva SGI-500-14 s 3,8 mas. % Si in kot tudi prilagojenih zlitin. Samo pri zlitini 3 z 0,3 mas. % aluminija se izboljša energija udara v preiskovanem temperaturnem razponu med 0 in 120 °C. Vendar pa se energija udara pri zlitinah z Ni ter kombinacijo Ni in Al v valju z zarezo ni izboljšala.

4 Razprava

Zaradi legiranja z 0,3 in 0,6 mas. % Al se vrednost UTS na začetku zmanjša, kar je posledica povečane degeneracije grafitnih nodul. Vendar pa začne nad 1,2 mas. % prevladovati učinek ojačanja trdne raztopine, kar vodi do povečanja UTS in YS. Nasprotno pa se raztezek do razpoke dosledno manjša zaradi negativnega učinka Al na morfologijo grafita. To potrjujejo tudi nadaljnje preiskave, ki so jih izvedli Soinski in sod. [15–17]. Ni močno poveča UTS in YS in je celo močnejši kot pri Al. Pri vsebnosti Ni nad 1 mas. % je treba upoštevati tudi nastajanje perlita, ki vodi v povečano trdnost. Zmanjšanje raztezka do razpoke je posledica bistveno nižjega števila nodul, kar je posledica nižje začetne ravni jeder v talini. Učinek zareze na mikro strukturo se je močno povečal zaradi formacije perlita in posledično večjih nodul grafita, kar je vodilo do povečanja A.

Tako numerične kot eksperimentalne raziskave so pokazale, da je mogoče na mikro segregacijo silicija vplivati z dodatkom aluminija. Vsebnost 1,2 mas. % vodi do obratnega profila mikro segregacije Si. V predhodnih raziskavah kot tudi v tem delu so jedkanje in meritve EDX pokazali, da vsebnost Al 0,3 do 0,6 mas. % vodi do bolj homogenega profila mikro segregacije Si. Predpostavlja se, da je tendenca za vdelavo atomov Al v avstenitno trdno raztopino med evtektičnim strjevanjem višja od atomov Si

4 Discussion

Due to the alloying with 0.3 and 0.6 wt.% Al the UTS initially decreases, which is attributed to the increased degeneracy of the graphite nodules. Above 1.2 wt.%, however, the solid solution strengthening effect of Al predominates, which leads to an increase in UTS and YS. In contrast, the elongation at fracture decreases continuously due to the negative effect of Al on the graphite morphology. This is confirmed by further investigations such as conducted by Soinski et al. [15-17]. Ni has a significantly enhancing effect on UTS and YS, which is stronger than that of Al. Above a Ni content of 1 wt.%, the formation of pearlite must also be considered, resulting in an additional increase in strength. The decrease in elongation at fracture is explained by the significantly lower nodule count, which could be explained with a lower initial nucleus level of the melt. The microstructural notch effect increases considerably due to the formation of both pearlite and less and thus larger graphite nodules, leading to a decrease in A.

Both, numerical and experimental investigations have shown that the microsegregation of silicon can be influenced by the addition of aluminum. Al contents of 1.2 wt.% even lead to a reversal of the microsegregation profile of Si. In preliminary investigations as well as in the present work, etchings and EDX measurements further showed that Al contents of 0.3 to0.6 wt.% tend to lead to a more homogeneous Si microsegregation profile. It is assumed that

the tendency to embed Al atoms into the austenite solid solution during eutectic solidification is higher than that of Si atoms in the investigated element content range. This leads to a suppression of embedding Si atoms in the austenite. According to znotraj preiskovanega razpona elementov. To vodi do zaviranja vdelave atomov Si v avstenit. Henke trdi, da je vsebnost Al omejena s formacijo karbida Fe3AlC0.05 pri vsebnosti Al nad 3,8 mas. % [18]. Prav tako legiranje aluminija močno poslabša livne lastnosti, kar vodi v potrebo po uporabi kompleksnejših obdelovalnih postopkov.

Podoben vpliv na mikro segregacijo Si se predpostavlja tudi pri dodatku niklja. Jedkanje po Klemmu kot tudi meritve EDX so pokazali prve znake, da vsebnosti Ni 1,0 to 2,0 mas. % vplivajo tudi na lokalno distribucijo Si. Pri vsebnosti Ni 1,0 mas. % so meritve EDX pokazali inverzijo profila segregacije Si. Te rezultate smo kvalitativno potrdili tudi s Klemmovim jedkalom. Kleinkröger in sod. so izpostavili, da je treba vsebnosti Ni pri vsebnosti Si med 2,5 in 4,5 mas. % omejiti na najv. 2,5 mas. %, da bi se izognili nastajanju perlita [19]. V tem delu pa smo vsebnosti perlita skoraj 10 % prilagodili z 2,0 mas. % Ni. Na podlagi ugotovitev v tem delu sklepamo, da z nikljem v preiskovanih količinah ni mogoče doseči homogenizacije mikro segregacije silicija. Predpostavlja se, da je vzrok za spodbujanje nastajanja perlita učinek niklja, ki spremeni kinetiko med evtektoidno transfrmacijo in tako preprečuje homogeno distribucijo Si. Vendar pa bi to lahko bila tudi posledica dejstva, da ni mogoče izračunati mikro segregacije Si ob prisotnosti Ni, saj je bilo upoštevano evtektično strjevanje. Nadaljnje študije bodo to dejstvo upoštevale. Posledično se bodo v prihodnjih raziskavah nastavljale nižje vsebnosti Ni, da bi izdelali popolnoma feritno matrico in tako zagotovili uravnoteženje profila mikro segregacije Si.

Predpostavlja se, da je mogoče učinek nastajanja super struktur FeSi, ki je opisan v 1. poglavju, zmanjšati z bolj homogenim profilom mikro segregacije Si. Na takšen način lahko Al postane koristno metalurško orodje, ki lahko vpliva na lokalno distribucijo

Henke, the Al content is limited by the formation of an Fe3AlC0.05 carbide above an Al content of 3.8 wt.% [18]. In addition, alloying of aluminum drastically reduces the casting properties, resulting in an elevated need for more complex process technology.

A similar effect on the microsegregation of Si was also supposed when nickel is added. Etching according to Klemm as well as EDX measurements provides first indications that Ni contents of 1.0 to 2.0 wt.% also have an impact on the local distribution of Si. For an Ni content of

1.0 wt.% an inversion of the Si segregation profile is obtained by EDX measurements. This result is qualitatively confirmed by Klemm etchings. Kleinkröger et al. point out that the Ni content at Si contents of 2.5 to 4.5 wt.% should be limited to 2.5 wt.% to avoid pearlite formation [19]. In the present paper, however, pearlite contents of nearly 10 % are adjusted by

2.0 wt.% Ni. Based on the findings of the present work, it is assumed that no homogenization of the silicon microsegregation can be achieved with nickel in the investigated contents. The reason is assumed to be the pearlite-promoting effect of nickel that changes the kinetics during eutectoid transformation and thus prevents a homogeneous distribution of Si. However, this could be the reason that is was not possible to calculate the Si microsegregation when Ni is present, since only the eutectic solidification was considered. Further studies will take this fact into account. For this reason, lower Ni contents are adjusted in further investigations in order to achieve a fully ferritic matrix and thus to achieve a leveling of the Si microsegregation profile.

It is assumed that the effect of FeSi superstructures formation, described in Section 1, can be reduced by a more homogeneous microsegregation profile

Si. Območja v neposredni bližini precipitatov grafita veljajo za kritična, saj lahko pod obremenitvijo v njih nastanejo razpoke.

Skozi preiskave v tem prispevku še ni uspelo potrditi neposrednega razmerja med modifikacijo profila mikro segregacije Si in makroskopskimi mehanskimi lastnosti, kot je žilavost. Dodatek 0,3 mas. % Al vodi v povečanje energije udara v preiskovanem temperaturne razponu, kar je posledica bolj homogenega profila mikro segregacije Si. Podobnega učinka ni bilo mogoče opaziti pri dodatku Ni.

Nadaljnje raziskave se bodo posledično osredotočale na preučevanje mikro strukturnih učinkov na žilavost, npr. učinek nizkih vsebnosti perlita.

5 Sklepi

Cilj tega prispevka je bil preučiti učinke aluminija in niklja na mikro segregacijo silicija in določitev korelacije med lokalno distribucijo Si in izhajajoče makroskopske mehanske lastnosti. Rezultate je mogoče povzeti, kot sledi:

- tako numerične kot eksperimentalne preiskave dokazujejo učinek Al na profil mikro segregacije Si. Vsebnost Al 1,2 mas. % vodi do obratnega profila segregacije, medtem ko vsebnost Al 0,3–0,6 mas. % zagotovi homogenizacijo mikro segregacije Si,
- učinek lokalne distribucije Si zaradi legiranja z Ni bi lahko bilo mogoče potrditi tako z jedkanjem kot z meritvami EDX. Mehanizem tega učinka velja za formacijo perlita zaradi Ni. Tega učinka trenutno ni mogoče zapisati numerično, kajti upošteva se samo evtektična reakcija,
- bolj homogen profil mikro segregacije Si zaradi dodatka 0,3 mas. % Al vodi v zmerno povečanje energije udara.

of Si. In this way, Al can serve as a useful metallurgical tool that might influence the local distribution of Si. Areas directly at the graphite precipitates should be regarded as critical, as they act as potential crack initiation sites under load.

The investigations in this paper have not yet confirmed whether there is a direct relationship between the modification of the Si microsegregation profile and the macroscopic mechanical properties such as toughness. An addition of 0.3 wt.% Al results in an increased impact energy in the temperature range considered, which is attributed to a more homogeneous Si microsegregation profile. A similar effect could not be observed so far when Ni is added.

Future investigations will therefore aim to take a closer look at the microstructural effect on the toughness properties, such as the effect of low pearlite contents.

5 Conclusions

The aim of the presented work was to study the effects of aluminum and nickel on the silicon microsegregation and to determine a correlation between the local distribution of Si and the resulting macroscopic mechanical properties. The results can be summarized as follows:

- Both, numerical and experimental investigations indicate an effect of Al on the Si microsegregation profile. Al contents of 1.2 wt.% lead to a reversal of the segregation profile, while 0.3 – 0.6 wt.% Al result in a homogenization of the Si microsegregation.
- An effect on the local Si distribution due to alloying with Ni could be confirmed by both etchings and EDX measurements. The mechanism of this effect is assumed to be the pearlite formation

Vendar pa nadaljnjih vplivov na trdnost ni mogoče ugotoviti na podlagi razpoložljivih rezultatov.

Zahvale

Avtorji se za podporo iskreno zahvaljujejo Ingu Braunu, Dietmarju Lembrechtu in Dirku Freudenbergu, ki so sodelovali pri proizvodnji vzorcev, Elke Schaberger-Zimmermann za pomoč z metalografskimi analizami in Jessici Frieß za pomoč pri preiskavah s pomočjo elektronskega mikroskopa. Nenazadnje se avtorji zahvaljujejo organizaciji AiF (»Arbeitsgemeinschaft industrieller Forschungsvereinigungen«) za finančno podporo v okviru projekta IGF 20290 N, ki ga je financiralo Nemško zvezno ministrstvo za gospodarstvo in energijo na podlagi sklepa nemškega zveznega parlamenta.

due to Ni. This effect can currently not be represented numerically, since only the eutectic reaction is taken into account.

- A more homogeneous Si microsegregation profile due to an addition of 0.3 wt.% Al results in a moderate increase of the impact energy. However, further effects on the toughness properties cannot be derived from the available results.

