U. Klančnik, A. Stergar, J. Bojanovič, M. Drobne,
Valji, d.o.o. Slovenija/ Slovenia

Vpliv hitrosti vrtenja kokile na razporeditev mikrostrukturnih konstituentov v železovi litini

Impact of Mold Rotation Velocity on Distribution of Microstructural Constituents in Cast Iron

Izvleček

Uliti valji za toplo valjanje so dvoplastni uliti ingoti, odpornejša zunanja plast je izdelana iz železove litine, žilavo jedro pa iz nodularne litine. Zunanja plast je danes najpogosteje centrifugalno lita, jedro pa statično. Fiziki centrifugalnega litja je bilo posvečeno veliko raziskav s poudarkom na aluminijevih zlitinah, ojačenih s SiC. Raziskave kažejo medsebojno povezavo med hitrostjo vrtenja kokile in pojavom zunanjih razpok v vročem, padanja, izcejanje karbida, plastenja in vpliva na hitrost strjevanja. Namen te raziskave je ugotoviti morebitno povezavo med hitrostjo vrtenja kokile in razporeditvijo mikrostrukturnih konstituentov, kot so evtektični karbidi in grafit, v posebnem litem železu za delovne plasti v valjih. Rezultati potrjujejo razliko pri litih mikrostrukturah v primeru treh različnih hitrosti vrtenja zlasti pri precipitaciji grafita, obliki evtektičnih karbidov in trdoti mase. Razumevanje posledic vpliva hitrosti vrtenja na lito mikrostrukturo lahko pomaga pri izboljšanju kakovosti končnega izdelka ter preprečevanju hudih napak pri litju.

Ključne besede: centrifugalno litje, hitrost vrtenja, legirana železova litina, mikrostruktura

Abstract

Cast rolls for hot rolling are two layered cast ingots composed of a harder, more resistant outer layer made of alloyed cast iron and a tough core made of nodular cast iron. The outer layer is nowadays most often centrifugally cast, while the core is cast statically. A lot of research has been done on the physics of centrifugal casting with emphasis on aluminum alloys reinforced with SiC. Previous research shows a correlation between the mould rotation speed and the occurrence of hot tearing, raining, carbide segregation, lamination and its impact on the rate of solidification. The goal of the present study was to establish a possible correlation between mould rotation speed and the distribution of microstructural constituents, such as eutectic carbides and graphite, in a highly alloyed cast iron for work layers in rolls. Results confirm a difference in as-cast microstructure between three different rotating speeds especially in precipitation of graphite, the form of eutectic carbides and bulk hardness. Understanding the implications of rotating speed influence on as-cast microstructure can help improve the quality of the finished product and to avoid serious casting failures.

Keywords: centrifugal casting, rotating speed, alloyed cast iron, microstructure

1 Uvod

Od uvedbe centrifugalnega litja kot delovne metode pri proizvodnji delovnih valjev pred približno dvajsetimi leti je pri sami tehnologiji postopka litja prišlo do malo sprememb. V uporabi sta dva glavna tipa postopkov centrifugalnega litja: horizontalni in vertikalni. Oba se lahko uporabljata pri proizvodnji valjev in tulcev, pa tudi drugih izdelkov, kot so jeklene cevi, Babbittovi ležaji, zavorni bobni, cevi in rotorji. Postopek litja je podoben v obeh primerih; kokila, ki je pogosto izdelana iz kovine, se postavi na žlebove in se vrti z visoko vrtilno hitrostjo. Nato se v vrtečo se kokilo ulije staljena kovina. Centrifugalna sila, ki deluje na tekočino, povzroči nastanek votlega valja valovite oblike v kokili. Kokila se vrti, dokler se kovina ne strdi. Nov strjeni valj tvori delovno plast valja. Učinkovit valj mora biti odporen proti nesrečam v valjarni, hkrati pa mora imeti časovno ugodno razmerje glede obrabe ter odpornosti proti razpokam, s čimer omogoča daljšo uporabo. Dobro razumevanje procesa litja je ključnega pomena pri izvajanju raziskav glede kakovosti in razvojnih projektov.

Splošna fizika pri horizontalnem centrifugalnem litju je precej osnovna. Kokila z notranjim premerom r_1 se vrti s kotno hitrostjo ω, ko vanjo ulijemo maso oziroma staljeno kovino m (Sl. 1a).

Prva tekočina ob stiku s kokilo skoraj v trenutku zamrzne, tako da lahko predvidevamo, da je trenje med tekočino/ulitkom in kokilo zadostno, da ne prihaja do zdrsov. Centrifugalno silo (F_C), ki deluje na vrtečo se kovino, lahko zapišemo kot:

$$F_C = m \cdot r_1 \cdot \omega^2 \text{ (N)}, \qquad (1)$$

ustvarjanje pritiska na notranjo površino kokile:

