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# Visoko in nizko legirana indefinitna železova litina: vpliv na mehanske lastnosti in mikrostrukturo

# High and low alloyed indefinite chill cast iron: impact on mechanical and microstructural properties

**Povzetek**

Kljub nenehnemu razvoju novejših, obstojnejših materialov za izdelavo delovnih plasti valjev za vroče valjanje ostaja indefinitna železova litina (ICDP) med bolj priljubljenimi in cenovno ustreznimi zlitinami. Najpogostejša uporaba ICDP litin je v primeru običajnih kontinuirnih valjarskih prog za valjanje v vročem (HSM) ter v primeru bluming in steckel ogrodij. K izboljšanju obstojnih lastnosti ICDP litin pripomore dodatek posebnih karbidotvornih elementov, kot so vanadij, niobij, titan in volfram. V tej raziskavi je predstavljen vpliv dodatka omenjenih elementov na razvoj mikrostrukture in mehanskih lastnosti (obrabna obstojnost, dinamična trdnost in odpornost na termično utrujanje). Rezultati kažejo, da se ob višjem dodatku karbidotvornih elementov (nad 1 mas. %) izboljšajo tako obrabna obstojnost, dinamična trdnost ob nižjih ciklih, kot tudi odpornost na termično utrujanje v smislu zmanjšanja števila in gostote termičnih razpok. Hkrati rezultati natezne trdnosti ne kažejo bistvenih razlik. Po drugi strani lahko visok dodatek karbidotvornih elementov vpliva na manjši delež izločenega grafita kot tudi na nastanek izjemno dolgih razpok, ki lahko vodijo do težav med valjanjem. Valji so po meri izdelani ulitki prilagojeni valjarskim pogojem posameznih naročnikov. Pri izdelavi takih izdelkov moramo upoštevati način in količino dodatka karbidotvornih elementov. Rezultati predstavljene raziskave lahko pomagajo pri doseganju zastavljenih parametrov.

**Ključne besede: indefinitna železova litina, mikrostruktura, liti valji, vroče valjanje, obraba, utrujanje**

**Summary**

As newer and improved materials are being constantly developed, indefinite chill cast iron (ICDP) remains one of the most suitable and cost efficient alloys used in cast rolls for last finishing stands of standard HSM, blooming or Steckel mills. Improvements of the ICDP alloy can be made by adding special carbide builders (SCB) such as vanadium, niobium, titanium and tungsten. The impact of these additions on microstructural development and mechanical properties of the ICDP working layer (wear resistance, dynamic strength and thermal fatigue resistance) has been studied. Research shows that by adding a higher amount (> 1 %, mass. fraction) of SCB wear resistance, dynamic strength at low cycles and thermal fatigue resistance in terms of reducing the number and density of cracks improved. Meanwhile tensile strength does not seem to change significantly. On the other hand, high SCB addition can inhibit graphite formation as well as cause severely long thermal cracks which can lead to problems during roll exploitation. As rolls are tailored to meet specific mill

conditions, a decision on the amount of SCB added must be made. Results of the presented study can help choose the appropriate amount in regards to the mill's demands.
**Key words: indefinite chill cast iron, microstructure, cast rolls, hot rolling, wear, fatigue**

## 1 Uvod

Pogoji na zadnjih ogrodjih v kontinuirnih valjarnah za vroče valjanje so zahtevnejši od začetnih ogrodij, zato je potreba po izboljšanju odpornosti na zlepljanje toliko bolj izražena. Melirana hipoevtektska sestava t. i. prilagojene Ni-hard zlitine dopolnjuje sestavo bele železove litine z izločki grafita. Na ta način se zagotovi dobre lastnosti proti zlepljanju kljub zmanjšanju obrabne obstojnosti materiala, ki je posledica prisotnosti mehkejšega grafita [1]. Kroglasti grafit je bistven pri zagotavljanju zadostnega maziva, s katerim se zmanjša koeficient trenja. Hkrati igra pomembno vlogo pri preprečevanju širjenja razpok v vročem. Indefinitna železova litina (angl. Indefinite Chill Double Pour, krajše ICDP) poleg prostega grafita vsebuje tudi visok delež cementita (nad 30 %) večinoma v obliki ledeburita z matrico iz transformiranega in zaostalega avstenita [2, 3]. Med različnimi stehiometričnimi oblikami karbidov ima cementit sorazmerno nizko trdoto, zato se pri izboljšanju obrabne obstojnosti med vročim valjanjem poslužujemo modifikacije običajne ICDP litine s posebnimi karbitvornimi elementi za doseganje trših oblik karbidov.

Ugoden vpliv dodatka posebnih karbidotvornih elementov (angl. Special Carbide Builders, krajše SCB) je predstavljen v mnogih raziskavah [2, 4-6]. Dodajanje vanadija, titana, niobija in volframa povzroča izločanje evtektskih MC karbidov znotraj železove matrice [4]. Ti karbidi so poznani po svoji trdoti, majhni velikosti in razpršeni porazdelitvi znotraj materiala. Obstajata dva

## 1 Introduction

Rolling conditions in the last finishing stands of standard hot strip mills are more demanding compared to earlier stands. As such, the demand for good anti-sticking properties in rolls is highlighted. The mottled hypoeutectic Ni-hard material combining white cast iron microstructure along with free graphite flakes enables good anti-sticking properties despite the decrease in wear resistance due to the softer graphite phase [1]. Nodular graphite is essential in providing sufficient lubrication for lowering friction and has a vital role in heat crack prevention. Besides free graphite flakes, ICDP microstructure consists of a high cementite ratio (above 30 %) mainly in the form of ledeburite, with a matrix consisting of transformed and retained austenite [2, 3]. Cementite has a relatively low hardness amongst carbides, so in order to increase wear resistance during hot rolling, modification of standard ICDP grade is made to obtain harder carbides.