Acknowledgements

The authors gratefully acknowledge the support of Ingo Braun, Dietmar Lembrecht and Dirk Freudenberg, who assisted the specimen production, Elke Schaberger-Zimmermann for assisting the metallographic analyses and Jessica Frieß for managing the electron microscopic investigations. Finally, the authors would like to thank the AiF ("Arbeitsgemeinschaft industrieller Forschungsvereinigungen") for the financial support within the IGF project 20290 N, which was funded by the Federal Ministry of Economics and Energy following a decision of the German Bundestag.

5 Viri / References

1. **DIN EN 1563**: *Gießereiwesen – Gusseisen mit Kugelgraphit* 2012.
2. **S. Seidel**. 2016. *Machbarkeitsstudie zur Herstellung von mischkristallverfestigtem ferritischem Gusseisen mit Kugelgraphit im Großguss*. In *Proceedings of the Deutscher Gießereitag*, Magdeburg 2016.
3. **W. Stets, H. Löblich, G. Gassner, P. Schumacher**. *Solution Strengthened Ferritic Ductile Cast Iron Properties, Production and Application*. International Journal of Metalcasting, 2014, 8(2), 35-40.
4. **K. Vollrath**. *Neue, hochinteressante Kugelgraphit Gusswerkstoffe*. Giesserei, 2013, 100, 70-73.
5. **K. Chailler, G. Regheere**. *Solid solution strengthened ferritic SG irons, Mischkristallverfestigung beim ferritischen Gusseisen mit Kugelgraphit*. Fonderie magazine, 2013, (39), 17-32.

6. **S. Liang, G. Erjun, W. Liping, L. Dongrong**. *Effects of Silicon on Mechanical Properties and Fracture Toughness of Heavy-Section Ductile Cast Iron*. Metals, 2015, 5, 150-161.
7. **L. E. Björkegren, K. Hamberg**. *Silicon Alloyed Ductile Iron with Excellent Ductility and Machinability*. Keith Millis Symposium on Ductile Cast Iron, 2003.
8. **J. Goroncy**. *Neues Gusseisen wiegt Leichtbaudefizite auf*. In *vdi-nachrichten.* 2004.
9. **P. Mikoleizik, G. Geier**. *SiWind - Werkstoffentwicklung für Offshore-Windenergieanlagen im Multi-Megawatt-Bereich*. Giesserei, 2014, 9(101), 64-69.
10. **R. Boeri, F. Weinberg**. *Microsegregation of alloying elements in cast iron*. Cast Metals, 1993, 6(3), 153-158.
11. **J. E. Wittig, G. Frommeyer**. *Deformation and fracture behavior of rapidly solidified and annealed iron-silicon alloys*. METALLURGICAL AND MATERIALS TRANSACTIONS A, 2008, 39(2), 252-265.
12. **P. Weiß, A. Tekavčič, A. Bührig-Polaczek**. *Mechanistic approach to new design concepts for high silicon ductile iron*. Materials Science and Engineering A, 2018, 713, 67-74.
13. **B. Pustal, B. Böttger, A. Ludwig, P. R. Sahm, A. Bührig-Polaczek**. *Simulation of Macroscopic Solidification with an Incorporated One-Dimensional Microsegregation Model Coupled to Thermodynamic Software*. Metallurgical and Materials Transactions B, 2003, 34 (August), 411-419.
14. **J. Pelleg**. Brit. Foundrym, 1962, 349.
15. **M. S. Soiński, A. Jakubus**. *The Influence of Small Amounts of Aluminium on the Effectiveness of Cast Iron Spheroidization with Magnesium*. Archives of Fourndry Engineering, 2013, 13(3), 80-83.
16. **M. S. Soiński, A. Jakubus, P. Kordas, K. Skurka**. *The Effect of Aluminium on Graphitization of Cast Iron Treated with Cerium Mixture*. ARCHIVES of FOUNDRY ENGINEERING, 2014, 14(2), 95-100.
17. **M. S. Soiński, A. Jakubus, P. Kordas, K. Skurka**. *Characteristics of Graphite Precipitates in Aluminium Cast Iron Treated with Cerium Mixture*. ARCHIVES of FOUNDRY ENGINEERING,
2015, 15(1), 93-98.
18. **F. Henke**. *Aluminium im Gusseisen*. Giesserei-Praxis, 1966, 76-82.
19. **Patent** – *Cast iron composition for high stress applications comprises*. W. Kleinkröger, E.-P. Warnke.

J. Medved[1], M. Godec[2], I. Paulin[2], S. Kores[3], M. Vončina[1] (SLO)
[1] University of Ljubljana, Faculty of Natural Sciences and Engineering, Department for Materials and Metallurgy, Ljubljana, Slovenia
[2] Institut of Metals and Technology, Lepi pot 11, 1000 Ljubljana
[3] Talum Tovarna aluminija d. d. Kidričevo, Tovarniška cesta 10, 2325 Kidričevo, Slovenia

Kemijska, mehanska in toplotna obraba orodij ob stiku z aluminijevimi livnimi zlitinami

Chemical, Mechanical and Heat Wear of Tools in Cast Aluminium Alloys

Povzetek

Tlačno litje je eden od vodilnih livarskih postopkov v sodobni industriji. V primeru tlačnega litja je talina v stiku z orodjem, medtem ko pride do kemične interakcije med orodjem, izdelanim iz orodnega jekla, in talino. Poleg tega pride tudi do mehanske in toplotne obrabe orodij. Visoka produktivnost zahteva visoko odpornost na te dejavnike.

V raziskavi smo uporabili vzorce iz jekel UTOP MO1 in RAVNEX HD, da bi preverili njihovo odpornost proti obrabi v aluminijevih zlitinah Al99,7 in AlSi12. S tem namenom je bila izdelana laboratorijska naprava za testiranje dveh različnih orodnih jekel v dveh različnih aluminijevih zlitinah pri dveh različnih temperaturah 4 ure pri 75 vrtljajih na minuto. Posledica interakcije je rast reakcijske plasti, ki se tvori iz treh ali štirih plasti. Odpornost orodnega jekla UTOP MO1 je boljša v staljeni aluminijevi zlitini AlSi12 kot v Al99,7, medtem ko je obrabna orodnega jekla RAVNEX HD v aluminijevih zlitinah veliko slabša. Debelina interakcijskega sloja se poveča z naraščajočo temperaturo.

Ključne besede: interakcija orodno jeklo/staljeni aluminij, obrabna odpornost, interakcijska plast, intermetalne faze iz sistema Al-Fe

Summary

Pressure casting is one of the leading casting processes in the modern industry. In the case of pressure casting the melt is in contact with the tool, whereas the chemical interaction between the tools, made of hot-working tool steel, and the melt occur. In addition, mechanical and heat wear of the tools also occurs. High productivity requires high resistance to these factors.

For the experiment, samples from UTOPMO1 and RAVNEX HD were used to test their wear resistance in aluminium alloys Al99.7 and AlSi12. With this aim a laboratory device was designed to test two different tool steels in two different aluminium alloys at two different temperatures for 4 hours at 75 revolutions per minute. The result of the interaction is the growth of a reaction layer, which is formed from three or four layers. The wear resistance of UTOPMO1 tool steel is better in AlSi12 aluminium alloy than in Al99.7, whereas the wear resistance of RAVNEX HD tool steel is much worse in molten casting aluminium alloys. The thickness of the interaction layer increases with the rising temperature.

Keywords: interaction tool steel/molten aluminium, wear resistance, interaction layer, intermetallic phases from system Al-Fe

1 Uvod

V mnogih postopkih litja, zlasti pa pri tlačnem litju, je talina v stiku z orodjem. Med postopkom litja pride do kemične interakcije med orodjem, ki je izdelan iz jekla za delo v vtročem, in talino. Poleg tega pride tudi do mehanske in toplotne obrabe orodja. Za visoko produktivnost je potrebna velika odpornost na te dejavnike. Kemična interakcija se pojavi med orodnim jeklom in staljenim aluminijem, ki v skladu z binarnim faznim diagramom Fe-Al tvori intermetalne faze. Najpogostejši fazi sta Al_5Fe_2 in $Al_{13}Fe_4$ (Al_3Fe), ki tvorita reakcijsko plast. Da bi dosegli optimalne mehanske in fizikalne lastnosti orodja, je treba omejiti oziroma preprečiti tvorbo interakcijskega sloja, hkrati pa je potrebno poznati tudi mehanizme nastanka.

Jekla, uporabljena v naši raziskavi, so UTOP MO1 (H11) in RAVNEX HD (SIJ Metal Ravne), ki se pogosto uporabljajo v skupini orodnih jekel za delo v vročem, kjer je glavni legirni element krom. Ta orodna jekla imajo visoko stopnjo utrjevanja zaradi sorazmerno nizke austenitizacijske temperature, ki je približno 1020 °C, dobro odpornost proti oksidaciji, odpornost na toplotno utrujanje, odpornost proti eroziji v kontaktu s tekočim aluminijem itd.[1,2]. Trdota po utrjevanju znaša med 50 in 56 HRC, po kaljenju s sekundarnim kaljenjem pa lahko dosežemo podobno trdoto. V ta namen je jeklo legirano s kromom, molibdenom in vanadijem, ki s precipitacijo sekundarnih karbidov utrdijo matrico. Po kaljenju dosežemo optimalno kombinacijo trdote in duktilnosti. Jeklo UTOP MO1 se uporablja za orodja za vroče kovanje, orodja za litje, orodja za izsekovanje in za izdelavo nožev, RAVNEX HD pa se večinoma uporablja za orodja za tlačno litje[2].

Odpornost proti obrabi, ki močno vpliva na življenjsko dobo orodnega jekla v stiku

1 Introduction

In many casting processes, especially in high pressure die casting, the melt is in contact with the tool. During the casting process the chemical interaction between the tool, made of hot-working tool steel, and the melt occurs. In addition, mechanical and heat wear of the tools also occurs. For a stong productivity a high resistance to these factors is required. The chemical interaction occurs between tool steel and molten aluminium, which forms intermetallic phases in accordance with the binary phase diagram Fe-Al. The most common phases are Al_5Fe_2 and $Al_{13}Fe_4$ (Al_3Fe), which form a reaction layer. In order to achieve the optimal mechanical and physical properties of the tools, it is necessary to limit or to prevent the forming of interaction layers, whereas the mechanisms of origin have to be known.

The steels used in our study are UTOP MO1 (H11) and RAVNEX HD (SIJ Metal Ravne) and are commonly used in the group of hot-working tool steels, where the main alloying element is chromium. Investigated tool steels have a good hardenability from a relatively low austenitization temperature of about 1020 °C, a good resistance to oxidation, tempering resistance, resistance to erosion with liquid aluminium, etc.[1,2]. Hardness after hardening is between 50 and 56 HRC, and after tempering with secondary hardening a similar hardness can be achieved. For this purpose, the steel is alloyed with chromium, molybdenum and vanadium, which, by precipitating secondary carbides, harden the matrix. After tempering, an optimal combination of hardness and ductility is achieved. The steel UTOP MO1 is used for hot-forging tools, die casting tools, punching tools and for production of knives and RAVNEX HD is s tekočim aluminijem, je odvisna od treh dejavnikov:

1. mehanski: zaradi visoke hitrosti in temperature taline med litjem v forme iz orodnih jekel pride do erozije materiala s površine orodja. Litje aluminija povzroča izmenične mehanske napetosti, kar vodi do zmanjšanja mehanskih lastnosti in do razpada[3];

2. kemični: zaradi raztapljanja atomov železa in drugih zlitinskih elementov iz orodnega jekla pride v aluminiju do tvorbe intermetalnih faz na medfazni površini med orodnim jeklom in tekočim aluminijem. Nastale intermetalne faze imajo različne fizikalno-kemijske lastnosti, kot pa osnova[4];

3. toplotni: toplotna utrujenost nastane zaradi porabe in krčenja jekla med delovnimi cikli pri litju aluminija. Orodje je običajno segreto na 400 °C, temperatura pa se lahko dvigne tudi do 700 °C. V tem primeru se površinske plasti jekla razširijo, kar je v nasprotju z notranjostjo jekla, posledično se na površini pojavijo tlačne, v jedru pa natezne napetosti. Ko odstranimo ulitek iz orodja, orodje mažemo z ločilnim sredstvom, ki orodje močno ohladi, kar povzroči natezne napetosti na površini in tlačne napetosti znotraj orodja. Te napetosti so zelo visoke in so blizu končne trdnosti orodnega jekla za delo v vročem. Ker je uporaba orodja ciklična in se ta postopek ponovi več kot deset tisočkrat, se na orodju pojavijo razpoke[1].