1 Introduction

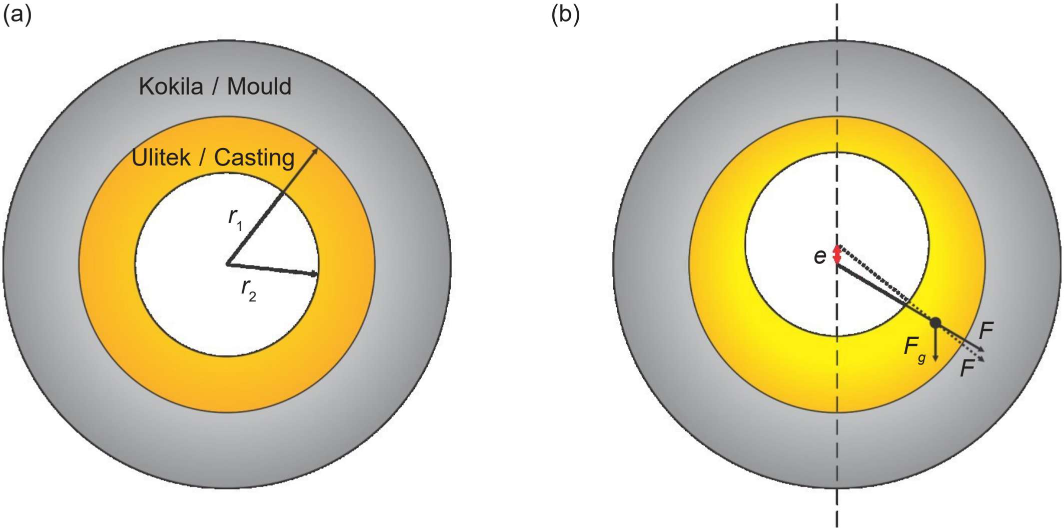
Since the implementation of centrifugal casting as a method for work roll production some twenty years ago, little change has been made on the technology of the casting procedure per se. There are two main types of centrifugal casting procedures; horizontal and vertical. Either can be used in the production of rolls and sleeves as well as other products such as steel tubes, Babbitt bearings, brake drums, pipes and rotors. The casting procedure is similar in both cases; the mould, most often made of metal, is placed on runners and rotated at a high rotating speed. Molten metal is then poured into the rotating mould. The centrifugal force acting on the liquid causes it to form a hollow cylinder contoured to the mould. The mould continues rotating until the metal solidifies. The now solid cylinder forms the working layer of a roll. An efficient roll should be resistant to incidents in the rolling mill and at the same time have a good wear and crack resistance enabling longer campaigns. A good understanding of the casting process is essential in tackling quality related research and development projects.

The general physics of horizontal centrifugal casting is quite straightforward. A mould with an internal radius r_1 is rotating at angular velocity ω when molten metal of mass m is poured into it (Fig. 1a).

The first liquid in contact with the mould freezes almost instantly so we can assume the friction between the liquid/casting and the mould is sufficing to prevent slippage. The centrifugal force (F_C) working on the rotating metal can be written as:

$$F_C = m \cdot r_1 \cdot \omega^2 \text{ (N)}, \qquad (1)$$

creating a pressure on the inner surface of the mould:



Slika 1: (a) Shematski prikaz prereza kokile s centrifugalno litim ulitkom; r_1 je polmer notranje površine kokile, r_2 pa je polmer notranje površine ulitka; (b) Prikaz sil, ki delujejo na ulitek med vrtenjem; pomeni oznak: *e* = ekscentričnost, F_g = gravitacijska sila, F_C = centrifugalna sila, *F* = rezultanta (povzeto po J. Honda)

Figure 1: (a) Schematic drawing of a mould cross section with a centrifugally cast casting; r_1 is the radius of the inner surface of the mould and r_2 the radius of the inner surface of the casting; (b) Depiction of the forces working on the casting during rotation; e represents eccentricity, F_g the force of gravity, F_C the centrifugal force and *F* the resultant (summarized after J. Honda).

$$p_C = \frac{\gamma\omega^2}{3g}\left(r_1^2 - \frac{r_2^3}{r_1}\right) \quad \left[\mathrm{N/m^2}\right], \qquad (2)$$

pri čemer je γ specifična teža staljene kovine, g je gravitacijski pospešek, r_2 pa notranji polmer taline. [1] Centrifugalna sila je usmerjena proč od vrtilne osi (Sl. 1) in je proporcionalna z ω^2 glede na En. 1. Gravitacijska sila (F_g) deluje tudi na talino, ki centrifugalno silo usmerja na zgornji del ($F_C - F_g$) in jo jača na dnu ($F_C + F_g$). Rezultat tega je nekoncentrična oblika z ekscentričnostjo e (Sl. 1b):

$$p_C = \frac{\gamma\omega^2}{3g}\left(r_1^2 - \frac{r_2^3}{r_1}\right) \quad \left[\mathrm{N/m^2}\right], \qquad (2)$$

where γ is the specific weight of the molten metal, g is the gravitational acceleration and r_2 is the inner radius of melt. [1] The centrifugal force is oriented away from the axis of rotation (see Fig. 1) and is proportional to ω^2 according to eq. 1. The force of gravity (F_g) also acts on the melt countering the centrifugal force on the top portion ($F_C - F_g$) and enhancing it on the bottom ($F_C + F_g$). The result is a non-concentric form with an eccentricity e (Fig. 1b):