Several studies have reported on the benefits of special carbide builder (SCB) addition [2, 4-6]. Addition of vanadium, titanium, niobium and tungsten enables precipitation of eutectic MC-type carbides inside the iron matrix [4]. These carbides are known for their hardness, small size and dispersed distribution. Two different technologies of adding special carbides into a standard ICDP alloy exist: the first one relies on addition of existing carbides directly into the melt and the second method relies on alloying, controlled solidification and precipitation [3, 7, 8]. Ready-made načina dodajanja posebnih oblik karbidov v ICDP litino: kot dodajanje že obstoječih karbidov v tekočo zlitino tik pred ulivanjem ali v obliki zlitinskih dodatkov in izločanja preko kontroliranega strjevanja [3, 7, 8]. Že obstoječi posebni karbidi so cenovno zelo neugodni in težko dostopni, zato je doseganje ustrezne porazdelitve le-teh skozi strjevanje in izločanje bolj učinkovita rešitev. Kot smo pokazali v že objavljenem delu [8], dovolj visok dodatek SCB-jev (npr. vanadij in volfram) vodi v strjevanje preko dodatne evtektske reakcije, skozi katero dosežemo izločanje karbidov MC tipa iz taline. Po drugi strani dodajanje SCB-jev lahko vpliva na znižanje deleža izločenega grafita v korist višjega deleža metastabilnega cementita. S prilagojenim cepljenjem taline se doseže izločanje grafita v kroglasti obliki, kar je v primerjavi s kosmičastim grafitom, ki ga običajno najdemo v standardnih ICDP litinah, bolj ugodno s stališča zaustavljanja razpok.

Raziskave opravljene na jeklenih litinah z visoko vsebnostjo kroma kažejo, da širjenje utrujenostnih razpok poteka po meji med matrico in karbidi [9, 10]. Visok delež karbidov v ICDP litinah zato ni ugoden s stališča odpornosti na nastanek in širjenje razpok. Ob tem se pojavi vprašanje: koliko odpornosti na razvoj in širjenje razpok lahko kot proizvajalci valjev žrtvujemo na račun doseganja boljše obrabne obstojnosti ter hkrati obdržimo zahtevano končno trdoto materiala in zadosten delež grafita? Na dveh izboljšanih ICDP litinah za delovne plasti valjev je bila zato opravljena študija, ki se osredotoča na razvoj mikrostrukture, lastnosti natezne trdnosti, dinamične trdnosti, obrabne obstojnosti in odpornosti na termično utrujanje v odvisnosti od deleža dodanih SCB-jev. Cilj predstavljene študije je prepoznati pozitivne in negativne posledice dodatka SCB-jev med proizvodnjo litih valjev.

special carbides are an expensive raw material, so achieving dispersed carbides through solidification and precipitation is a more efficient solution. As we had indicated in previously published work [8] a high enough addition of SCB (i.e. vanadium and tungsten) results in a eutectic reaction, where eutectic MC-type carbides are precipitated from the melt. In turn, SCB alloying can inhibit graphite formation in favour of the metastable cementite eutectic reaction. By adjusting melt inoculation, a more nodular graphite form is achieved. This is in stark contrast to the interdendritic graphite found in a standard ICDP and should work in favour of reducing crack propagation.

Research conducted on fatigue cracking and crack propagation in high chromium steel shows that the most favourable path of crack propagation is via the carbide-matrix boundary [9, 10]. A high carbide ratio in ICDP does not work in its favour and increasing this ratio could worsen the material's crack resistance. This leads to a dilemma: how much crack resistance can the roll designer risk losing in order to achieve a better wear resistance while retaining a high enough hardness and graphite ratio to meet the user's demands? A study of two ICDP alloy grades used in working layers for rolls was conducted to determine microstructural properties, static tensile strength and resistance to fatigue with dynamic loading, wear resistance and resistance to thermal cracking in dependence on the amount of added SCB. The aim of this research is to shed some light on the benefits and downsides of SCB addition in cast roll production.

## 2 Experimental methodology

A comparison was made between two separate grades of alloyed ICDP to

## 2 Eksperimentalno delo

Za ugotavljanje vpliva dodatka različnih količin SCB-jev na razvoj mikrostrukture in mehanskih lastnosti je bila opravljena primerjava med dvema izboljšanima ICDP litinama. Nizko legirana ICDP litina nosi oznako CIND in vsebuje manj kot 1 mas. % dodatka SCB, medtem ko ima visoko legirana ICDP (z oznako CINA) dodatek večji od 1 mas. %. Kemijska analiza izbranih zlitin je bila opravljena z emisijskim spektrometrom znamke Spectrolab. Rezultati so predstavljeni v Tabeli 1.

Vzorci, na katerih je bila opravljena metalografska analiza z meritvami mehanskih lastnosti, so bili odvzeti iz segmenta delovne plasti centrifugalno ulitega valja. Razrezani so bili z uporabo vodne abrazije, s čimer se je preprečil morebitni nastanek toplotno vplivanih con na vzorcih.