Na mejnih plasteh nastanejo intermetalne faze jekla/staljenega aluminija kot posledica kemijske reakcije orodnega jekla in aluminijeve taline. Pogoj za nastanek faz je optimalno omočenje in difuzija, ki izhaja iz razlike med kemijskimi potenciali elementov v tekočem aluminiju in trdnem orodnem jeklu. Na mejni fazi med trdnimi jeklenimi in intermetalnimi fazami, atomi aluminija in železa reagirajo in tvorijo nove intermetalne faze z uporabo atomov

mostly used for tools for high pressure die casting[2].

The wear resistance, that strongly affects the life of the tool steel in contact with liquid aluminium, depends on three factors:

1. Mechanical: due to the high speed and temperature of the melt during casting into permanent moulds from tool steels, erosion of material from the surface of the tool occurs. Aluminium die- casting produces alternating mechanical stresses, which leads to a reduction in mechanical properties and decay[3].

2. Chemical: due to the dissolution of iron atoms and other alloying elements from the tool steel in aluminium, the formation of intermetallic phases on the interphase surface between tool steel and liquid aluminium occurs. The resulting intermetallic phases have different physicochemical properties as the basis[4].

3. Heat: thermal fatigue occurs due to expending and shrinking of steel during working cycles at aluminium die-casting. The tool is usually preheated to 400 °C, but the temperature can rise to 700 °C. In this case, the surface layers of steel are expanded, which is in contrary to the interior of the steel, consequently on the surface the compression and at the core the tensile stresses appear. When the casting is removed from the tool, the tool is lubricated with a separating agent, which greatly cools the tool, causing tensile stresses on the surface and compression stresses inside the tool. These tensions are very high, close to the ultimate strength of the hot-working tool steel. Since cyclic use of the tool, this process repeats more than ten thousand times, cracks on the tool occur[1].

At the boundary layer tool steel/molten aluminium intermetallic phases as a result of the chemical reaction of the tool steel and aluminium melt are generated. The trdnih kovin, kar povzroča premikanje fazne meje v smeri orodnega jekla[5]. Poleg atomov železa in aluminija so v mejni (reakcijski) plasti prisotni tudi drugi zlitinski elementi, zlasti legirani elementi orodnega jekla, kot so silicij, mangan, krom, molibden in vanadij. Ti elementi na splošno zmanjšujejo debelino intermetalne plasti, največji učinek pa ima silicij. Rast intermetalne faze Al_5Fe_2 poteka prednostno v smeri [001] z difuzijo skozi prosta mesta in ima zato visoko orientirano morfologijo v obliki jezika. Raziskave[6,7,8] so pokazale, da je v fazi Al_5Fe_2 v tej smeri delež prostih mest 30 %. Domneva se, da atomi silicija zasedajo mesta v intermetalni fazi Al_5Fe_2, kar povzroča izkrivljanje kristalne rešetke in zmanjšanje aktivacijske energije. Da bi zmanjšali vsebnost prostih mest v Al_5Fe_2, se zmanjša tudi difuzijski koeficient železa in aluminija v fazi Al_5Fe_2 in posledično kinetika tvorbe intermetalnih faz. Posledično se spremeni morfologija faze Al_5Fe_2, znotraj te faze pa se tvorijo drobni delci τ_1/τ_9, značilni za trojni sistem Al-Fe-Si[9]. Selverian et al. [10] so odkrili, da dodajanje silicija v talino aluminija in cinka močno zmanjša eksotermičnost reakcije med aluminijem in jeklom, na katero se nanaša mazivo, saj silicij tvori trdno reakcijsko plast, ki deluje kot pregrada med jeklom in talino. Pregrada močno omejuje difuzijo atomov aluminija in železa, tako da se reakcijska kinetika močno zmanjša.

V študiji prednostne rasti Fe-Al intermetalnih faz v temperaturnem območju med 600–1050 °C, s poudarkom na tvorbi faz Fe_3Al in FeAl, so ugotovili, da se ti dve fazi pojavita le pri temperaturah nad 1000 °C. Faza Fe_3Al in FeAl imata večjo vsebnost železa, zato je njihova obrabna odpornost boljša. Nasprotno pa je dokazano, da se faze $FeAl_2$, Fe_2Al_5, in $FeAl_3$ tvorijo pri temperaturah pod 1000 °C in imajo višjo

condition for the formation of phases is the optimal wetting and diffusion, resulting from the difference between the chemical potentials of the elements in liquid aluminium and solid tool steel. At the phase boundary between solid steel and intermetallic phases, atoms of aluminium and iron react and form new intermetallic phases, using solid metal atoms, causing the movement of phase boundary in the direction of tool steel[5]. In addition to the atoms of iron and aluminium, other alloy elements, in particular the alloying elements of the tool steel, such as silicon, manganese, chromium, molybdenum and vanadium, are also present in the boundary (reaction) layer. In general, these elements reduce the thickness of the intermetallic layer, whereas the greatest effect has silicon. The growth of the intermetallic phase Al_5Fe_2 takes place preferably in the direction [001] by diffusion through the vacancies, and therefore have a highly oriented morphology in the form of a tongue. Researches[6,7,8] showed that the proportion of vacancies in this direction for the phase Al_5Fe_2 is 30 %. It is assumed that silicon atoms occupy gaps in the intermetallic phase Al_5Fe_2, causing the distortion of the crystal lattice and the reduction of activation energy. In order to reduce the vacancies content in Al_5Fe_2, the diffusion coefficient of iron and aluminium in the phase Al_5Fe_2 and, consequently, the kinetics of the formation of intermetallic phases, is also reduced. As a consequence, the morphology of the Al_5Fe_2 phase changes, and inside this phase fine particles τ_1/τ_9, characteristic for the ternary Al-Fe-Si system, are formed[9]. Selverian et al.[10] have discovered, that the addition of silicon to the melt of aluminium and zinc greatly reduces the exothermic nature of the reaction between aluminium and steel on which the lubricant is applied, since silicon forms a solid reaction layer acting as a barrier between steel and melt.

vsebnost aluminija. Te faze so krhke in zato manj obstojne[11,12].

Pri preučevanju interakcijskega sloja med legiranim jeklom H13 v talini zlitine AlSi9Cu3 in pri kontaktnem času 500 s je bilo dokazano, da debelina intermetalne plasti hitreje raste pri višjih temperaturah in istem kontaktnem času[13]. S časom se debelina intermetalnih plasti poveča, hitrosti rasti intermetalnih faz pa se spreminjajo. Dokazano je, da rast faze Fe_2Al_5 poteka po paraboličnem zakonu, kar na začetku (v kratkem času testiranja) ne velja. Rast fazne meje na podlagi $FeAl_3$ faze poteka linearno glede na čas[14].

S tem ciljem je bil preučen vpliv medsebojnega delovanja dveh različnih aluminijevih zlitin in orodnih jekel za delo v vročem. Preučena je bila obraba vzorcev vroče obdelanih orodnih jekel UTOP MO1 in RAVNEX HD in reakcijska plast, ki je bila vzpostavljena na meji med tekočim aluminijem in jeklom, kot rezultat kemijske reakcije. Poskusi so bili izvedeni na posebej zasnovani napravi, medtem ko so bili vzorci metalografsko analizirani, z namenom določitve interakcije.

2 Eksperimentalno delo

Za eksperimentalne vzorce so bili uporabljeni vzorci iz orodnega jekla, katerih kemična sestava je prikazana v tabeli 1.

Shema uporabljenega vzorca je prikazana na sliki 1a. Poskusi so bili izvedeni na laboratorijski napravi, prikazani na sliki 1b. Napravo sestavljajo talilna peč z električnim uporom s krmilnim sistemom, s katerim se vzdržuje konstantna temperatura; nosilec, na katerega je bil nameščen elektromotor in keramični lonček za talino. Eksperimentalni vzorec je pritrjen na elektromotor s pomočjo jeklene ali

The barrier greatly limits the diffusion of the atoms of aluminium and iron, so that the reaction kinetics is greatly reduced.

In the study of the preferred growth of Fe-Al intermetallic phases in the temperature range between 600–1050 °C, with the emphasis on the formation of Fe_3Al and FeAl phases, it was found that these two phases occur only at temperatures above 1000 °C. Fe_3Al and FeAl phases have a higher iron content, and therefore their wear resistance is better. Conversely, it has been shown that the $FeAl_2$, Fe_2Al_5, and $FeAl_3$ phases are formed at temperatures below 1000 °C and have a higher aluminum content. These phases are fragile and therefore less persistent[11,12].

In the study of the interaction layer between the H13 alloy steel in the alloy melt AlSi9Cu3 and at the contact time of 500 s, it was demonstrated that at higher temperatures and the same experiment time, the thickness of the intermetallic phase layer is growing faster[13]. With time, the thickness of the intermetallic phases in layer increases, whereas the growth rates of the intermetallic phases varies. It has been proven that the growth of the Fe_2Al_5 phase is carried out according to the parabolic law, which initially (at short testing time) does not apply to this law. The growth of the phase boundary on the basis of the $FeAl_3$ phase takes place linearly with respect to time[14].

With this aim, the influence of the interaction between two different aluminium alloys and hot- working tool steels was studied. The wear of the sample from the UTOP MO1 and RAVNEX HD and the reaction layer, which is established at the boundary between liquid aluminium and steel as a result of a chemical reaction, was investigated. Experiments were performed on a specially designed device, whereas the samples were metallographically analysed in order to determine the interaction.

Tabela 1. Kemijska sestava jekel UTOP MO1 in RAVNEX HD v masnih odstotkih v skladu z internim standardom SIJ Metal Ravne[2]

Table 1. Chemical composition of UTOP MO1 and RAVNEX HD in wt. % according to the internal standard SIJ Metal Ravne[2]

	C	Si	Mn	Cr	Mo	V	Ni
UTOP MO1	0,37	1,00	0,38	5,15	1,30	0,40	-
RAVNEX HD	0,36	0,30	0,40	5,00	1,7	0,60	1,65

grafitne palice, ki vrti vzorec s vrtenjem (vrt./min) v talini aluminijeve zlitine.