$$e = \frac{F_g}{F_C} \cdot r = \frac{g}{\omega^2}, \quad (3)$$

Skladno z En. 3 je ekscentričnost obratno proporcionalna kvadratni hitrosti vrtenja. Pri nižjem ω (kar pomeni visoko ekscentričnost) pri vrteči se talini prihaja do motenj, zaradi česar pride do nastanka napak, kot so padanje, plastenje in močna oksidacija. Z večanjem ω lahko ekscentričnost postane zanemarljivo majhna, nikoli pa ne more biti enaka nič. Če kljub temu hitrost vrtenja povečamo nad določeno omejitev, lahko visoka napetost znotraj taline, ki se strjuje, privede do razpok v vročem, notranjih razpok in velikih preostalih obremenitev. To je zlasti pomembno pri zlitinah, ki se med strjevanjem bolj krčijo in imajo nižjo trdnost pri razžarjenosti. Viri in praksa kažejo, da naj bi hitrost vrtenja na splošno dosegla vsaj centrifugalno silo 100 do 120-kratnika sile težnosti *g*. [1]

Pri zelo nizkih ali visokih hitrostih vrtenja pride do težav s stabilnostjo ulitka, vendar pa lahko učinki izcejanja negativno vplivajo na kakovost delovne plasti tudi pri normalni hitrosti vrtenja. To še zlasti drži za zlitine z dodanimi delci (npr. aluminijeve zlitine, ojačene s SiC) ali evtektične karbide z neenakimi gostotami glede na gostoto razsutega staljenega materiala, ki je v našem primeru večinoma železo. Ravnovesje sil, ki delujejo na delce med vrtenjem (centrifugalna sila, sila viskoznosti), je mogoče izraziti kot:

$$\rho_p V \frac{d^2 r}{dt^2} = V\omega^2 \left(\rho_p - \rho_L\right) - 6\pi\eta r \frac{dr}{dt}, \quad (4)$$

pri čemer sta ρ_p in ρ_L gostoti delca in okoliške tekočine, V je prostornina delca, η pa je viskoznost staljene kovine, v kateri so prisotni delci, navadno je podana kot prostornina delca. Evtektični karbidi nižje gostote, kot so vanadijevi karbidi, se bodo premaknili proti notranji površini ulitka,

$$e = \frac{F_g}{F_C} \cdot r = \frac{g}{\omega^2}, \quad (3)$$

According to eq. 3, eccentricity is inversely proportional to rotating speed squared. At lower ω (meaning a high eccentricity) the rotating melt is subjected to disturbance giving rise to defects such as raining, lamination and intense oxidation. By increasing ω eccentricity can become negligible, although never really zero. However, if rotational speed is increased above a certain limit, the high tension stresses inside the solidifying melt can lead to hot tearing, internal cracking and high residual stresses. This is especially important for alloys with greater shrinkage during solidification and lower red, hot strength. Literature and practice show that rotating speeds should generally achieve a centrifugal force of at least 100-120 times *g*. [1]

With extremely low or high rotating speeds problems arise with the casting's stability, but even with normal rotating speeds the quality of the working layer can be hindered due to segregation effects. This is especially true for alloys that contain added particles (for example aluminum alloys enforced with SiC) or eutectic carbides with dissimilar densities in relation to the density of the bulk molten metal which in our case consists mostly of iron. The balance of forces working on the particles during rotation (centrifugal force, viscous force) can be expressed as:

$$\rho_p V \frac{d^2 r}{dt^2} = V\omega^2 \left(\rho_p - \rho_L\right) - 6\pi\eta r \frac{dr}{dt}, \quad (4)$$

where ρ_p and ρ_L are the densities of the particle and surrounding liquid, respectively, V is the volume of the particle and η is the viscosity of the molten metal containing particles, usually given as a function of particle volume. Eutectic carbides with a gostejši delci pa so nagnjeni k izcejanju proti zunanji površini. [2, 3, 4]

Enako kot izcejanje delcev različnih gostot lahko tudi centrifugalna sila vpliva na jedra, saj se v prvi fazi strjevanja izločajo znotraj taline (okrog T_L). Učinek na mikrostrukturo neobdelanega ulitka je velik. Raziskave, opravljene na zlitinah Al-Si in Al-Cu, kažejo, da večja hitrost vrtenja kokile stebričasto območje v bližini zunanje površine ulitka ter enakoosno območje, pričakovano v središču ulitka, spremeni v strukturo s fino zrnavostjo proti zunanji površini, v središču ulitka pa v sekundarno stebričasto območje. Avtorji ta pojav pripisujejo večjemu ločevanju kristalov v beli plasti in primarnih dendritnih vejah, pa tudi fragmentaciji večjih kristalov, ker ti trkajo drug ob drugega. To povečuje nukleacijo, rezultat katere sta udrobnjevanje in zmanjšanje nabiranja topljenca v končnem območju strjevanja. [5]

Hipoevtektično lito železo, ki se uporablja v delovnih plasteh valjev, vsebuje grafit, cementit in trde karbide tipa MC, vgrajene v jekleno matrico. Na podlagi zgoraj navedenega lahko centrifugalna sila vpliva tako na izcejanje karbidov kot tvorbo grafita in cementita, ki nastaja na podlagi stabilne in metastabilne evtektične reakcije. Študija je bila izvedena z namenom ocene morebitnega vpliva, ki ga imajo lahko različne hitrosti vrtenja na razporeditev, obliko in velikost primarnih mikrostrukturnih konstituentov.