Metalografska analiza je bila opravljena na obrusih, ki so predstavljali presek po celotni globini delovne plasti valja. Obrusi so bili pripravljeni s standardnim postopkom brušenja s SiC brusnim papirjem (granulacije 120, 350 in 500) in polirani s sintetično krpo z 2 µm diamantno pasto. Analiza je potekala z optičnim mikroskopom znamke Olympus BX51M opremljenim z Olympus DP-12 kamero. Kvantitativna metalografska analiza je zahtevala uporabo programa JMicroVision v.1.2.7.

Vzorci za določanje natezne in dinamične trdnosti so bili ravno tako odrezani iz segmenta delovne plasti valja

determine the impact of SCB amount on microstructural development and mechanical properties. The low alloyed ICDP grade is labelled CIND and has an SCB amount less than 1 % mass. fraction while the high alloyed (enhanced) ICDP grade is labelled CINA with an SCB amount greater than 1 %. Chemical composition of the analysed material was measured using a spark ignition spectrometer from the producer Spectrolab (mean results are presented in Table 1).

The samples used for metallographic examination and mechanical testing were taken from a segment of the working layer from a centrifugally cast roll. The samples were cut using abrasive water blast technology to prevent the formation of heat affected zones.

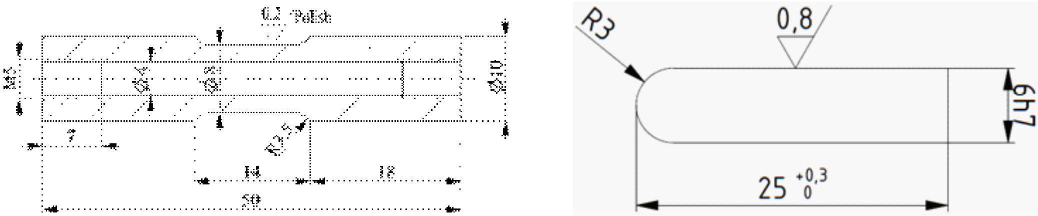
Metallographic analysis was performed on cross sectional samples throughout the working layer thickness. The samples were ground using SiC grinding paper with 120, 350 and 500 grit sizes and polished using a synthetic cloth with 2 µm diamond paste. They were inspected under an Olympus BX51M optical microscope equipped with an Olympus DP-12 camera. Microstructure was evaluated using JMicroVision v.1.2.7 software.

Samples for static tensile strength and fatigue testing were likewise cut from the working layer section and prepared according to the ISO 6892-1 and DIN 50113 standards, respectively [11, 12]. Testing was performed on the Zwick/Roell tester at the Faculty of Mechanical Engineering

**Tabela 1:** Kemijska sestava izbranih izboljšanih ICDP litin

**Table 1:** Chemical composition range of the analysed ICDP materials

| Oznaka litine / Roll Grade | Element, mas. %˝/ mass fraction % | | | | | |
|---|---|---|---|---|---|---|
| | C | Si | Cr | Ni | SCB | Fe |
| CIND | 3.0 – 3.2 | 0.90 – 1.2 | 1.50 – 1.70 | 4.20 – 4.50 | 0.5 – 1.0 | Ost. / Bal. |
| CINA | 3.0 – 3.2 | 1.30 – 1.6 | 1.50 – 1.70 | 4.20 – 4.50 | 1.0 – 2.0 | Ost. / Bal. |




**Slika 1:** a) Oblika in dimenzije preizkušancev za določanje odpornosti na termo-mehansko utrujanje, b) Preizkušanec za določanje odpornosti na obrabo z metodo valjček-plošča

**Figure 1:** a) Shape and dimensions of the thermal fatigue testing specimen, b) Sample for pin-on-disc wear resistance test

in pripravljeni po ustreznih standardih ISO 6892-1 in DIN 50113 [11, 12]. Samo testiranje je bilo opravljeno na napravi Zwick/Roell na Fakulteti za strojništvo Univerze v Mariboru v normalni atmosferi pri 20 °C pri obremenitvenem razmerju R = -1, ki predstavlja čisto izmenično napetost.

Za namen preiskave odpornosti na termično utrujanje sta bili opravljeni dve seriji testiranj na termo-mehanskem simulatorju Gleeble 1500D [13, 14]. Testiranje je potekalo na Naravoslovnotehniški fakulteti Univerze v Ljubljani. Na Sliki 1a so prikazane dimenzije preizkušancev.

Test za odpornost na abrazijsko obrabo je bil opravljen v podjetju Valji, d. o. o. z uporabo metode valjček-plošča. Izgradnja naprave kot tudi priprava preizkušancev (Slika 1b) in sama meritev so bili opravljeni po ASTM G99-04 standardu [15]. Disk s 120 µm SiC brusnim papirjem je predstavljal ploščo. Hitrost preizkusa je znašala 0.25 m/s z 1000 m opravljene poti ob obremenitvi 10 N. Preizkus je bil opravljen v normalni atmosferi (T = 21-23 °C; ~ 55 % relativna vlažnost zraka) brez uporabe maziv (prisilno hlajenje z zrakom).

Vsi opisani preizkusi so bili opravljeni na toplotno obdelanih vzorcih.

at University of Maribor under normal atmosphere at 20 °C with a loading ratio of R = -1.

To investigate the working roll surface layer material behaviour subjected to thermal fatigue cracking phenomenon, two different tests using the Gleeble 1500D thermo-mechanical simulator were performed [13, 14]. Testing was performed at the Faculty of Natural Sciences and Engineering at University of Ljubljana. The shape and dimensions of the specimens are presented in Figure 1a.

