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Prenos znanja iz univerze v industrijo - optimiranje proizvodnje drogov iz aluminijeve zlitine EN AW-6082 visoke kakovosti

Knowledge Transfer from University to Industry - Optimization of Billets Production from High-Quality Aluminum Alloy EN AW-6082

Povzetek

V sklopu visokošolskega izobraževanja študenti pridobivajo napredna znanja, veščine in kompetence, potrebne za uspešno kariero v izbranem poklicu. Na Oddelku za materiale in metalurgijo se osredotočamo na usmerjeno izobraževanje in usposabljanje novih strokovnjakov in prenos njihovega znanja v industrijo, ki je ključnega pomena za razvoj in napredek v industriji in raziskavah. Iz tega razloga študenti med študijem sodelujejo pri raziskovalnih projektih, povezanih z gospodarstvom. V tem prispevku je predstavljen primer dobre prakse prenosa znanja iz univerze v industrijo v okviru zaključne magistrske naloge študenta.

V proizvodnem procesu izdelave zlitine na kvaliteto končnega izdelka vpliva veliko faktorjev in sicer: delež založenega primarnega in sekundarnega aluminija v talilno peč, obdelava taline, čiščenje taline v peči, udrobnjevanja taline, čiščenja taline izven peči, procesni parametri pri litju in pogoji homogenizacije drogov. Namen raziskave v sklopu magistrskega dela je bil izdelava drogov zlitine EN AW-6082 dolžine 7000 mm z minimalnim izmetom, oziroma znižanje tehnološkega izmeta, kar pomeni boljšo stroškovno učinkovitost in konkurenčnost na trgu. Ugotovljeno je bilo, da je za doseganje ustrezne mikrostrukture po celotni dolžini droga zlitine EN AW-6082 potrebno zagotoviti višjo temperaturo taline na začetku litja. To je bilo doseženo z dodatnimi izolacijskimi pokrovi, ki imajo na spodnji strani električne grelce. V sklopu raziskave smo dosegli zmanjšanje tehnološkega izmeta, kar predstavlja boljšo stroškovno učinkovitost in konkurenčnost na trgu.

Ključne besede: zlitina EN AW-6082, optimizacija procesa litja drogov, zmanjšanje tehnološkega izmeta, prenos znanja v industrijo

Abstract

Within higher education, students acquire advanced knowledge, skills, and competencies required for a successful career in their chosen profession. At the Department of Materials and Metallurgy, we focus on the targeted education and training of new professionals and the transfer of their knowledge to industry, which is crucial for the development and progress of industry and research. For this reason, students take part in research projects related to industry during their studies. This article presents an example of a good practice of knowledge transfer from university to industry as part of the student's final Master's thesis.

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In the alloy production process, the quality of the final product is influenced by many factors, namely: the proportion of primary and secondary aluminium stored in the melting furnace, the melt treatment, the melt purification in the furnace, the melt grain refining, the melt purification outside the furnace, the process parameters during casting and the conditions for homogenizing the ingots. The investigation which was part of Master thesis aimed to produce 7000 mm long bars from the alloy EN AW-6082 with minimal rejection or to reduce the technological rejection, which means better cost efficiency and competitiveness on the market. It was found that to achieve a suitable microstructure over the entire length of the EN AW-6082 alloy bar, a higher melting temperature is required at the start of casting. This was achieved with additional insulating covers, which have electrical heaters on the underside. As part of the Master thesis, a reduction in technological waste was achieved, which means better cost efficiency and competitiveness in the market.