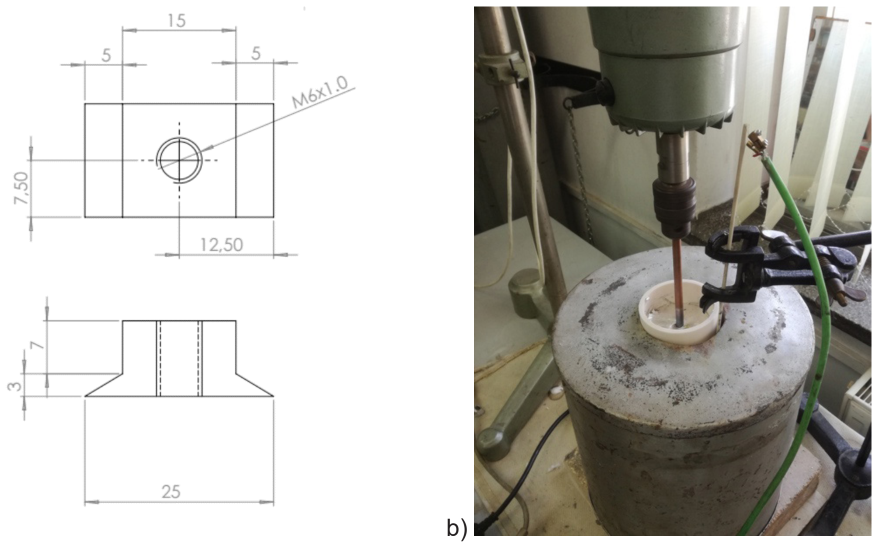
Najprej je bila Al-zlitina staljena v električni uporni peči. Vhodni parametri, uporabljeni med poskusi, so prikazani v tabeli 2. Ko je temperatura taline dosegla 670 ali 700 °C, se je vzorec dalo v talino, pri čemer je bila naprava za vrtenje vzorca vklopljena 4 ure pri 70 ali 150 vrt./min. Po končanem poskusu so bili vzorci vzeti iz peči in ohlajeni na zraku.

Za metalografsko analizo reakcijske plasti med jeklom in Al-zlitino so bili vzorci

2 Experimental Work

For the experiment samples from the tool steel were used, which chemical composition is shown in Table 1.

The scheme of the used sample is shown in Fig. 1a. The experiments were carried out on the laboratory device shown in Fig. 1b. The device consists of an electric resistant melting furnace with a control system with which a constant temperature was maintained, the carrier on which the electric motor was placed and the ceramic



a) b)

Sl. 1. Shematski prikaz vzorca orodnega jekla (a) in laboratorijske naprave za določanje interakcije med orodnim jeklom in tekočim aluminijem (b)

Fig. 1. Schematic representation of the tool steel sample (a) and laboratory device for determining the interaction between tool steel and liquid aluminium (b)

Tabela 2. Uporabljeni materiali in parametri za izvedbo poskusov

Table 2. Used materials and parameters to perform the experiments

Vzorec / Sample	Jeklo / Steel	Talina / Melt	Temperatura taline / Melt temperature [°C]	Rpm [min^{-1}]	Čas / Time [h]
1	RAVNEX HD	Al99,7	670	70	4
2	RAVNEX HD	Al99,7	700	150	4
3	UTOP MO1	Al99,7	670	150	4
4	UTOP MO1	Al99,7	700	150	24
5	UTOP MO1	AlSi12	600	70	4
6	UTOP MO1	AlSi12	700	70	4

prerezani na pol. Vzorci so bili pripravljeni po standardnem metalografskem postopku. Na mikroskopu Olympus BX 61 je bila izvedena svetlobna mikroskopija. Identifikacija faz in interakcijskih plasti v pregledanih vzorcih je bila izvedena na elektronskem mikroskopu (SEM) JEOL JSM-5610 na Naravoslovnotehniški fakulteti. Del SEM analiz pa je bilo opravljenih tudi na Inštitutu za kovinske materiale in tehnologije s SEM JSM-6500F.

3 Rezultati in diskusija

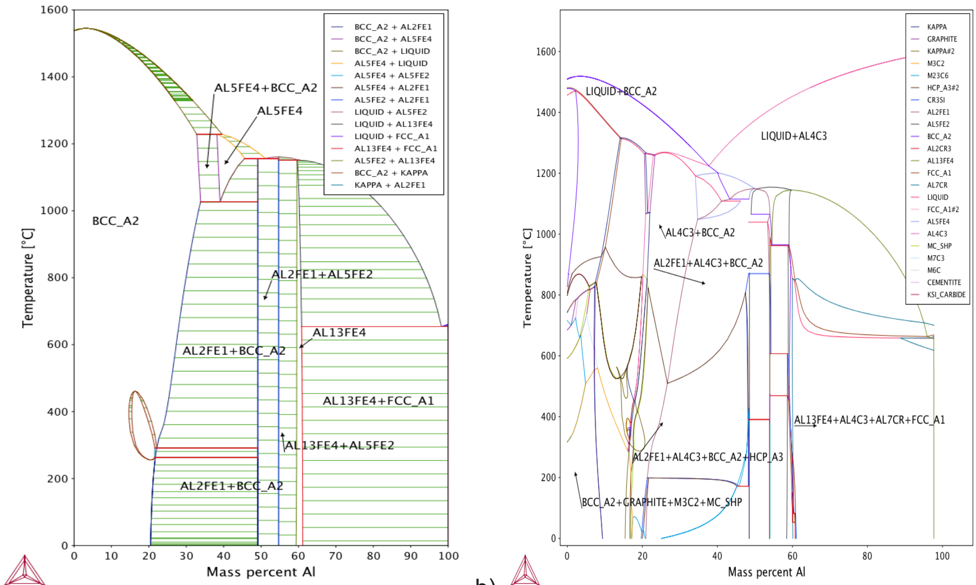
Interakcija med orodnim jeklom in staljenim aluminijem je bila termodinamično proučena z modeliranjem faznih ravnotežij in faznih diagramov. V sistemu Al-Fe so prisotne tri faze $Al_{13}Fe_4$, Al_5Fe_2 in Al_2Fe (slika 2a). V sistemu Al-Fe-C-Cr-Mo pa so poleg omenjenih binarnih faz prisotni tudi karbidi, pri čemer se lahko tvori tudi aluminijev karbid. Aluminij s kromom tvori fazo Al_7Cr, molibden pa Mo_3Al fazo (slika 2b).

Slika 3 prikazuje makro slike eksperimentalnih vzorcev jekla v zlitini Al99,7 in AlSi12. Vidna je oblika orodnega jekla, obdana z aluminijem. Že iz makro posnetkov se vidi reakcijsko območje med jeklom in aluminijem, pa tudi razpoke in poroznost zaradi krčenja med strjevanjem aluminija. Obraba vzorcev je različna in je

crucible for the melt. The experimental sample is fixed to an electric motor via a steel or graphite rod, which rotates the sample with a constant revolution per minute (rpm) in aluminium alloy melt.

Firstly, the Al-alloy was melted in an electric resistance furnace. The input parameters, which were used during the experiments, are shown in Table 2. When the temperature of the melt reached 600, 670 or 700 °C the sample was placed into the melt and the device for rotating the sample was turned on for 4 hours at 70 or 150 rpm. After the experiment was completed, the samples were taken from the furnace and left to cool in air.

For the metallographic analysis of the reaction layer between the steel and the Al-alloy, the samples were cut in half. The samples were prepared by standard metallographic procedure. Light microscopy was performed on the Olympus BX 61 microscope. The identification of phases and interaction layers in the examined samples was carried out on the scanning electron microscope (SEM) JEOL JSM-5610 at the Faculty of Natural Sciences and Engineering and JEOL JSM-6500F at the Institute for Metals, Materials and Technologies.



a) b)

Sl. 2. Fazna ravnotežja v sistemih Al-Fe (a) in Al-Fe-C-Cr-Mo (b)

Fig. 2. Phase equilibria in Al-Fe (a) and Al-Fe-C-Cr-Mo (b) systems

odvisna od temperature ter časa preskusa, kar je razvidno iz geometrije vzorca. Na obrabo ima večji vpliv število obratov kot temperatura. Največja obraba je razvidna iz vzorca 4, kjer je preskus trajal 24 ur.

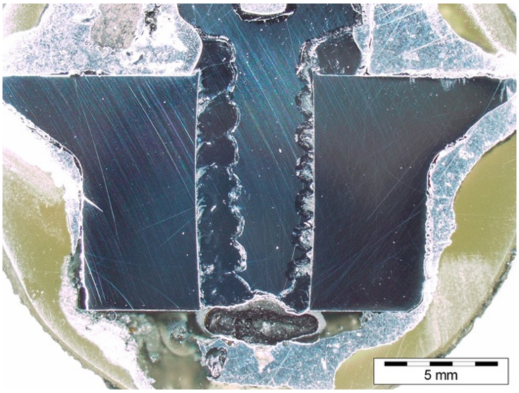
Vsi vzorci so bili analizirani po istem postopku. Mikrostrukture reakcijskih plasti med orodnim jeklom in Al99,7, odvzete na istem mestu (vrh in rob) vzorcev, so prikazane na sliki 4. Plast je sestavljena iz dveh območij. Na aluminijasti strani je plast najverjetneje sestavljena iz Al-Fe in Al-faze. Na jekleni strani pa je plast v obliki prstov, ki rastejo v jeklo. Pri aluminiju opazimo povečan delež železnih faz (igel).

Iz mikrostrukture vzorcev 1 in 2 je razvidno, da je vmesni reakcijski sloj pri vzorcu, ki je bil preizkušan pri višjih vrtljajih, porozen. Reakcijska cona je pri nižjih vrtljajih debelejša. Vzorca 2 in 4 smo preskusili pri višji temperaturi. Iz

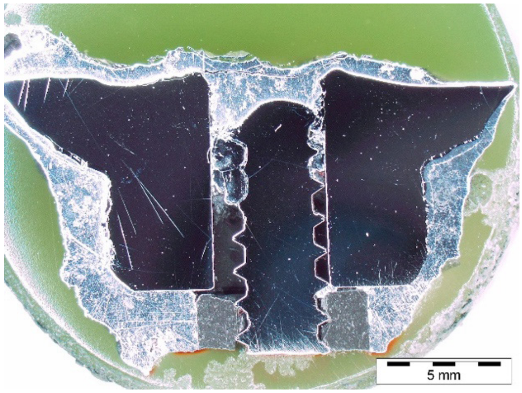
3 Results and Discussion

The interaction between tool steel and molten aluminium was studied thermodynamically by modelling phase equilibria and phase diagrams. There are three phases in the Al-Fe system: $Al_{13}Fe_4$, Al_5Fe_2 and Al_2Fe (Fig. 2a). In the Al-Fe-C-Cr-Mo system, besides the mentioned binary phases, there are also carbides, whereas the aluminium carbide can also be formed. Aluminium with chromium forms the Al_7Cr phase, and with molybdenum Mo_3Al phase (Fig.2b).