Abrasive wear testing was performed at Valji, d. o. o. using a custom made pin-on-disc tribometer. The design of the machine as well as sample preparation (see Figure 1b) and the measurement itself was done according to the ASTM G99-04 standard [15]. The disc was composed of a 120 µm SiC grinding paper. The testing speed was 0.25 m/s with a 1000 m sliding distance and a testing load of 10 N. The test was conducted under normal atmosphere (T = 21-23 °C; ~ 55 % relative air humidity) without the use of a lubricant (cooled with pressurized air).

All tests were conducted on heat treated specimens.

## 2 Rezultati in diskusija

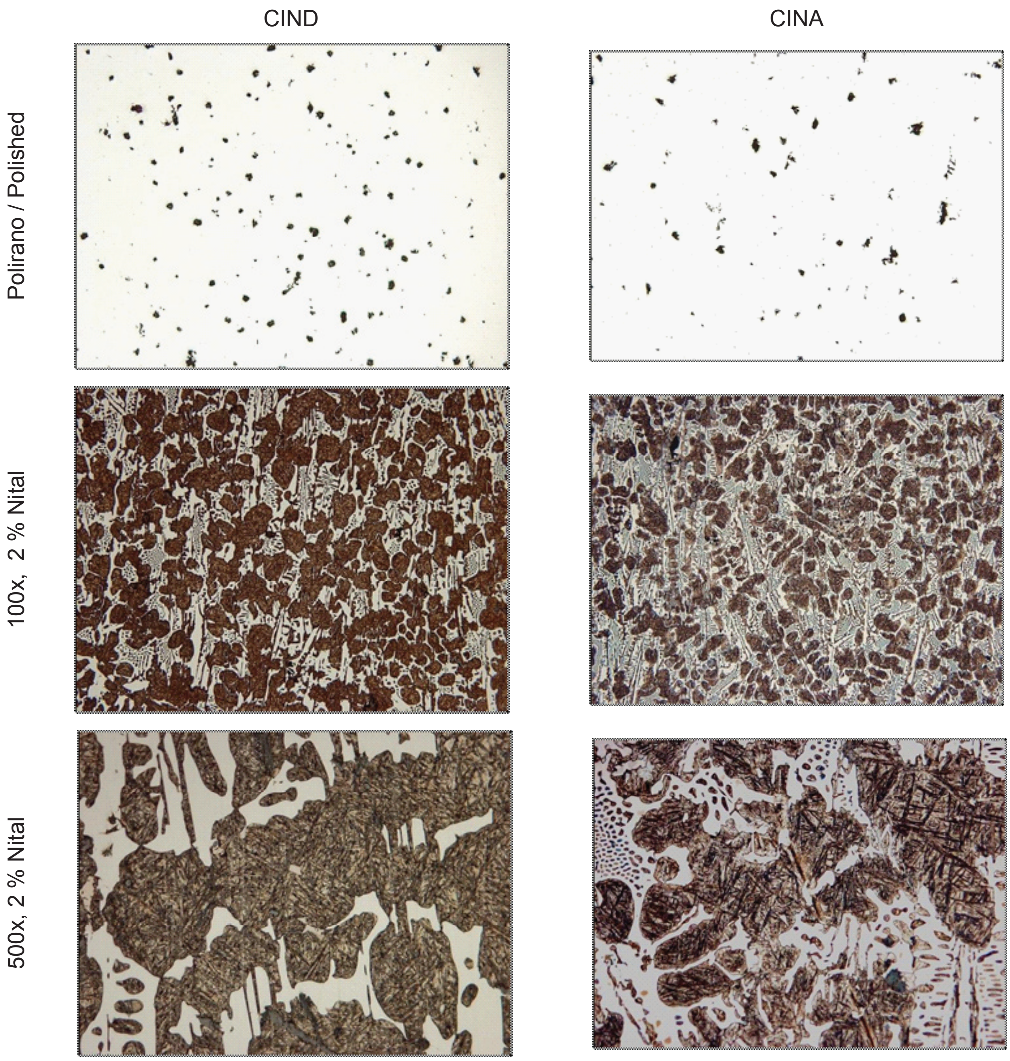
### 2.1 Metalografska analiza

Na Sliki 2 so prikazani optični mikroposnetki nizko legirane CIND in visoko legirane CINA.

## 2 Results and discussion

### 2.1 Metallographic analysis

Figure 2 shows optical microphotographs of heat-treated low alloyed CIND and high alloyed CINA grade.




**Slika 2:** Primerjava mikrostruktur med nizko (CIND) in visoko legirano ICDP litino (CINA)

**Figure 2:** Comparison of microstructure between low alloyed (CIND) and high alloyed ICDP grade (CINA)

Opazimo lahko razliko v mikrostrukturi med primerjanima kvalitetama ICDP litin. V obeh primerih prihaja do izločanja kroglastega grafita (oblika V to VI po ISO 945-1-2009 standardu [16]), vendar z višjim dodatkom SCB-jev delež izločenega grafita pade v korist tvorbe cementita. To opažanje potrjuje kvantitativna analiza opravljena na vzorcih (Tabela 2).

Rezultati, prikazani v Tabeli 2, se skladajo z običajno mikrostrukturo ICDP litin; pokaže se povišanje deleža grafita in sočasno znižanje deleža cementita od zunanjega roba delovne plasti proti globini. Poleg tega je v primeru nizko legirane CIND delež grafita za 0.5 do 0.7 % višji (približno 30 % povišanje), medtem ko je delež cementita do 4 % nižji. To kaže na zaviralni učinek dodatka visokega deleža SCB-jev na izločanje grafita. Matrica po žarjenju je pri obeh analiziranih kvalitetah martenzitno-bainitna.