Key words: EN AW-6082 alloy, casting process optimization of bars, technological waste reduction, knowledge transfer to industry

1 Uvod

Aluminijeva zlitina EN AW-6082 se uporablja za različne namene v gradbeništvu, strojništvu, avtomobilski industriji ipd. [1]. Dolgoletne izkušnje uporabe zlitine EN AW-6082 v komercialne namene so pokazale, da je ta zlitina odporna na vremenske vplive brez zaščitnih prevlek. Med zlitinami serije 6xxx dosega najboljše mehanske lastnosti (npr. meja tečenja 320 MPa, raztezek 12 %) [2]. Mikrostruktura in mehanske lastnosti zlitine EN AW-6082 so odvisne od legirnih elementov (tvori se veliko število intermetalnih faz) in od vrednosti procesnih parametrov pri izdelavi taline, litja, strjevanja, homogenizacije, preoblikovanja ter toplotne obdelave [3,4,5]. V proizvodnem procesu izdelave zlitine na kakovost končnega izdelka vpliva veliko faktorjev in sicer: delež založenega primarnega in sekundarnega aluminija v talilno peč, obdelava taline, čiščenje taline v peči, udrobnjevanje taline, čiščenje taline izven peči, procesni parametri pri litju in pogoji homogenizacije drogov [6].

Prednost zlitine EN AW-6082 v primerjavi z drugimi materiali (npr. jeklom) je njena relativno majhna gostota ob relativno

1 Introduction

The aluminium alloy EN AW-6082 is used for various purposes in the construction industry, mechanical engineering, automotive industry, etc [1]. Many years of experience in the application of the alloy EN AW-6082 for commercial purposes have shown that this alloy is resistant to weather conditions without protective coatings. Among the alloys of the 6xxx series, it achieves the best mechanical properties (e.g. yield strength 320 MPa, elongation 12%) [2]. The microstructure and mechanical properties of the EN AW-6082 alloy depend on the alloying elements (many intermetallic phases are formed) and on the values of the process parameters during the production of the melt, casting, solidification, homogenization, transformation and heat treatment [3,4,5]. In the production process of manufacturing aluminium alloy EN AW-6082 the quality of the final product is influenced by many factors, namely: what is the proportion of stocked primary and secondary aluminium into the melting furnace, what is the treatment of the melt, what is the treatment of the melt in the furnace, modification

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visoki meji tečenja [7]. V sodobnih livarnah se talina za pripravo zlitine EN AW-6082 izdela v določenem deležu iz primarnega in sekundarnega aluminija. Že pri pripravi taline se pojavijo v talini nečistoče oz. vključki, ki so lahko kovinskega ali nekovinskega izvora in lahko negativno vplivajo na livne in mehanske lastnosti ulite zlitine. Da zagotovimo homogeno kemijsko sestavo taline v livni peči, je pred začetkom litja potrebno pravilno izvesti tehnološke operacije, kot so: legiranje, čiščenje, mešanje in odstajanje [8,9]. Za obdelavo taline izven peči se uporablja udrobnjevalec AlTi5B1 [10], ki prispeva k udrobnjevanju primarnih zmesnih kristalov α-Al in SIR filter (sifonski inertni reaktor), ki je učinkovita naprava za rafiniranje in odstranjevanje vodika iz taline. Postopek litja poteka na polkontinuirnem vertikalnem livnem stroju, po tehnologiji imenovani „Hot top - gas slip“. Hot top je naziv za postopek litja drogov s posebno konstrukcijo kokile, ki je sestavljena iz keramičnega in grafitnega obroča. Po litju je potrebno drogove toplotno obdelati in na ta način zagotoviti optimalne mehanske lastnosti za nadaljnjo predelavo (iztiskanje drogov) [9].

Primerjali smo rezultate preiskav in analiz iz dveh šarž aluminijeve zlitine EN AW-6082 pred in po predelavi livnega sistema. Za karakterizacijo preiskovane aluminijeve zlitine EN AW-6082 visoke kakovosti in doseganje ustrezne mikrostrukture na drogovih premera 228 mm, so bile opravljene naslednje analize in preiskovalne metode: temperaturne meritve, kemijska analiza, termodinamična simulacija faznih ravnotežij (Thermo-Calc) ter optična mikroskopija in elektronska mikroskopija. Ugotovljeno je bilo, da je za doseganje ustrezne mikrostrukture po celotni dolžini droga zlitine EN AW-6082 potrebno zagotoviti višjo temperaturo taline na začetku litja. Namen raziskave

agent added to the melt, how is the cleaning of the melt outside the furnace, what are the parameters of the casting process and the conditions under which the billets are homogenized [6].