2 Metodologija poskusa

Talino litega železa smo pripravili s 3,1 wt. % C, 0,9 wt. % Mn in 4,3 wt. % Ni; kemično sestavo smo preverjali s pomočjo pulzirajočega spektrometra. Talino smo ulivali in spremenili s posebnimi karbidnimi graditelji (Nb, V, Ti itd.) z vsebnostmi med

smaller density, such as vanadium carbides, will move towards the inner surface of the casting, while denser particles are prone to segregation towards the outer surface. [2,3,4]

Like segregation of particles with various densities, the centrifugal force can affect nuclei as they precipitate inside the melt during the first stage of solidification (around T_L). As such, the effect on the as-cast microstructure is profound. Research done on Al-Si and Al-Cu alloys suggests that increasing the rotating speed of the mould changes the columnar zone near the outer surface of the casting and the equiaxed zone expected in the center of the casting into a fine grained structure towards the outer surface and a second columnar zone in the center of the casting. The authors attribute this to the enhanced detachment of chill crystals and primary dendrite arms as well as fragmentation of larger crystals as they collide with each other. This enhances nucleation with the result of grain refinement and a reduction in solute pile up in the final solidification zone. [5]

Hypo-eutectic alloyed cast iron used for work layers in rolls consists of graphite, cementite and hard MC-type carbides embedded in a steel matrix. According to above, centrifugal force can affect both segregation of carbides and the form of graphite and cementite formed through the stable and metastable eutectic reaction, respectively. A study was conducted with the objective of ascertaining a possible effect, different rotating speeds may have on the distribution, form and size of primary microstructural constituents.

Preglednica 1: Parametri treh poskusnih litij z različnimi hitrostmi vrtenja

Table 1: Parameters of three trial castings cast with different rotating speeds

Oznaka litja / Casting label	Hitrost vrtenja / Rotating speed		Livna temperatura / Pouring temperature (°C)	Razmerje / ratio (Nb+V+Ti) (%)
	(Sila G) / (G-force)	(vrt./min) / (rpm)		
A	80	850	1.350	1,3
B	120	1.000	1.351	1,5
C	160	1.200	1.347	1,5

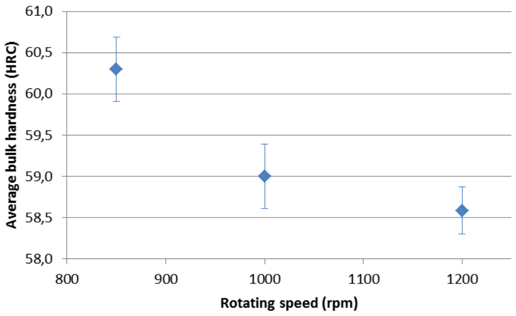
1,3 in 1,5 wt. % in inokulirali z železovo zlitino na osnovi silicija, namenjeno grafitizaciji. Litje je potekalo pri temperaturi 1.350 °C (±5 °C) v laboratorijskem livnem stroju za horizontalno centrifugalno litje. Temperaturo litja med kroženjem smo spremljali s pomočjo umerjenega optičnega pirometra. Pri temperaturi pribl. 1.000 °C smo napravo zaustavili ter pustili, da se je ulitek ohladil v kokili.

Izdelali smo tri različne ulitke z različnimi hitrostmi vrtenja (Preglednica 1). Zunanji premer ulitkov je bil 270 mm, po dolžini so merili 310 mm, plast pa je bila debela 35 mm. Nato smo ulitke razrezali. Metalografske vzorce (celotne debeline stene) smo pripravili iz sredinskega prereza ulitka. Sredino ulitka smo izbrali, ker je temperaturni gradient med strjevanjem pravokoten na v kokili staljene mejne površine, fronta strjevanja pa poteka enosmerno. Vzorce smo pripravili s standardnim metalografskim postopkom brušenja, loščenja in jedkanja v 2-% nitalu, da smo odkrili mikrostrukturo. Optično mikroskopijo smo izvajali s pomočjo optičnega mikroskopa Olympus BX51M, opremljenega s kamero Olympus SC50. Oceno frakcije karbidov in obliko grafita, razporeditve ter velikosti smo izvedli s pomočjo programske opreme Olympus Stream Basic skladno z določili standarda EN-ISO 945-1:2009. Analizo posnetkov karbidov tipa MC smo opravili s programsko

2 Experimental Methodology

A cast iron melt was prepared with 3.1 wt. % C, 0.9 wt. % Mn and 4.3 wt. % Ni; chemical composition was controlled using a spark spectrometer. The melt was alloyed and modified with special carbide builders (Nb, V, Ti, etc.) between 1.3 and 1.5 wt. % in total and inoculated with a siliconbased ferroalloy for graphitization. The casting was done at 1350 °C (± 5 °C) in a laboratory scale horizontal centrifugal casting machine. The temperature of the casting during spinning was monitored using a calibrated optical pyrometer. At around 1000 °C the device was stopped and the casting left to cool inside the mould.