## 2.2 Dinamična trdnost

V primeru nizko legirane CIND izmerjena natezna trdnost znaša 484.6 MPa, pri visoko legirani CINA pa 474.0 MPa. Glede na nizko absolutno razliko med rezultatoma (10 MPa) lahko trdimo, da med litinama ni opaznejših razlik.

Na Sliki 3 sta prikazani Wohlerjevi krivulji za obe analizirani litini.

Rezultati kažejo na podoben trend pri obeh litinah. Pri nizkih ciklih (N < 105) visoko legirana CINA doseže nekoliko višje napetosti (~ 30 MPa) v primerjavi z nizko legirano CIND. Trend, ki se kaže na krivuljah na Sliki 3, nakazuje na boljšo dinamično trdnost pri nizkih ciklih ob višjem dodatku SCB-jev.

A difference in microstructure between the two ICDP grades is visible, Figure 2. Nodular-type graphite flakes are precipitated in both cases (form V to VI acc. to ISO 945-1-2009) [16]. However, with a higher amount of SCB added, the graphite ratio decreases in favour of cementite formation. A quantitative metallographic examination supports this assumption (shown in Table 2).

**Tabela 2:** Kvantitativna metalografska analiza nizko in visoko legirane ICDP litine; primerjava med zunanjim robom delovne plasti in 40 mm v globino

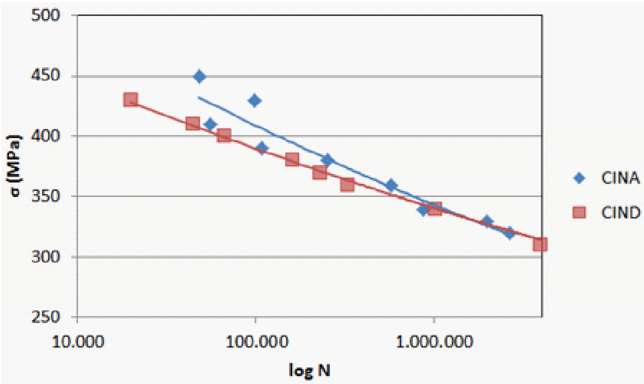
**Table 2:** Quantitative metallographic analysis of low and high alloyed ICDP grades; comparison between the outer edge of the working layer and 40 mm in depth

| | Delež grafita (%) / Graphite ratio (%) | | Delež karbidov (%) / Carbide ratio (%) | |
|---|---|---|---|---|
| | Rob / Edge | 40 mm | Rob / Edge | 40 mm |
| CIND | 1.53 | 1.92 | 30 | 26 |
| CINA | 1.08 | 1.25 | 29 | 30 |

The results shown in Table 2 are as expected for a standard ICDP microstructure; an increase in graphite ratio and decrease in carbide ratio from the outer edge towards the centre of the roll. Furthermore, low alloyed CIND has a 0.5 to 0.7 % higher ratio of graphite (app. 30 % increase) and up to 4 % less cementite. This shows the inhibitory nature of high SCB addition on graphite precipitation. After annealing, both grades show a matrix microstructure consisting of tempered martensite and bainite.

## 2.2 Fatigue testing under dynamic loading

The measured static tensile strength is 484.6 MPa for the low alloyed CIND and




**Slika 3:** Wohlerjevi krivulji za visoko in nizko legirani ICDP litini testirani pod pogoji: 20 °C in obremenitveno razmerje R = -1

**Figure 3:** S-N curves of high and low alloyed ICDP grades under testing conditions: temperature of the test 20 °C and loading ratio R = -1

## 2.3 Odpornost na termično utrujanje

Testiranje na termično utrujanje je bilo načrtovano tako, da simulira specifične pogoje, ki so prisotni na valjarskih progah za vroče valjanje. Testni cikel je tako vključeval: uporovno gretje vzorca s sobne temperature na 600 °C (2 s), držanje na temperaturi (0.2 s), hlajenje z vodo (0.5 s), hlajenje na zraku (0.5 s) in prisilna izpraznitev vzorca z zrakom (0.2 s). Predpisane temperature so bile določene na podlagi industrijskih pogojev. Opravljena je bila serija testov, ki jo je sestavljalo 1000 opisanih ciklov. Na Sliki 4 so prikazane termične razpoke, ki so nastale med serijo testov v obeh litinah.

Slika 4: Optični mikroposnetki razpok, ki so nastale med testiranjem termičnega utrujanja: v nizko legirani CIND (a, b) in visoko legirani CINA (c, d)

Rezultati kažejo, da širjenje razpok poteka skozi ledeburit, večinoma po mejah med karbidom in matrico. Te razpoke so transkristalne po izvoru. V nekaj primerih so bile opažene tudi interkristalne razpoke ob kristalnih mejah. Razpoke so se v nekaterih primerih, ko so naletele na kroglasti grafit, celo zaustavile. V Tabeli 3 so zbrane karakteristične meritve razpok.

Karakteristike razpok kažejo na izboljšanje v odpornosti na termično utrujanje

474.0 MPa for high alloyed CINA. With a difference of 10 MPa we can state that there is no significant difference in the static tensile strength between the two analysed grades.

Figure 3 shows the results of fatigue measurement under dynamic loading for both analysed grades.