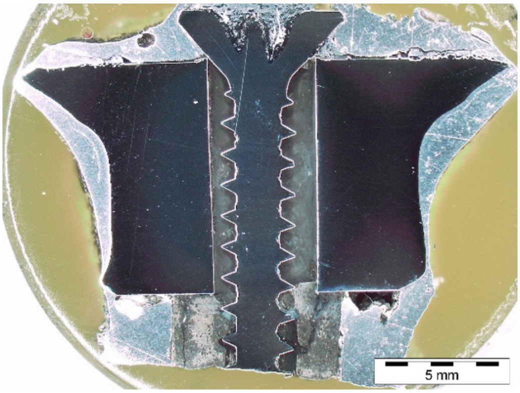
Fig. 3 shows macro images of tested steel specimens in alloy Al99.7 and AlSi12. The patterns of tool steel, surrounded by aluminium, are seen. Already from the macro shots, the reaction zone between steel and aluminium is seen, as well as cracks and porosity due to shrinkage during the hardening of aluminium. The wear of



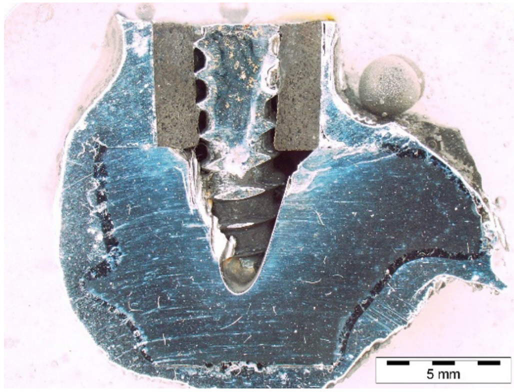
1: RAVNEX HD, Al99.7, 670 ºC, 70 min^{-1}, 4h



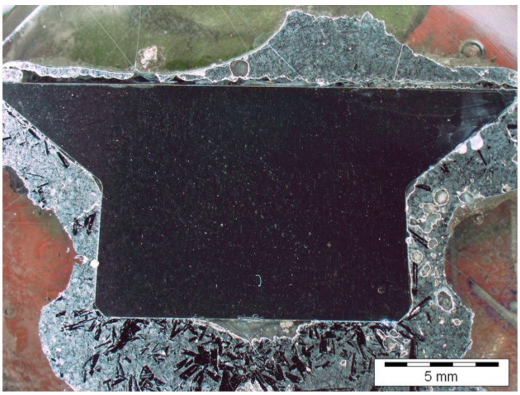
2: RAVNEX HD, Al99.7, 670 ºC, 150 min^{-1}, 4h



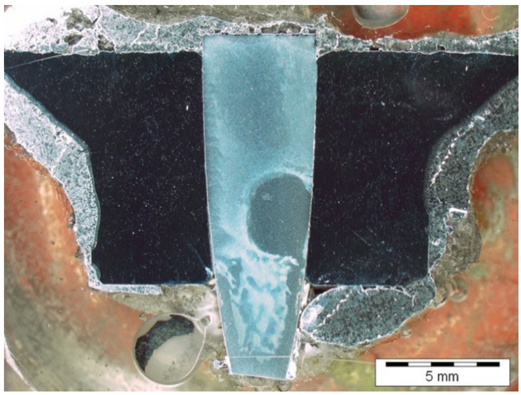
3: UTOP MO1, Al99.7, 670 ºC, 150 min^{-1}, 4h



4: UTOP MO1, Al99.7, 700 ºC, 150 min^{-1}, 24h



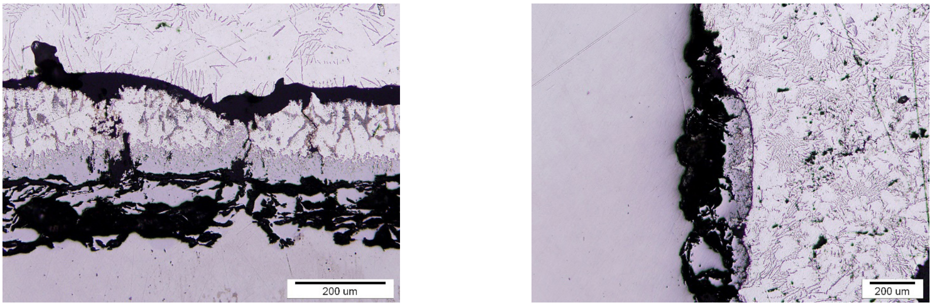
5: UTOP MO1, AlSi12, 670 ºC, 70 min^{-1}, 4h



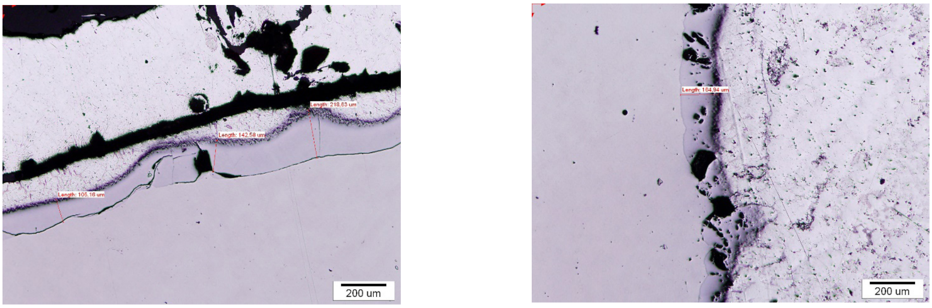
6: UTOP MO1, AlSi12, 700 ºC, 70 min^{-1}, 4h

Sl. 3. Makro posnetki preiskovanih vzorcev

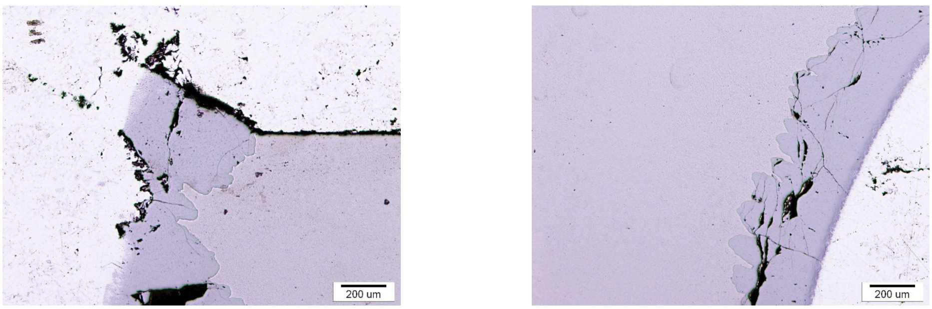
Fig. 3. Macro image of investigated samples



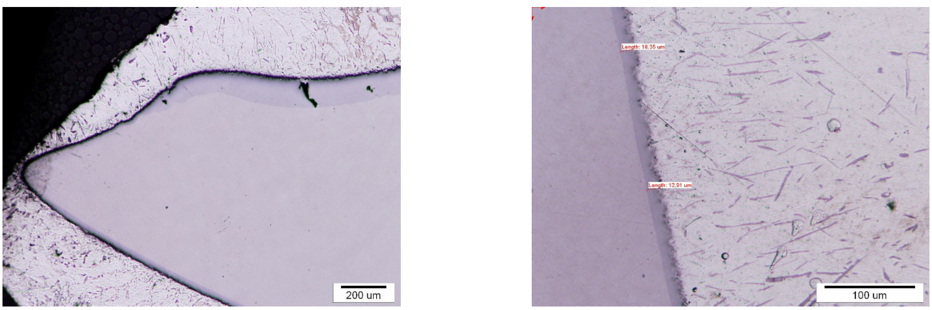
1: RAVNEX HD, Al99,7, 670 ºC, 70 min^{-1}, 4 h



2: RAVNEX HD, Al99,7, 670 ºC, 150 min^{-1}, 4 h



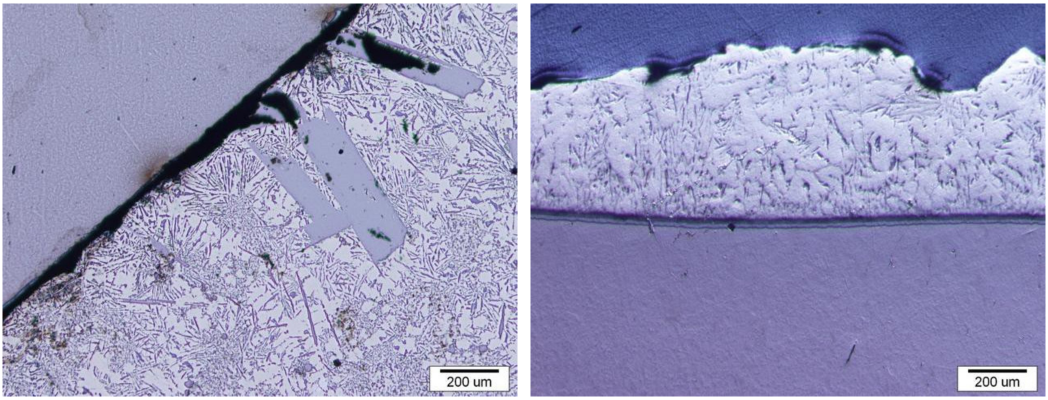
3: UTOP MO1, Al99,7, 670 ºC, 150 min^{-1}, 4 h



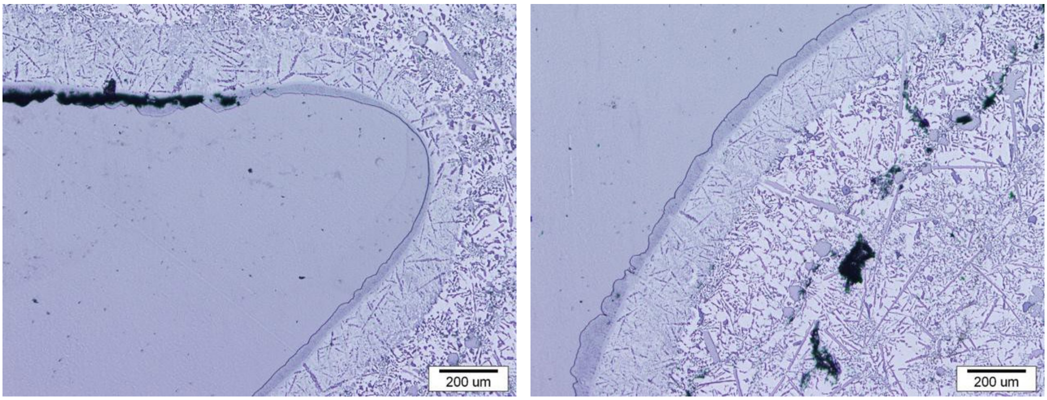
4: UTOP MO1, Al99,7, 700 ºC, 150 min^{-1}, 24 h

Sl. 4. Mikrostrukture reakcijskega sloja orodnega jekla/Al99,7

Fig. 4. Microstructures of the reaction layers tool steel / Al99.7



5: UTOP MO1, AlSi12, 600 ºC, 70 min^{-1}, 4h



6: UTOP MO1, AlSi12, 700 ºC, 70 min^{-1}, 4h

Sl. 5. Mikrostrukture reakcijskega jekla orodje jekla/AlSi12

Fig. 5. Microstructures of the reaction layers tool steel / AlSi12

mikrostrukture na sliki 4 je mogoče videti, da je reakcijska plast debelejša in ima večjo poroznost. V aluminiju se pojavijo razpoke takoj za plastjo s povečano železovo fazo v obliki igel.

Reakcijski sloj je razpokan, razpoke pa so vidne tudi v aluminiju, kjer opazimo obsežna območja evtektike (največ raztopljenega železa). Po razpokah reakcijske plasti se reakcijski sloji razgradijo in pomešajo s tekočim aluminijem. Takšne faze potrebujejo veliko časa, da se raztopijo v aluminiju. Odpornost jekla UTOP MO1 je the samples is different and depends on the temperature and the time of the test, as can be seen from the geometry of the sample. The wear is more influenced by rpm than the temperature. The highest wear can be seen from sample 4, where the experiment lasted for 24 h.