Three separate castings were made with different rotating speeds (Table 1). The dimensions of the castings were 270 mm in outer diameter, 310 mm in length and with a 35 mm thick layer. The castings were then cut apart. Metallographic samples (of the entire wall thickness) were prepared from the middle section of the casting. The middle of the casting was chosen, since the temperature gradient during solidification is perpendicular to the mould-melt interface and the solidification front advances in a unidirectional path. The samples were prepared with a standard metallographic procedure of grinding, polishing and etching in 2 % Nital to reveal the microstructure. Optical microscopy was conducted using

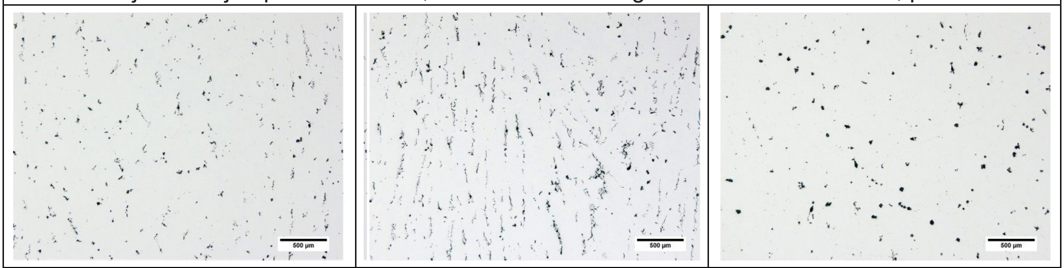


Slika 2: Rezultati meritev trdote glede na hitrost vrtenja (v HRC)

Figure 2: Results of the hardness measurement in dependence on the rotating speed (in HRC)

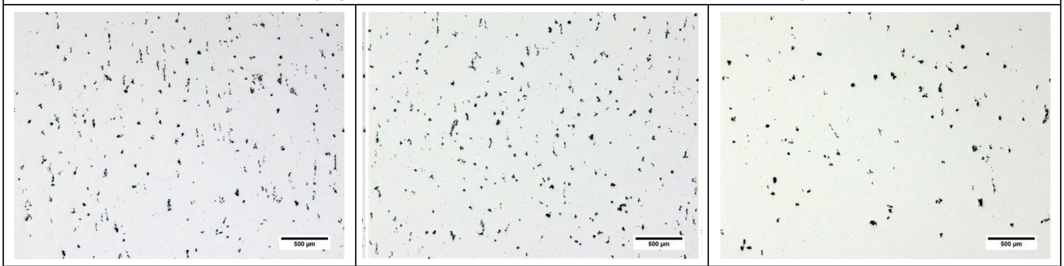
an Olympus BX51M optical microscope equipped with Olympus SC50 camera. Evaluation of the carbide fraction as well as graphite form, distribution and size were performed with Olympus Stream Basic software according to EN-ISO 945-1:2009 standard. Image analysis of MC-type carbides was done with ImageJ software v.1.50i. Hardness of the samples was measured using an Emco test Rockwell hardness tester. The investigation was performed on as-cast specimens.

Zunanji rob mejne površine kokile, loščeno / Outer edge at the mould interface, polished



A B C

25 mm od zunanjega roba, loščeno / 25 mm from the outer edge, polished



A B C

Slika 3: Mikrofotografije loščenih vzorcev kažejo grafitne delce na zunanjem robu ulitka (kokila/lita mejna površina) in 25 mm od zunanjega roba proti vrtilni osi v odvisnosti od hitrosti vrtenja. Merilo je 500 µm.

Figure 3: Microphotographs of the polished specimens revealing graphite particles on the outer edge of the casting (mould/casting interface) and 25 mm from the outer edge towards the axis of rotation in dependence on the rotating speed. The bar represents 500 µm.

opremo ImageJ v.1.50i. Trdoto vzorcem smo izmerili s pomočjo Rockwellovega merilnika trdote Emco. Raziskavo smo opravili na vzorcih v litem stanju.

3 Rezultati in razprava

Rezultati meritev trdote (predstavljeni na Sl. 2) kažejo rahel padec za pribl. 2 HRC celotne trdote razsutega materiala. To nakazuje, da bi morala biti opazna tudi razlika v sami mikrostrukturi.

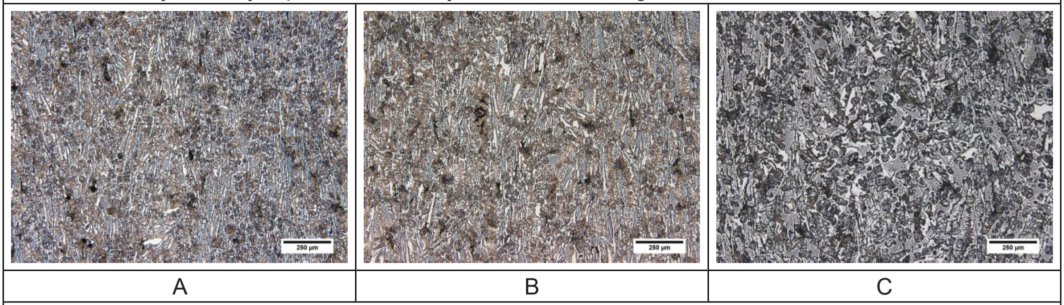
Preučitev Sl. 3 kaže razliko v precipitaciji grafita med prvima dvema ulitkoma in ulitkom C; razporeditev ostaja enaka pri