Results shown in Figure 3 indicate a similar fatigue trend for both grades. However, at low cycles (N < 105) the high alloyed CINA reached somewhat higher stress levels (~ 30 MPa) compared to the low alloyed CIND. The trend observed in the S-N curves indicates that increasing the amount of added SCB can improve the material's resistance to fatigue at low cycles.

## 2.3 Thermal fatigue resistance

The performed thermal fatigue testing cycles were designed to simulate specific conditions that the working layer is subjected to during hot rolling. As such, a cycle comprised of resistance heating from room temperature up to 600 °C (2 s), holding on the prescribed temperature (0.2 s), water cooling (0.5 s), air cooling (0.5 s) and emptying the specimen by using air pressure (0.2 s). The prescribed temperatures and times were evaluated from

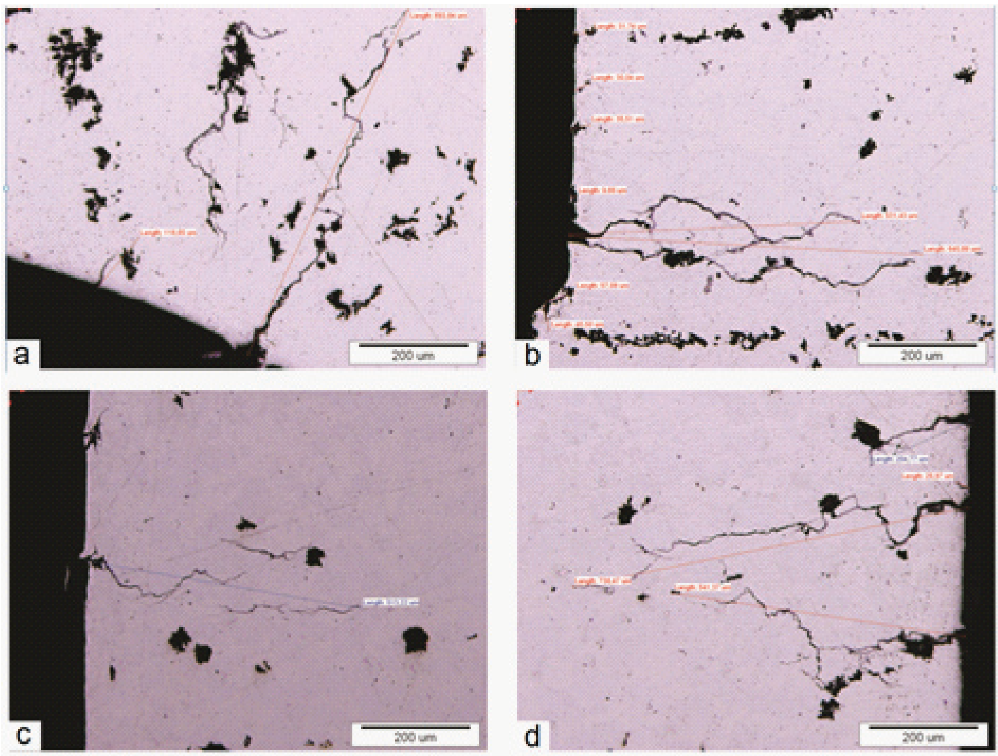
**Tabela 3:** Karakteristike termičnih razpok v CIND in CINA litini

**Table 3:** Measurements of thermal fatigue crack characteristics formed in CIND and CINA grades during testing

| | CIND | CINA |
|---|---|---|
| Število razpok / Number of cracks | 178 | 143 |
| Povprečna dolžina / Average length (μm) | 114 | 145 |
| Največja dolžina / Maximal length (μm) | 865 | 905 |
| Skupna dolžina / Sum length (mm) | 20.3 | 20.8 |
| Gostota (št. razpok/mm) / Density (cracks/mm) | 6.8 | 5.1 |

real-time industrial conditions. A set of tests using the described cycle was performed with 1000 cycles. Figure 4 depicts thermal fatigue cracks formed during testing in both analysed grades.

Results show that cracks propagate mainly through ledeburite, mostly along the carbide-matrix boundaries. These cracks are transcrystalline in origin although in some rare cases intercrystalline cracks were also visible along grain boundaries. Sometimes crack propagation is halted when the crack reaches a graphite flake or nodule. Table 3 represents measurements of crack characteristics.




**Slika 4:** Optični mikroposnetki razpok, ki so nastale med testiranjem termičnega utrujanja: v nizko legirani CIND (a, b) in visoko legirani CINA (c, d)

**Figure 4:** Optical microphotographs of cracks formed during thermal fatigue testing for low alloyed CIND (a, b) and high alloyed CINA (c, d)

v primeru visoko legirane CINA. Skupno število in gostota razpok sta se znižali za 20 %. To je v nasprotju s pričakovanjem, da bo višji delež karbidov poslabšal odpornost na termično utrujanje. Sklepamo lahko, da višji dodatek SCB-jev dodatno utrdi trdno raztopino avstenita (in posledično transformacijska produkta martenzita in bainita), kar poveča odpornost matrice na sam nastanek termičnih razpok.