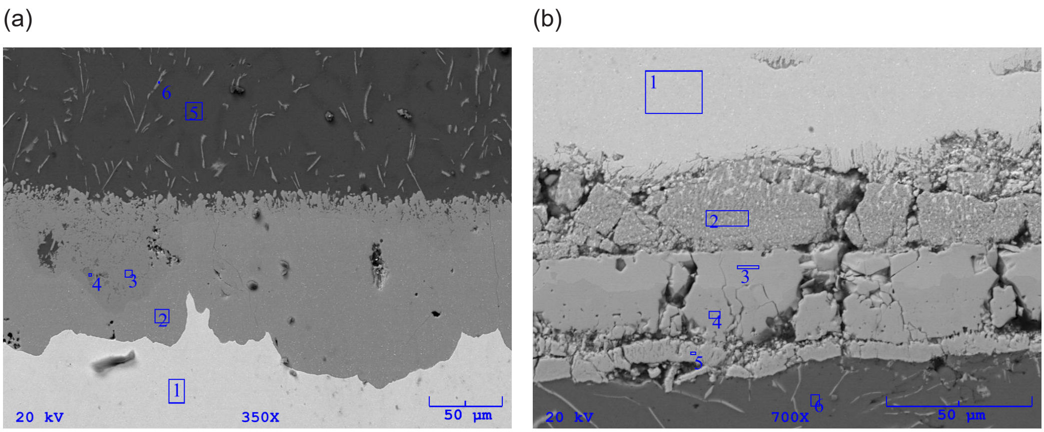
All samples were analysed by the same procedure. Microstructures of reaction layers between tool steel and Al99.7 taken in the same place (top and edge) of the samples are shown in Fig. 4. The layer is composed of two sections. On the višja v primerjavi z jeklom RAVNEX HD zaradi tanjše reakcijske plasti in manjšega deleža razpok.

Za primerjavo je bila preizkušena odpornost proti obrabi UTOP MO1 v aluminijevi zlitini AlSi12 pri temperaturi 600 in 670 °C (slika 5). Reakcijska plast vzorca 5 (nižja temperatura) je oblikovana iz enakomerne plasti. Veliko debelejši reakcijski sloj je viden pri vzorcu 6 (višja temperatura), ki je sestavljen vsaj iz treh različnih slojev. Ocenjeno je bilo, da se delež železa v aluminiju blizu fazne meje poveča zaradi boljše difuzije železa, medtem ko vsaj ena plast vsebuje tudi večji delež silicija.

Na sliki 6, na kateri je prikazan SEM posnetek z EDS analizo vzorca 1, opazimo v staljenem aluminiju rast intermetalnih Fe-faz v obliki jezika. Razlikujemo dve različni plasti, ena je kompaktna, nekoliko svetlejša in debelejša (bližje jeklu), druga pa v obliki aluminium side, most likely it consists of Al-Fe and Al-phase. On the steel side there is a layer in the form of fingers that grow into steel. An increased proportion of iron phases (needles) is observed in aluminium.

From the microstructure of the samples 1 and 2, the intermediate reaction layer is porous in sample tasted at higher rpm. The reaction zone at lower rpm is thicker. Samples 2 and 4 were tested at a higher temperature. From the microstructure in Fig. 4 it can be concluded that the reaction layer is thicker, with more porosity. In the aluminium, cracks appear immediately behind the layer with an increased Fe-based needle phase.

The reaction layer is cracked, and cracks are also visible in aluminium, where extensive areas of eutectics (most dissolved iron) are observed. Such phases need a lot of time to dissolve in aluminium. The resistance of steel UTOPMO1 is higher



(a)
1 (mas.%): Cr 4,5, Mo 1,8, V 0,71, Fe ostalo
2 (mas.%): Fe 45, Cr 2,7, Mo 0,73, Al ostalo
3 (mas.%): Fe 37, Cr 2,2, Mo 0,72, Al ostalo
5 (mas.%): Al 100
6 (mas.%): Al 91, Fe 9

(b)
1 (mas.%): Cr 4,7, Mo 1.8, V 0,6, Fe ostalo
2 (mas.%): Cr 10,2, Mo 4,1, V 1,3, Si 0,9, Fe ostalo
3 (mas.%): Cr 0,3, O 4,6, Fe ostalo
5 (mas.%): O 5,6, Fe ostalo
6 (mas.%): Fe 0,5, Al ostalo

Sl. 6. Mikroposnetki in EDS analiza interakcijskega sloja v vzorcu 1 (a) in 4 (b)

Fig. 6. Micrograph and microanalysis of the interaction layer in the sample 1 (a) and 4 (b)

igel ali jezika. EDS analize predstavljajo: 1 – sestava jekla, 2 - faza Al-Fe v stiku z orodnim jeklom z večjim deležem kroma, 3 in 4 - faza Al-Fe z manjšo količino železa bližje aluminiju, 5 - sestava aluminija in 6 – Fe-faza iz aluminija. Koncentracija aluminija je večja v območju plasti, ki je bližje aluminijevi zlitini, ki je lahko faza $Al_{13}Fe_4$ in se zmanjša, ko je bližje jeklu, kar bi lahko bila faza Al_5Fe_2. Plast bližje aluminiju je razdrobljena, pri čemer se železo raztopi v staljenem aluminiju v obliki igel iz Fe-faze.

Slika 6. predstavlja mikrostrukturo in mikroanalizo vzorca 5 in 6, kjer je orodje jeklo UTOP MO1 v stiku z zlitino AlSi12.

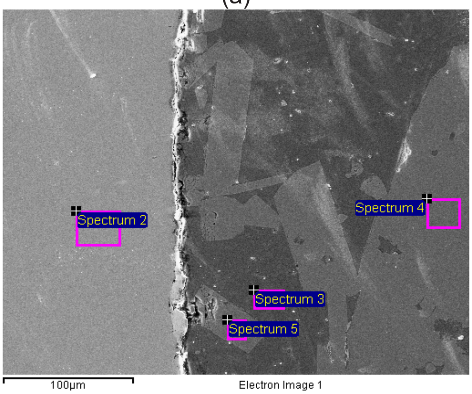
V vzorcu 5 (slika 7 (a)) je reakcijska plast tanka z široko plastjo raztopljenih Fe-faz v zlitini AlSi12. Pri višji temperaturi je obraba vzorca veliko večja, reakcijski sloj je sestavljen iz treh plasti, kar je razvidno iz mikrostrukture in mikroanalize EDS. Večje Fe-faze plavajo v aluminijevi zlitini.

compared to steel RAVNEX HD due to a thinner reaction layer and a smaller fraction of cracks.

For comparison, the wear resistance of UTOPMO1 in AlSi12 aluminium alloy at a temperature of 600 and 670 °C was tested (Fig. 5). Reaction layer of sample 5 (lower temperature) is formed from thin end even layer. A much thicker reaction layer is seen by sample 6 (higher temperature), which is composed at least from three different layers. It was estimated that the proportion of iron in aluminium near the phase boundary is increased due to better diffusion of iron, whereas at least one layer contains also higher portion of silicon.

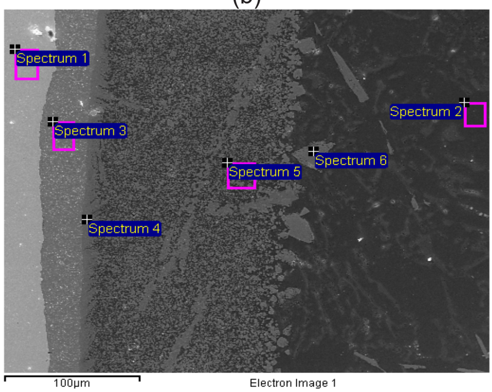
In the case of sample 1 in Fig. 6, the growth of intermetallic Fe-phases in molten aluminium is observed in the form of a tongue. Two different layers, one is compact, slightly brighter and thicker (closer to steel), and the other in the form

(a)



2 (mas.%): Cr 5,7, Mo 2.2, Si 1,1, Al 0,9, Fe ostalo
3 (mas.%): Fe 1,2, Si 15,4, Al ostalo
4 (mas.%):, Fe 26, Si 17,4, Al ostalo
5 (mas.%): Fe 28, Si 16,3, Al ostalo

(b)

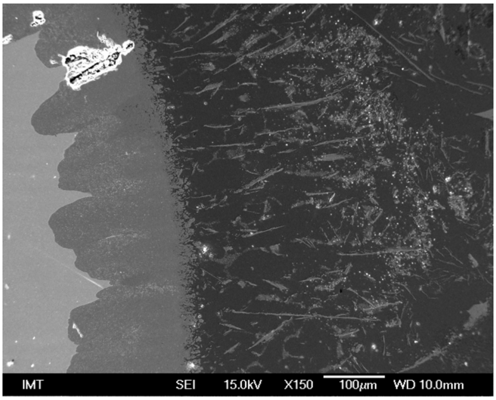


1 (mas.%): Cr 5,3, Mo 1,4, Si 1,1, Al 1,1, Fe ostalo
2 (mas.%): Si 2,7, Al ostalo
3 (mas.%): Fe 42, Cr 2,4, Si 4,5, Al ostalo
4 (mas.%): Fe 27, Cr 2.0, Si 14, Al ostalo
5 (mas.%): Fe 9,9, Cr 1,7, Si 15, Al ostalo
6 (mas.%): Fe 24, Cr 1,4, Si 10, Al ostalo

Sl. 7. Mikroposnetki in EDS analiza interakcijskega sloja v vzorcu 5 (a) in 6 (b)

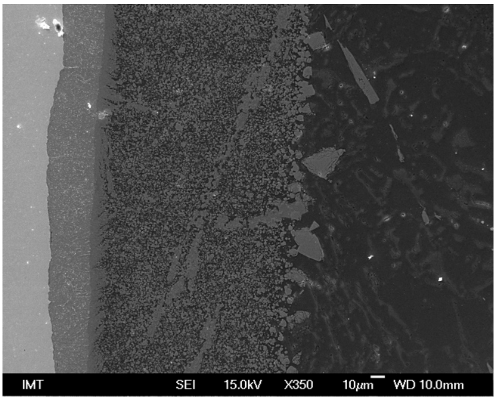
Fig. 7. Micrograph and microanalysis of the interaction layer in the sample 5 (a) and 6 (b)

(a)



UTOP MO1, Al99.7, 700 ºC, 70 min^{-1}

(b)



UTOP MO1, AlSi12, 700 ºC, 70 min^{-1}

Sl. 8. Mikroposnetki interakcijskega sloja v vzorcu 3 (a) in 6 (b)

Fig. 8. Micrograph of the interaction layer in the sample 3 (a) and 6 (b)

Slika 8 predstavlja primerjavo mikrostrukture reakcijske plasti med vzorci 3 in 6; vzorec 3 (UTOP MO1) je bil preizkušan v zlitini Al99,7 in vzorec 6 (UTOP MO1) v zlitini AlSi12. Po debelini, morfologiji in kemični sestavi je reakcijska plast popolnoma drugačna. Formirane Fe-faze v vzorcu 3 so v obliki igel (tipa Al_3Fe) in v vzorcu 6 v obliki globulita (tipa AlFeSi).

of needles or tongue can be distinguished. Analyses represent: 1 - steel composition, 2 - Al-Fe-phase in contact with tool steel with a higher proportion chromium, 3 and 4 - Al-Fe-phase with smaller amount of iron closer to aluminium, 5 - composition of the aluminium and 6 – iron phase in aluminium. The concentration of aluminium is greater in the region of the layer closer to the aluminium alloy, which could be $Al_{13}Fe_4$ phase and decreases when closer to the steel, which could be Al_5Fe_2 phase. The layer closer to aluminium is fragmented, whereas iron dissolves in molten aluminium in the form of needles from Fe-phase.

Fig. 7 represents the microstructure and microanalysis of the sample 5 and 6 where the tool steel UTOP MO1 is in contact with AlSi12 alloy. At sample 5 (Fig. 7a), the reaction layer is thin with a wide layer of dissolved Fe - phases in the alloy AlSi12. At a higher temperature, the wear of the sample is much larger, the reaction layer is composed of three layers as seen from the microstructure and EDS microanalysis. Larger Fe-phases float in aluminium alloy.