3 Results and Discussion

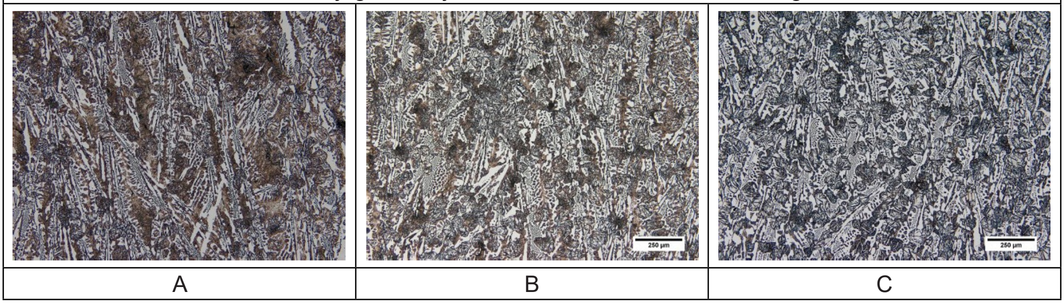
The results of the hardness measurement (presented in Fig. 2) show a slight drop of about 2 HRC in the overall bulk hardness. This suggests, that there should also be an observable difference in the microstructure itself.

Examination of Fig. 3 indicates a difference in graphite precipitation between the first two castings and casting C; while the distribution remains the same in all three castings (distribution A), the form changes from forms IV (edge) and III (25 mm) in casts A and B to a uniform form IV in cast C. The size also increases from 7 (1.5

Zunanji rob mejne površine kokile, jedkano / Outer edge at the mould interface, etched



25 mm od zunanjega roba, jedkano / 25 mm from the outer edge, etched



Slika 4. Mikrofotografije jedkanih vzorcev kažejo cementit in matrico na zunanjem robu ulitka (kokila/lita mejna površina) in 25 mm od zunanjega roba proti vrtilni osi v odvisnosti od hitrosti vrtenja. Merilo je 250 µm.

Figure 4. Microphotographs of the etched specimens revealing cementite and the matrix on the outer edge of the casting (mould/casting interface) and 25 mm from the outer edge towards the axis of rotation in dependence on the rotating speed. The bar represents 250 µm.

vseh treh ulitkih (razporeditev A), oblika pa se spreminja iz oblike IV (rob) in III (25 mm) pri ulitkih A in B v enakomerno obliko IV pri ulitku C. Tudi velikost se je spremenila s 7 (1,5 do 3 mm) pri ulitkih A in B v velikost 6 (3–6 mm) pri ulitku C.

Kaže, da frakcija karbidov raste proporcionalno s hitrostjo vrtenja, ki iz vidnejšega cementita (ulitka A in B) prehaja v bolj grobo mikrostrukturo pri ulitku C (Sl. 4 in 5). Natančnejši pregled kaže bolj enakomerno mikrostrukturo med robom in 25 mm v notranjost ulitka pri ulitku C v primerjavi z ulitkoma A in B. To potrjuje tudi analiza grafitnih delcev (Sl. 3).

Na Sl. 6 so prikazane mikrofotografije zloščenih vzorcev. Karbidi tipa MC se pri povečavi na loščeni površini pojavljajo v nežno roza odtenku, zaradi lažje določitve velikosti in razporeditve pa smo jih še dodatno označili z belo (rezultati so predstavljeni na Sl. 7).

Rezultati, prikazani na Sl. 7, kažejo trend rasti povprečne velikosti karbidov tipa MC z večanjem hitrosti vrtenja, medtem ko frakcija območja ne kaže velike odvisnosti. Na splošno bi lahko ocenili, da je tudi frakcija območja večja pri višjih hitrostih vrtenja (ulitka B in C).

Rezultati načeloma potrjujejo trditev, da centrifugalna sila med strjevanjem vpliva na tvorbo mikrostrukture. Pri nižjih

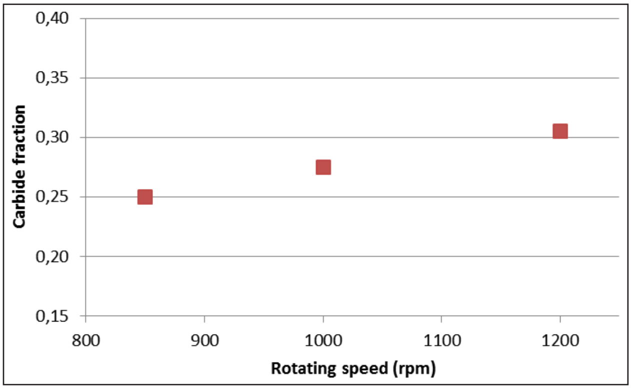
to 3 mm) in casts A and B to size 6 (3 – 6 mm) in cast C.