The advantage of the EN AW-6082 alloy compared to other materials (e.g. steel) is its relatively low density with a relatively high yield strength [7]. In modern foundries, the melt for preparing the EN AW-6082 alloy is produced in a certain proportion from primary and secondary aluminium. During the preparation of the melt, impurities appear in the melt or inclusions that may be of metallic or non-metallic origin and may adversely affect the casting properties and mechanical properties of the cast alloy. To ensure a homogeneous chemical composition of the melt in the casting furnace, technological operations such as: alloying, cleaning, mixing, and settling [8,9] must be performed correctly before the start of casting. An AlTi5B1 [10] grain refiner, which contributes to the refining of the primary α-Al crystals, and a SIR filter (siphon inert reactor), which is an efficient device for refining and removing hydrogen from the melt, are used for processing the melt outside the furnace. The casting process takes place on a semi-continuous vertical casting machine, the technology called “Hot top - gas slip” is used. Hot top is the name for the process of casting billets with a special construction of the mold, which consists of a ceramic and graphite ring. After casting, it is necessary to heat treat the billets and ensure optimal mechanical properties for further processing (extrusion of the billets) [9].

The results of investigations and analyses from two batches of cast aluminium alloy EN AW-6082 before and after the reconstruction of the casting system were compared. For the characterization of the investigated aluminium alloy EN je bil izdelava drogov zlitine EN AW-6082 dolžine 7000 mm z minimalnim izmetom, oziroma znižanje tehnološkega izmeta, kar pomeni boljšo stroškovno učinkovitost in konkurenčnost na trgu.

2 Eksperimentalno delo

Meritve temperatur so bile izvedene na livnih kokilah tik pred litjem ter med litjem v talini zlitine EN AW-6082. Meritve temperatur na livnih kokilah so se izvajale s prenosnim digitalnim termometrom znamke Voltcraft IR 550-10S, meritve taline pa so se izvajale preko temperaturne sonde v livni peči in z ročnim digitalnim termometrom znamke Therm 225-1. Meritve so se izvajale pred in po predelavi livnega sistema.

Kemijska analiza na vzorcih iz zlitine EN AW-6082 je bila narejena z optično emisijskim spektrometrom OES ARL 4460 v podjetju Talum Inštitut d.o.o. v Kidričevem. Iz analizirane kemijske sestave smo z računalniškim programom Thermo-Calc in bazo podatkov TCAl4 izvedli simulacijo termodinamično ravnotežnega strjevanja preiskovane zlitine EN AW-6082. Z računalniškim programom smo izračunali izopletne ravnotežne fazne diagrame z vsemi termodinamično obstojnimi fazami.

V okviru raziskave smo analizirali tudi mikrostrukturne sestavine na drogu iz zlitine EN AW-6082 pred in po predelavi livnega sistema. Za karakterizacijo mikrostrukture zlitine EN AW-6082 smo opravili analize na 48 vzorcih homogenizirane aluminijeve zlitine EN AW-6082, ki so bili odvzeti iz šestih odrezov (diskov) iz homogeniziranega droga. Debelina diska je bila 20 mm, premer pa 228 mm. Trije diski so bili odvzeti iz prve šarže (oznaka A) na dolžini droga 5900 mm, 6500 mm in 7000 mm, ki je bila lita pred predelavo livnega sistema, trije diski pa so bili odvzeti iz druge šarže (oznaka B) na dolžini droga 5900 mm, 6500 mm in

AW-6082 of high quality and to achieve appropriate microstructure on billets of 228 mm diameter the following measurements and investigation methods were used: temperature measurement, chemical analysis, thermodynamic simulation of phase equilibria (Thermo-Calc), optical microscopy and electron microscopy. It was found that to achieve the appropriate microstructure over the entire length of the billet from alloy EN AW-6082 it is necessary to provide a higher temperature of the melt at the start of the casting. The purpose of the investigation was to cast billets from alloy EN AW-6082 of length 7000 mm with minimal rejection, which means better cost efficiency and market competitiveness.