Fig 8. represents a comparison of the microstructure of a reaction layer between samples 3 and 6, whereas sample 3 (UTOP MO1) was tested in aluminium 99.7 and sample 6 (UTOP MO1) was tested in AlSi12 alloy at the same temperature and rpm. The reaction zone is completely different regarding to thickness, morphology and chemical composition. Formed Fe-phases in sample 3 are in form of needles (Al_3Fe type) and in sample 6 in a globulite form (AlFeSi type).

4 Conclusions

It can be concluded that the stability of the hot-working tool steel RAVNEX HD and UTOP MO1, which are in contact with molten

4 Zaključek

Sklepamo lahko, da je stabilnost orodnega jekla za delo v vročem RAVNEX HD in UTOP MO1, ki sta v stiku s staljenim aluminijem, odvisna od več parametrov. Med orodnim jeklom in tekočim aluminijem hitro poteka reakcija, medtem ko nastane intermetalna reakcijska plast. Metalografske preiskave so pokazale nastanek intermetalnih Fe-faz, verjetno Al_5Fe_2 in $Al_{13}Fe_4$. Reakcijska cona je večplasten. Najverjetneje se faza Al_5Fe_2 pojavila na fazni meji z orodnim jeklom in je debelejša, medtem ko se faza $Al_{13}Fe_4$ tvori na fazni meji z aluminijem. V reakcijski plasti se raztopijo tudi drugi legirni elementi, kot sta krom in molibden. Poroznost in razpoke opazimo v reakcijski plasti, kar je še posebej opazno pri jeklu RAVNEX HD. Razpoke so bile prisotne tudi v območju aluminija zaradi večje koncentracije železa. Rezultati so pokazali povečano obrabo vzorcev, pri katerih je bilo število vrtljajev višje in/ali je bila temperatura višja. Reakcijska plast ni popolnoma enakomerna; na določenih mestih se lušči in je pri višji temperaturi debelejša. Železo iz orodnega jekla se skozi reakcijsko plast difundira v tekoči aluminij. Pri nasičenju nastajajo železne faze. Opaženo je bilo tudi, da med obrabo orodnega jekla sloj odstopa, posledično so manjši in večji delci železove intermetalne faze in vključkov orodnega jekla prešli v aluminijevo talino.

Zahvala

To delo so podprli Republika Slovenija, Ministrstvo za izobraževanje, znanost in šport ter Evropska komisija za evropski regionalni razvoj in je bilo narejeno v okviru programa Materiali in tehnologije za nove aplikacije (MARTINA, številka nepovratnih sredstev: C3330-16-529008).

aluminium, depends on several parameters. A reaction takes course rapidly between the tool steel and the liquid aluminium, whereas the intermetallic reaction layer forms. Metallographic investigations have demonstrated the formation of intermetallic Fe-phases, presumably Al_5Fe_2 and $Al_{13}Fe_4$. The reaction cone is multilayer. Presumably, phase Al_5Fe_2 appeared on the phase boundary with tool steel and is thicker, whereas phase $Al_{13}Fe_4$ forms on the phase boundary with aluminium. In reaction layer also other alloying elements like chromium and molybdenum dissolved. Porosity and cracks are observed in the reaction layer, which is especially noticeable for RAVNEX HD steel. Cracks were also present in the aluminium region due to the concentration gradient of iron. The results showed increased wear on samples where the rpm was higher and/or the temperature was higher. The reaction layer is not completely uniform; in certain places it is departed and is thicker at a higher temperature. Iron from tool steel diffuses through the reaction layer into liquid aluminium. At the saturation, iron phases are formed. It was also observed that during the wear of the tool steel, the layer departs. Consequently, the smaller and larger particles of the iron intermetallic phase and the inclusion of the tool steel go into the aluminium melt.

Acknowledgements

This work was supported by the Republic of Slovenia, the Ministry of Education, Science and Sport, by the European Commissionand the European Regional Development. This work was made within a frame of the program Materials and Technologies for New Applications (MARTINA, grant number: C3330-16-529008).

Reference

1 R. A. Mesquita, Tool Steels: Properties and Performance, CRC Press, Taylor & Francis Group, 2017, pp.258.

2 Steelselector: Steel SINOXX 4542, SIJ Metal Ravne, d.o.o., 2016, Accessible on Internet: https://steelselector.sij.si/steels/PK346.html,

3 A. Persson, J. Bergstrom, Influence of surface engineering of the performance of tool steels for die casting, Proceedings of the 6th International Tooling Conference: the use of tool steels: experience and research, (J. Bergström, G. Fredriksson, M. Johansson, O. Kotik, F. Thuvander), Karlstad University, 10-13 September 2002., Karlstad, Sweden, pp. 1003.

4 K. N. Obiekea, S. Y. Aku, D. S. Yawas, Effect of pressure on mechanical properties and microstructure of die cast aluminium A380 alloy, Journal of minerals and materials characterization and engineering, 2(2014), pp.248.

5 N. Tang, Experimental and theoretical research in interfacial reaction of solid Co with molten aluminium and its alloys, Transactions of nonferrous metals society of China, 25(2015)6, pp. 1715.

6 M. Yan, Z. Fan, Durability of materials in molten aluminium alloys, Journal of materials science, 36(2001), pp. 285.

7 F. Yin, M. Zhao, Y. Liu, Z., Li, Effect of Si on growth kinetics of intermetallic compounds during reaction between solid iron and molten aluminium, Transactions of nonferrous metals society of China, 23(2013)2, pp. 556.

8 S. Hwang, J. Song, Y. Kim, Effects of carbon content of carbon steel on its dissolution into a molten aluminium alloy, Materials science and engineering A, 390(2005)1-2, pp.437.

9 Y. Erarslan, Wear performance of in-situ aluminium matrix composite after micro-arc oxidation, Transactions of nonferrous metals of China, 23(2013)2, pp. 347.

10 J. H. Selverian, A. R., Marder, M. R., Notis, Reaction between solid iron and liquid Al-Zn Baths, Metallurgical Transactions A, 19(1988), pp. 1193.

11 I. I. Danzo, Y. Houbaert, K. Verbeken, Diffusion driven columnar grain growth induced in an Al–Si-coated steel substrate. Surface and coatings technology, 2014, Vol. 251, 15-20

12 A. Molinari, M. Pellizzari, G. Straffelini, M. Pirovano, Corrosion behaviour of a surface-treated AISI H11 hot work tool steel in molten aluminium alloy. Surface and coatings technology, 2000, Vol. 126, no.1, 31-38

13 M. Sundqvist, S. Hogmark, Effects of liquid aluminium on hot-work tool steel. Tribology international, 1993, Vol. 26, no. 2, 129-134

14 A. Bouayad, C. Gerometta, A. Belkebir, A. Ambari, Kinetic interactions between solid iron and molten aluminium. Materials science and engineering: A, 2003, Vol. 363, no. 1-2, 53-61

AKTUALNO / CURRENT

60. IFC Portorož 2020

60th IFC Portoroz 2020

Odločili smo se, da v tej številki Livarskega vestnika oziroma v tem prispevku o letošnji jubilejni 60. IFC in razstavi v Portorožu, ki je potekala od 16. do 18. septembra letos, podamo samo kratko splošno poročilo o dogodku z nekaj fotografskega materiala. V naslednji, 4. številki Livarskega vestnika pa bomo podrobno predstavili program predavanj in razstavljavce na razstavi.

Mednarodna livarska konferenca v Portorožu je z uspešno organizacijo, dobro mednarodno udeležbo ter zanimivi predavanji slavnostno obeležila svojo 60. letnico delovanja in ponovno potrdila svojo

Otvoritveni govor predsednice, mag. M. Jan Blažić

Opening Address from president Msc. M. Jan-Blazic

We decided to deliver in this issue of Livarski vestnik, a short general report about this year's jubilee 60th IFC and exhibition in Portoroz together with some photos. In the next, 4th issue of Livarski vestnik, we will present the lectures program and exhibitors in more detail.

International foundry conference, with successful organization, good international participation, and interesting lectures, celebrated it's 60th jubilee of working, and confirmed its successful and traditional integrating in world's foundry profession again. Already chosen slogan of this traditional international meeting of foundry experts: "Tradition and future", led to thinking that foundry has an outstanding tradition, and with respecting the fast scientific and technical development, great future as well. The main organizer of the conference was Slovenian foundrymen Society, collaborating with University of Ljubljana, Faculty of natural sciences and engineering and Faculty of Mechanical Engineering, University of Maribor.

Jubilee 60th IFC was attended formally by 172 participants, together from 12 different countries, which is for the time when the world is facing health problems of pandemic, an evidence of respect to one of

Foto Tihomir Sumić

Plenarno predsedstvo po otvoritvi: mag. A. Mikložič, MLM d.d., g. C. Töscher, Omco Metals Slovenia d.o.o., predsedujoči prof. dr. J. Medved in predsednica M. Jan-Blažić /

Plenary chairmen after the Opening; MSc. A. Mikložič, MLM d.d., g. C. Töscher, Omco Metals Slovenia d.o.o., chairperson prof. Dr. J. Medved and president , M. Jan-Blazic

uspešno ter tradicionalno vključevanje v svetovni prostor livarske stroke. Že izbran moto tega tradicionalnega mednarodnega srečanja livarskih strokovnjakov, »Tradicija in prihodnost«, je vodilo k razmišljanju, da ima livarstvo izjemno tradicijo, ob tem pa ob upoštevanju hitrega znanstvenega in tehniškega razvoja tudi prihodnost.

the world's oldest foundry conference, and knowing that Slovenia is leading by criteria 95 kg of produced castings by resident yearly.

Lectures on jubilee 60th IFC Portoroz 2020 were divided into 3 groups: Plenary lectures – together 10; Section A: Cast iron and casting technology – together 12;

Pogled na plenarno dvorano

View of the plenary hall

Glavni organizator posvetovanja je bilo Društvo livarjev Slovenije, ob sodelovanju Univerze v Ljubljani, Fakultete za naravoslovje in tehnologijo, ter Univerze v Mariboru, Fakultete za strojništvo.

Jubilejne 60. IFC se je udeležilo 172 udeležencev iz 12 držav, kar je za čas, ko se ves svet sooča z izjemnimi zdravstvenimi težavami, dokaz spoštovanja ene izmed najstarejših svetovnih livarskih konferenc in vedenja, da je Slovenija po kriteriju 95-kg proizvedenih ulitkov na prebivalca letno vodilna v svetu.

Predavanja na jubilejni 60. IFC Portorož 2020 so bila razdeljena v tri skupine: plenarna predavanja - skupaj 10; sekcija A: Litine železa in jekla ter tehnologije pomembne za livarstvo – skupaj 12 predavanj; sekcija B: Litine neželeznih zlitin - skupaj 11 predavanj. Ob 33 predavanjih je bilo še 8 predstavitev s posterji. Skupaj 41 predstavitev je zajelo zelo široko tematiko livarstva: raziskave in preizkušanje materialov, nove tehnološke rešitve, razvojne usmeritve, digitalizacija

dr. M. Vončina, povezovalka pri podelitvi medalj

dr. M. Voncina, announcer at the medal ceremony

Medalja DLS – umetniški livarski izdelek akademskega kiparja mag. Jureta Smoleta

Society's Medal – Artistic foundry product of academic sculptor MSc. Jure Smole

Section B: Non-ferrous alloys – together 11 lectures. Beside together 33 lectures, there were 8 poster presentations as well. Together 41 presentations captured very wide foundry thematic: researches and material testing, new technological solutions, development standpoints, digitalization of processes and technological procedures, additive technologies and circular economy. This conference as well was accompanied by foundry exhibition, with presentations from 40 companies.