Čeprav sta se število in gostota razpok zmanjšali, je v primeru visoko legirane CINA izmerjeno največje število ekstremno dolgih razpok (daljših od 0.5 mm). To bi lahko bila posledica nižjega deleža grafita v CINA, če upoštevamo zaviralni učinek kroglastega grafita na širjenje razpok. Nastanek teh ekstremno dolgih razpok med vročim valjanjem vodi do večjih odvzemov pri brušenju med posameznimi vgradnjami v valjarni in posledično do slabše učinkovitosti valja (pogosto merjeno v prevaljanih tonah na milimeter delovne plasti, ton/mm). V kolikor se te dolge razpoke ne odpravijo v celoti, lahko napredujejo globlje v delovno plast, kar vodi v krušenje oz. v najhujšem primeru (v kombinaciji z neugodnimi pogoji na progi) celo do luščenja delovne plasti valja. Zaradi tega se visoko legirana CINA smatra kot nekoliko bolj občutljiva litina in zahteva večjo pozornost operaterja, da temeljito odpravi razpoke, ki se pojavijo na površini valja med obratovanjem.

Crack measurements show an improvement in thermal fatigue resistance for the high alloyed CINA. The total number and density of cracks decreased for about 20 %. This contradicts the assumption that a higher carbide ratio would lessen the material's thermal crack resistance. We may assume that through SCB addition, the solid solution of austenite (and therefore martensite and bainite) is enhanced thus increasing the ability of the matrix to withstand crack initiation.

Although the number and density of cracks decreased, the high alloyed CINA showed the highest number of extremely long cracks (longer than 0.5 mm). This may be the result of a lower graphite ratio in CINA, since graphite nodules have been known to halt crack propagation. Formation of these long cracks during hot rolling automatically causes a higher grind rate in the mill and consequently a loss in roll efficiency (often measured in tons rolled per millimetre of working layer, ton/mm). If left unchecked, these long cracks can propagate further into the working layer and may cause chipping or in worst case scenarios, coupled with inappropriate mill settings, even spalling. This can make the high alloyed CINA a somewhat more sensitive material and requires mill operator's care to completely remove any thermal cracks that may have formed during rolling.

## 2.4 Odpornost na abrazijsko obrabo

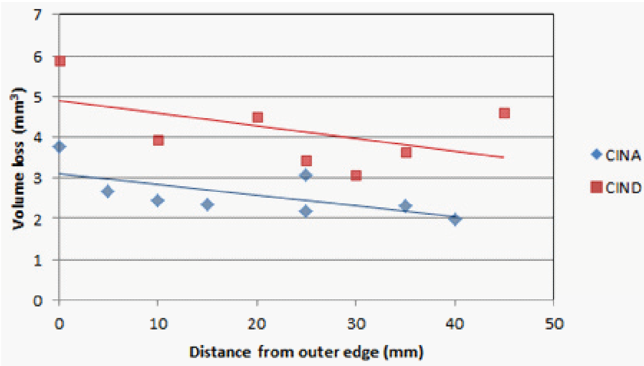
Na Sliki 5 so predstavljeni rezultati meritev z metodo valjček-plošča.

Z diagrama je razvidno, da se odpornost na obrabo povečuje od zunanjega roba delovne plasti proti globini, kar je lahko posledica spremembe v mikrostrukturi. Med strjevanjem pri postopku centrifugalnega ulivanja se tvorita dve specifični območji:

## 2.4 Abrasive wear resistance

Results of the pin-on-disc measurements are presented in Figure 5.

As can be seen in Figure 5, abrasive wear resistance increases from the outer edge towards the centre of the roll. This can be explained with an alteration of microstructure. During the course of centrifugal casting, two distinct zones




**Slika 5:** Rezultati abrazivne obrabe z metodo valjček-plošča za obe analizirani ICDP kvaliteti

**Figure 5:** Results of the pin-on-disc abrasive wear measurement for both analysed ICDP grades

dendritno območje tik ob stiku s kokilo in enakoosno območje v globini plasti [17]. Mikrostruktura se zaradi heterogene nukleacije med strjevanjem udrobni, zato lahko pričakujemo večje število bolj drobnih MC karbidov v globini plasti. Slednje ravno tako prispeva k izboljšanju obrabne obstojnosti materiala. Ker CINA litina vsebuje višji dodatek SCB-jev, je v splošnem delež MC karbidov pričakovano višji. Rezultati potrjujejo, da je zaradi tega CINA litina bolj obrabno obstojna na abrazijo.

are formed: a dendritic zone near the mould-melt interface and an equiaxed zone towards the centre of the roll [17]. As the microstructure is refined through the process of solidification, more refined and distributed MC-type carbides can be expected further into the working layer. This in turn increases the wear resistance of the material. As the CINA grade is highly alloyed the ratio of hard MC-type carbides is therefore higher, making it the more wear resistant material.

## 3 Zaključki

Rezultati predstavljene študije kažejo na merljive razlike med primerjanima ICDP litinama za delovne plasti valjev. Na podlagi meritev lahko zaključimo:

- višji dodatek SCB-jev zavira izločanje grafita celo do 20 % v korist višjega deleža cementita. Izločen prosti grafit, ki v standardnih ICDP kvalitetah privzame kosmičasto meddendritno obliko, se v primeru izboljšanih legiranih litin izloča v kroglasti obliki;
- meritev dinamične trdnosti je pokazala trend boljše trdnosti pri nizkih ciklih v primeru visoko legirane ICDP litine. Rezultati natezne trdnosti ne kažejo opaznih razlik med nizko in visoko

## 3 Conclusions

Results of this study reveal a difference between high and low alloyed ICDP grades used for working layers in rolls. Based on numerous analyses and testing several conclusions can be made:

- Higher SCB addition inhibits graphitization for up to 20 % in favour of the cementite phase. Free graphite flakes, commonly interdendritic in standard ICDP grades, take a more nodular form in alloyed ICDP.
- Fatigue measurement under dynamic loading shows a trend of increasing fatigue resistance at low cycles for high alloyed ICDP compared to low alloyed ICDP. No significant difference

legirano litino;

- visoko legirana ICDP litina je pokazala boljšo odpornost na razvoj termičnih razpok v primerjavi z nizko legirano litino (nižje skupno število in nižja gostota razpok). Po drugi strani se je pokazala nagnjenost k tvorbi ekstremno dolgih razpok (daljših od 0.5 mm), ki lahko povzročajo težave med valjanjem;
- odpornost na abrazijsko obrabo se povečuje od zunanjega roba delovne plasti proti globini najverjetneje zaradi spremembe (udrobnitve) v mikrostrukturi. Visoko legirana ICDP litina je pokazala do 35 % boljšo odpornost na obrabo kot nizko legirana.