The carbide fraction seems to increase proportionally with the rotating speed ranging from finer cementite (casts A and B) to a bulkier microstructure in cast C (Figs. 4 and 5). A closer look also shows a more uniform microstructure between the edge and 25 mm in cast C as opposed to A and B. This is also in agreement with the analysis of graphite particles (Fig. 3).

Fig. 6 shows microphotographs of polished samples. The MC-type carbides appear light pink on the polished surface under magnification and were additionally marked in white for an easier assessment of size and distribution (results presented in Fig. 7).

The results shown in Fig. 7 reveal a trend of increasing average size of MC-type carbides as the rotating speed increases, while the area fraction does not show a clear dependence. A general remark can be made, that the area fraction at higher rotating speeds (casts B and C) is also higher.

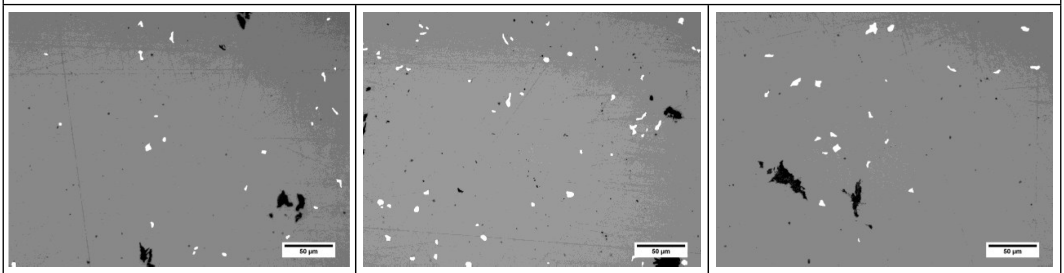
The results shown above seem to confirm the statement that centrifugal force during solidification has an impact on microstructure formation. At lower rotating speeds the overall hardness is higher, graphite particles and MC-type carbides are



Slika 5. Grafična predstavitev povezave med frakcijo karbidov in hitrostjo vrtenja

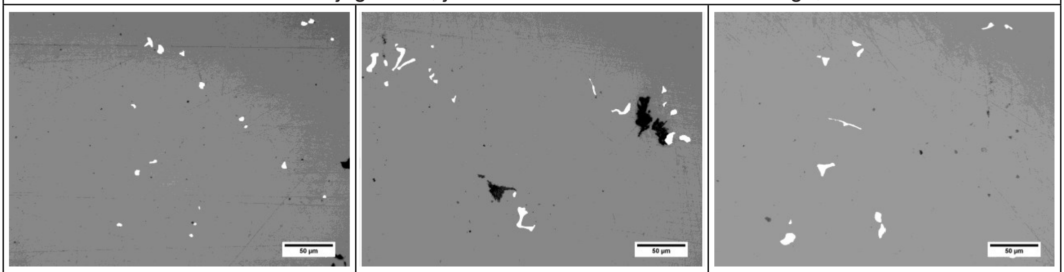
Figure 5. Graphic presentation of the relation between carbide fraction and rotating speed

Zunanji rob mejne površine kokile, loščeno / Outer edge at the mould interface, polished



A B C

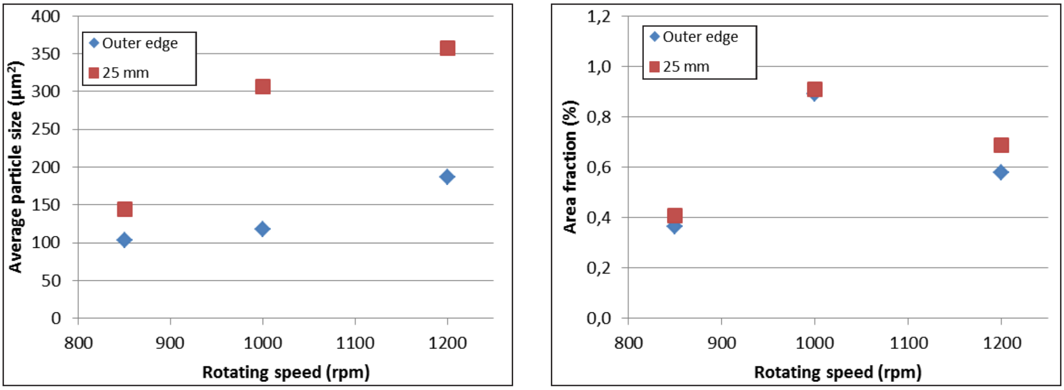
25 mm od zunanjega roba, jedkano / 25 mm from the outer edge, etched



A B C

Slika 6. Mikrofotografije loščenih vzorcev z označenimi karbidi tipa MC (z belo) na zunanjem robu ulitka (kokila/lita mejna površina) in 25 mm od zunanjega roba proti vrtilni osi v odvisnosti od hitrosti vrtenja. Merilo je 50 µm

Figure 6. Microphotographs of the polished specimens with marked MC-type carbides (white) on the outer edge of the casting (mould/casting interface) and 25 mm from the outer edge towards the axis of rotation in dependence on the rotating speed. The bar represents 50 µm



Slika 7. Rezultati meritev velikosti in razporeditve karbidov tipa MC glede na hitrost vrtenja

Figure 7. Results of size and distribution measurements of MC-type carbides in dependence on rotating speed.