The president of Slovenian foundrymen Society and organizational committee of IFC Portoroz, MSc. Mirjam Jan-Blazic, had an Opening Address, where she stressed the tradition of Slovenian foundrymen Society, its meaning for foundry growth, 67 years of publishing Slovenian technical magazine Livarski vestnik, and many collaborations with other foreign associations. After the speech, followed the Award ceremony – Slovenian foundrymen Society medals as a special recognition for collaboration and contributions to quality

Dobitniki medalj s predsednico mag. M. Jan-Blažić: prof.dr. P. Schumacher in G. Schindelbacher za ÖGI Leoben ; dr. K. Weiss, RWP GmbH; prof. dr. R. Döpp, TU Clausthal, emer. prof. dr. A. Križman, Univerza v Mariboru in mag. M. Debelak, DLS

Winners of the Society's medals, with the president MSc M. Jan-Blažić : Prof. Dr. P. Schumacher and Mr. G. Schindelbacher for ÖGI Leoben ; Dr. K. Weiss, RWP GmbH; prof. Dr. R. Döpp, TU ClPod sliko se popravi število razstavljvcev na 40austhal; emer. Prof. Dr. A. Križman, University of Maribor and MSc. M. Debelak, Society

procesov in tehnoloških postopkov, aditivne tehnologije ter krožno gospodarstvo. Tudi tokratno konferenco je spremljala razstava, na kateri je s svojo predstavitvijo sodelovalo 40 podjetij.

Uvodni nagovor je imela predsednica Društva livarjev Slovenije in predsednica organizacijskega odbora IFC Portorož 2020, mag. Mirjam Jan-Blažič, ki je izpostavila tradicijo Društva livarjev Slovenije, njen pomen za razvoj livarstva, 67 let izhajanja slovenske strokovne revije Livarski vestnik ter številna sodelovanja z društvi v drugih državah. Po nagovoru je sledila podelitev medalj Društva livarjev Slovenije ob 60. letnici IFC v Sloveniji, kot posebnega priznanja za sodelovanje in prispevek h kakovostni rasti te mednarodne konference, ki so ga prejeli: Oesterreichisches Giesserei Institut Leoben; dipl.ing. mont. Erich Nechtelberger; prof. dr. Reinhard Döpp, growth of this international conference, that went to: Austrian Foundry Research Institute Leoben, Dipl.-Ing. Mont. Erich Nechtelberger; Prof. Dr. Reinhard Döpp, Technical University of Clausthal Germany; Dr.-Ing. Konrad Weiβ, Executive director of RWP GmbH Germany; Emeritus Prof. Dr. Mont. Alojz Križman University of Maribor, Edidot-in-chief of Livarski vestnik and President of the Scientific Committee of IFC Portoroz; and MSc. Martin Debelak, longtime secretary of the Slovenian Foundry Society.

At the Acquaintance Evening, the night before the official start of the Conference with exhibition, at the Cultural Center Georgios' garden, next to the Cathedral church in Piran, the participants were traditionally greeted by the mayoralty of Municipality Piran. This year present was the deputy mayor, Mr. Karlo Radovac,

Prof. Dr. Döpp z zahvalnimi besedami v imenu prejemnikov medalj

Prof. Dr. Döpp expressing thanks in the name of all medal receivers

TUniversität Clausthal, Nemčija; dr. Konrad Weiβ, direktor RWP GmbH Nemčija; zaslužni prof. dr. Alojz Križman, Univerza v Mariboru, glavni in odgovorni urednik Livarskega vestnika in dolgoletni predsednik programskega odbora IFC v Portorožu; in mag. Martin Debelak, dolgoletni strokovni tajnik Društva livarjev Slovenije.

Na pozdravno-spoznavnem večeru na predvečer uradnega začetka konference in razstave na vrtu Kulturnega centra Georgius pri stolni cerkvi v Piranu je udeležence konference ter razstave tradicionalno pozdravilo županstvo Občine Piran. Letos se je srečanja udeležil podžupan, Karlo Radovac, kateremu je predsednica Društva izročila medaljo Društva livarjev Slovenije, ki jo je Izvršni odbor Društva livarjev podelil Občini Piran ob 60. jubileju za dolgoletno in zvesto sodelovanje ter podporo temu pomembnemu mednarodnemu livarskemu dogodku.

Navkljub dokaj zahtevnim pogojem, ki smo jim morali zadostiti zaradi varovanja pred korona virusom, so udeleženci letošnji livarski dogodek ocenili zelo pozitivno in nam kot organizatorjem namenili veliko

Podžupan Občine Piran, g. Radovac Karlo ob podelitvi medalje s predsednico DLS, M. Jan-Blažić

Deputy major of Municipality Piran, Mr. Karlo Radovac, with Society's president M. Jan-Blazic, at the medal ceremony

who received the Slovenian foundrymen Society medal from President of Society, that the Executive board decided to give to Municipality of Piran, at 60th anniversary, for long-time and loyal collaboration and support to this important international foundry event.

Despite relatively difficult conditions, that we had to fulfill to protect ourselves against coronavirus, the participants rated this year’s foundry event very positively, and gave us organizers a lot of praises, which is a big satisfaction for all our efforts that we put in the preparations for this event. The fact, that foundry experts have been able to socialize after months of standstill, is a

Livarska kulisa – cerkvena zvona iz leta 1921 na vrtu kulturnega centra Georgios, s prof. F. Kleinom in emer. prof. A. Križman

Foundry scenery – church bell from 1921, at the Cultural center Georgios, with Prof. F. Klein and emer. Prof. A. Krizman

pohval, kar nam je v veliko zadoščenje za ves trud in napore, ki smo jih vložili v fazi priprav in v času same izvedbe konference ter razstave. To, da smo se livarski strokovnjaki po kar nekajmesečnem zastoju lahko družili, je posebna dodana vrednost, ki so jo naši udeleženci iz Portoroža lahko v obliki veliko pozitivne energije odnesli domov, v upanju, da se tudi naslednje leto srečamo na

61. IFC in razstavi, v času od 15. do 17. septembra 2021.

Hvala še enkrat vsem, ki ste se skupaj z nami opogumili in tudi letos prišli v Portorož ter nam s tem izkazali zaupanje, da zmoremo ustrezno in predvsem varno organizirati tradicionalni livarski dogodek tudi v spremenjenih in zahtevnih pogojih.

Predsednik Programskega odbora IFC zasl. prof. dr. Alojz Križman

Predsednica Organizacijskega odbora IFC mag. Mirjam Jan-Blažić

special value that our participants were able to bring home, in a shape of positive energy. We are hoping to meet again next year, at

61st IFC with exhibition, at the time from 15th to 17th September 2021

Again, thank you all for stepping up and coming to Portoroz, and showing us your trust into that we can suitably and mainly safely organize this traditional foundry event, even in these difficult changed conditions.

President of Program-Scientific Committee IFC, Emer. Prof. Alojz Križman

President of Organizational Committee IFC MSc. Mirjam Jan-Blazic

IN MEMORIAM

IM MEMORIAM, dipl. ing. Erich Nechtelberger

Dipl. ing.
Erich Nechtelberger

V zadnjem koledarskem tednu septembra je bitko z nekaj letno boleznijo izgubil naš cenjeni stanovski kolega, velik livar po znanju in pripadnosti livarstvu, naš dolgoletni prijatelj in več desetletij redni udeleženec livarske konference v Portorožu ter častni član Društva livarjev Slovenije, **dipl. ing. Erich Nechtelberger.**

Januarja letos je praznoval svoj 83 osebni praznik. Najpomembnejše mejnike iz njegovega bogatega življenjepisa povzemamo v nadaljevanju.

Po študiju metalurgije na visoki šoli za montanistiko v Leobnu se je leta 1962 zaposlil kot asistent v preizkusni livarni Avstrijskega livarskega inštituta v Leobnu. Leta 1979 je bil imenovan za namestnika vodje Inštituta in leta 1983 za direktorja za praktične livarske raziskave kot tudi direktorja Avstrijskega livarskega inštituta. Že od leta 1989, ko se je upokojil je vodil rudarski svet za poklice Republike Avstrije.˝Leta 2001 je sprejel funkcijo namestnika predsedujočega direktorja Društva avstrijskih livarjev, leta 2002 pa redakcijo osrednjega avstrijskega livarskega časopisa »Giesserei-Rundschau« Že od 1960 leta dalje je bil član Društva livarjev Slovenije in s redkimi presledki reden .udeleženec našega tradicionalnega livarskega dogodka v Portorožu. Po sklepu organov Društva livarje Slovenije je bil imenovan za častnega člana Društva livarjev Slovenije in letos je bil tudi dobitnik medalja Društva livarjev Slovenije ob 60 jubileju mednarodne livarske konference v Sloveniji. V njegovi odsotnosti sta medaljo na otvoritvi 60. IFC Portorož 2020 prevzela člana poslovodstva OGI- Avstrijskega livarskega inštituta, dipl,ing. Gerhard Schindelbacher in prof. Peter Schumacher. Že od 1965 leta dalje je bil tudi član Društva nemških livarjev. Za posebne zasluge v livarstvu je leta 2010 prejel Bernhard-Osann medaljo VDG- Društva nemških livarjev. Vrsto let je v njegovem strokovnem delokrogu v ospredju bilo lito železo in lito železo z kroglastim grafitom.

Moje poznanstvo in stanovsko sodelovanje s Erichom Nechelbergerjem sega že v sedemdeseta leta prejšnjega stoletja. To se je še posebno poglobilo v zadnjih 15 letih mojega vodenja Društva livarjev Slovenije. Srečevala sva se zelo pogosto na vrsti livarskih dogodkov po svetu in kontinuirano izmenjevala pomembne strokovne informacije in si medsebojno pomagala s ocenami, pogledi ali raznimi potrebnimi rešitvami v danem trenutku. V vsakem trenutku je bil pripravljen vzeti čas in prisluhniti problemom, idejam ali dilemam. Erich je bil po naravi zelo umirjen in preudaren ter v prvi vrsti zelo zanesljiv in tudi po duši zelo dober človek.

Zato se ga bomo z velikim veseljem spominjali in črpali iz njegove bogate zakladnice dobrih delin idej rešitve in izkušnje, ki so še zmeraj zelo dragocene in aktualne. V imenu Društva livarjev Slovenije in v mojem imenu ti se, dragi Erich lepo zahvaljujem za pomemben prispevek, ki si ga tekom svojega zelo aktivnega življenja vlagal v napredek in nenehno rast livarstva in livarske stroke v svoji domači Avstriji, Sloveniji in drugih državah po svetu.

Predsednica Društva livarjev Slovenije
Mag. Mirjam Jan-Blažić

AKTUALNO / CURRENT

POKROVITELJI 60. IFC PORTOROŽ 2020

SILVER SPONSORS

OMCO OMCO METALS SLOVENIA d.o.o.

MAGMA

BRONZE SPONSOR

DiFA TLAČNA LIVARNA IN OBDELAVA ULITKOV

LTH Castings

LIVARNA MARIBOR

FOUNDRY

WORK BETTER. FASTER. SAFER.

When it comes to foundry applications, Weiler has the solutions!

Years of partnering with end users has driven our innovation efforts. To achieve the highest level of performance, Weiler's wheels are specially formulated based on work material properties.

Whether you are grinding gray cast iron or stainless steel, Weiler has the solution.

High performance foundry products for the most demanding jobs.

WEILER