V primeru specializiranih valjarn z dobro nastavljenimi parametri valjanja lahko priporočamo visoko legirano izboljšano ICDP litino zaradi boljših mehanskih lastnosti odpornosti na obrabo in termo-mehansko utrujanje. Po drugi strani bi v starejših valjarnah s širokim izborom valjanih kvalitet priporočali nižje legirano izboljšano ICDP litino zaradi višjega deleža grafita in bolj robustnih lastnosti.

was observed in static tensile strength measurement.

- High alloyed ICDP showed a higher resistance to thermal crack formation compared to low alloyed ICDP (lower total number of cracks formed along with a lower crack density). However there is a tendency to form extremely long cracks (longer than 0.5 mm) which can cause problems during the roll’s exploitation.
- Abrasive wear resistance increases from the outer edge of the working layer towards the centre of the roll due to microstructure refinement. The high alloyed ICDP showed an increase in wear resistance for about 35 %.

In the case of a highly specialized rolling mill with finely tuned mill settings, a high alloyed ICDP can be recommended for its improved wear and fatigue resistance. In the case of older mills or mills with a wider range of rolled grades, a low alloyed ICDP can be recommended due to its high graphite ratio and robust properties.

## 4 Viri / References

[1] J. Asensio-Lozano, J.F. Álvarez-Antolín, Saturated fractional design of experiments: Toughness and graphite phase optimizing in Nihard cast irons, Journal of Materials Engineering and Performance, Vol. 17, Nr. 2, 2008, p. 216-23

[2] G. Huang, Z. Li, J. Tang, Y. Tian, Effect of chemical composition on the microstructure of carbide reinforced indefinite chilled rolls, ISIJ International, Vol. 51, Nr. 6, 2011, p. 939-44

[3] J.B. Mess, G.E. Lee (ed.), Rolls for the Metalworking industries: The metallurgy of indefinite chill cast iron, Iron and Steel Society, Warrendale USA, 2002, p. 574

[4] J. Lecomte-Beckers, J. Tchoufang Tchuindjang, Structural Investigations of Solidification and Heat Treatments Influence on High Alloyed Cast Irons Grades with Nb-V-Ti Additions, Defect and Diffusion Forum, Vols. 289-292, 2009, p. 77-86

[5] J. Tinoco, Akers AB, Centrifugally cast roll for last finishing stands in hot strip mills, Patent nr. EP 2 660 344 A1, 2012, Sweeden.

[6] B.S. Villanueva, K. Yamamoto, K. Ogi, Influence of Nb and V on the microstructure of Ni-hard type cast iron for hot steel strip mill, CAMP-ISIJ, Vol. 17, 2014, p. 718-21

[7] D. Wragg, P.H. Hewitt, J. Nutting, Engineering Ferrous Metals and Method of making thereof, Patent nr. 5,720,830, 1998, UK.

[8] U. Klančnik, J. Habjan, G. Klančnik, J. Medved, Thermal analysis of indefinite chill cast iron modified with ferrovanadium and ferrotungsten, Journal of Thermal Analysis and Calorimetry, (online) 2016, DOI 10.1007/s10973-016-5434-6

[9] M. Drobne, T. Vuherer, I. Samardžič and S. Glodež, Fatigue crack growth and fracture mechanics analysis of a working roll surface layer material, Metallurgy, Vol. 53, Nr. 4, 2014, p. 481-84

[10] M. Drobne, N. Gubeljak, S. Godež, Experimental determination of fatigue parameters of high chromium steel under different loading and temperature conditions, Technical Gazette Vol. 21, Nr. 4, 2014, p. 853-860

[11] …ISO 6892-1:2016, Metallic materials – Tensile testing – Part 1: Method of test at room temperature

[12] …DIN 50113, Testing of metals; Rotating bar bending fatigue test

[13] M. Terčelj, M. Fazarinc, P. Mrvar, B. Žužek, P. Fajfar, Modelling surface degradation in hot rolling work rolls, RMZ – Materials and geoenvironment, Vol. 61, Nr. 1, 2014, p.11-17

[14] M. Drobne, I. Kogovšek, U. Klančnik, P. Fajfar, Influence of alloying elements on thermal fatigue cracking phenomenon of working rolls, 10th International and 7th European Rolling Conference, Graz, Austria, 2016

[15] …ASTM G99-04, Standard Test Method for Wear Testing with a Pin-on-Disk Apparatus

[16] …ISO 945-1:2008, Microstructure of cast irons – Part 1: Graphite classification by visual analysis

[17] U. Klančnik, M. Drobne, B. Košec, P. Mrvar, J. Medved, Effect of melt superheat on the microstructural development of centrifugally cast high carbon high speed steel alloy, 15th International Foundrymen Conference, Opatija, Croatia, 2016