hitrostih vrtenja je splošna trdnost višja, grafitni delci in karbidi tipa MC so manjši, splošna mikrostruktura pa je bolj fina. Z večanjem hitrosti vrtenja postaja splošna mikrostruktura bolj enakomerna po prečnem prerezu stene, velikost grafitnih delcev in tudi karbidov tipa MC pa se povečuje. Enakomerno mikrostrukturo pri ulitku C je mogoče pripisati večji nukleaciji zaradi ločevanja kristalov v beli plasti in primarnih dendritnih vejah skupaj s fragmentacijo večjih kristalov, kar je podobno odkritjem, o katerih poroča vir [5]. Zato je tudi nukleacija po debelini stene ulitka enakomernejša in nalaganje topljenca v prednjem delu fronte strjevanja se zmanjšuje. Posledično se karbidi (Sl. 4 in 6) zdijo večji z večjimi ledeburitnimi celicami, grafitni delci pa delujejo bolj okrogli (oblika IV). Na gostoto vezanega izcejanja karbidov tipa MC zaradi večje centrifugalne sile nismo opazili (Sl. 7). Treba je poudariti, da v tem delu poročamo o trendih, opaženih pri preučevanih vzorcih, samo kot o delu poglobljene sistematične študije. Vendar pa rezultati kažejo na možnost izboljšanja kakovosti s prilagajanjem hitrosti vrtenja.

4 Sklepi

Izvedli smo študijo vpliva centrifugalne sile na tvorbo mikrostrukture pri litem železu. Na podlagi rezultatov študije lahko sklepamo, da se s povečevanjem hitrosti vrtenja:

- trdota mase nekoliko zmanjša;
- grafitni delci postanejo bolj okrogli (prehod iz oblike III v obliko IV) in večji (prehod iz velikosti 7 na velikost 6);
- ko karbidi postanejo večji, se zveča frakcija cementita;
- celotna mikrostruktura je enakomernejša pri prerezu stene ulitka in prisotne so večje ledeburitne celice;
- karbidi tipa MC se povečajo, pri

smaller and general microstructure is finer. With increasing rotating speed, the general microstructure becomes more uniform across the wall cross section, while graphite particles as well as MC-type carbides seem to increase in size. The even microstructure in cast C can be attributed to the increased nucleation as a result of chill crystal and primary dendrite arm detachment along with fragmentation of larger crystals, similar to findings reported in Ref. [5]. In turn the nucleation throughout the thickness of the casting wall is more even and the solute pile up in front of the solidification front decreases. As a result, the carbides (Figs. 4 and 6) appear bulkier with larger ledeburitic cells and graphite particles appear more spherical (form IV). Density related segregation of MC-type carbides due to a larger centrifugal force has not been observed (Fig. 7). At this point it should be emphasized that this paper reports on the trends noticed in the studied specimens as only a part of a thoroughly systematic study. However, the results indicate a possible margin for quality improvement through rotation speed adjustment.

4 Conclusions

A study of the impact of centrifugal force on microstructure formation in an alloyed cast iron has been carried out. Based on the results of the study we can conclude that by increasing rotating speed:

- the bulk hardness lowers slightly;
- graphite particles become more spherical (from form III to IV) and larger (from size 7 to 6);
- cementite fraction increases with the carbides becoming bulkier;
- the overall microstructure is more even throughout the casting wall cross section with larger ledeburitic cells;

čemer pa spremembe hitrosti vrtenja načeloma ne vplivajo na razporeditev.

Pri analiziranih vzorcih prav tako nismo opazili z gostoto povezanega izcejanja karbidov tipa MC. Rezultati kažejo obetavne možnosti za nadaljnje sistematično raziskovanje pri izvedbi zlitin za valje, ki so bolj odporne proti nesrečam.

- MC-type carbides increase in size while the distribution does not appear to be inflicted by changes in rotating speeds.

Also, no density related segregation of MC-type carbides was observed in the analyzed samples. The results are promising for further, systematic investigation in achieving a more incident resistant alloy for rolls.

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AKTUALNO / CURRENT

Koledar livarskih prireditev 2020

Datum dogodka	Ime dogodka	Lokacija
14.-16.01. 2020	EUROGUSS	Nürnberg, Nemčija
12.02. 2020	20. Car Symposium „Roll-Out der Elektromobilität”	Bochum, Nemčija
02.-03.04.2020	64. Österreichische Gießerei-Tagung	Schladming, Avstrija
18.-19.05. 2020	WFO World Foundry Summit 2020,	New York City, ZDA
08.-09.06. 2020	Industrijski forum IRT	Portorož, Slovenija
16.-18.06.2020	CastForge 2020	Stuttgart, Nemčija
15.-17.07. 2020	CHINA DIECASTING	Šanghaj, Kitajska
15.-19.09.2020	AMB-Internationale Ausstellung für Metallbearbeaitung	Stuttgart, Nemčija
16.-18.09.2020	60. IFC Portorož 2019	Portorož, Slovenija
18.-22.10. 2020	74th World Foundry Congress	Busan, Južna Koreja
15.-19.06. 2020	AMB-Internationale Ausstellung für Metallbearbeitung	Stuttgart, Nemčija