2 Experimental Work

Temperature measurements were performed on continuous casting molds just before casting and during casting in the EN AW-6082 alloy melt. Temperature measurements on the casting molds were carried out with a portable digital thermometer of the brand Voltcraft IR 550-10S, and measurements of the melt were carried out via a temperature probe in the casting furnace and with a hand-held digital thermometer of the brand Therm 225-1. Measurements were carried out before and after the reconstruction of the casting system.

Chemical analysis on samples from alloy EN AW-6082 was performed with an optical emission spectrometer OES ARL 4460 in the company Talum Institut d.o.o. in Kidričevo. Based on the analyzed chemical composition, a simulation of the thermodynamic equilibrium solidification of the investigated alloy EN AW-6082 using the Thermo-Calc computer program and the TCAl4 database was performed. Using

7000 mm, ki je bila lita po predelavi livnega sistema. Merjenje dolžine preiskanega droga se je izvajalo od glave droga (konec litja) proti peti droga (začetek litja), kar pomeni, da je bila dolžina droga na 7000 mm dejansko dolžina droga po 150 mm litja, dolžina droga 6500 mm je bila dejanska dolžina po 650 mm litja, dolžina droga 5900 mm pa je bila dejanska dolžina po 1150 mm litja. Končna livna dolžina drogov znaša 7300 mm, pri čemer odrez glave in pete ulitega droga znašata skupaj 300 mm. Za analizo zrnatosti so bile narejene preiskave z optičnim mikroskopom Olympus BX61 v polarizirani svetlobi. Vzorce zlitine EN AW-6082 smo preiskali tudi z vrstičnim elektronskim mikroskopom JEOL JSM 5610, ki je opremljen z energijsko disperzijskim spektrometrom rentgenskih žarkov.

3 Rezultati in diskusija

Temperaturne meritve so se najprej izvajale na livnih žlebovih in livni garnituri (kokilah) pred in po predelavi livnega sistema. Ugotovili smo, da izolacijski pokrovi bistveno prispevajo k ogrevanju livnega sistema pred začetkom litja. Po predelavi livnega sistema je bila temperatura taline na začetku litja višja (slika 1), kar ugodno vpliva na mikrostrukturo droga zlitine EN AW-6082.

Merjenje temperature taline pred predelavo livne garniture se je izvajalo na začetku litja in nato pri dolžini ulitega droga 150 mm. Temperatura taline se je merila s termo-sondo pri izlivu livne peči in je znašala 722 °C. Temperatura taline se je merila tudi v livnem žlebu in je znašala 695 °C. Temperatura taline v zadnji najbolj oddaljeni kokili livne garniture Φ 228 mm pa je znašala 650 °C. Po predelavi livne garniture pa je temperatura taline pri izlivu livne peči znašala 722 °C, v livnem žlebu

a computer program, isopleth equilibrium phase diagrams with all thermodynamically stable phases were calculated.

In a frame of the work, the microstructural components on the EN AW-6082 alloy billet before and after processing the casting system were analyzed. To characterize the microstructure of the EN AW-6082 alloy, analysis on 48 samples of the homogenized aluminium alloy EN AW-6082, which were taken from six discs from the homogenized billets was performed. The thickness of the disk was 20 mm, and the diameter was 228 mm. Three discs were taken from the first batch (designation A) at billet lengths of 5900 mm, 6500 mm and 7000 mm, which were cast before the casting system was reconstructed, and three discs were taken from the second batch (designation B) at a billet length of 5900 mm, 6500 mm and 7000 mm, which was cast after the reconstruction of the casting system. The length of the examined billet was measured from the head of the billet (end of casting) to the heel of the billet (beginning of casting), which means that the length of the billet at 7000 mm was actually the length of the billet after 150 mm of casting, the length of the billet of 6500 mm was the actual length after 650 mm casting, and the billet length of 5900 mm was the actual length after 1150 mm casting. The final casting length of the billet is 7300 mm, with the cut of the head and heel of the cast billet totalling 300 mm. For grain analysis, examinations were made with an optical microscope Olympus BX61 in polarized light. The EN AW-6082 alloy samples were also examined with a JEOL JSM 5610 scanning electron microscope equipped with an energy-dispersive X-ray spectrometer.

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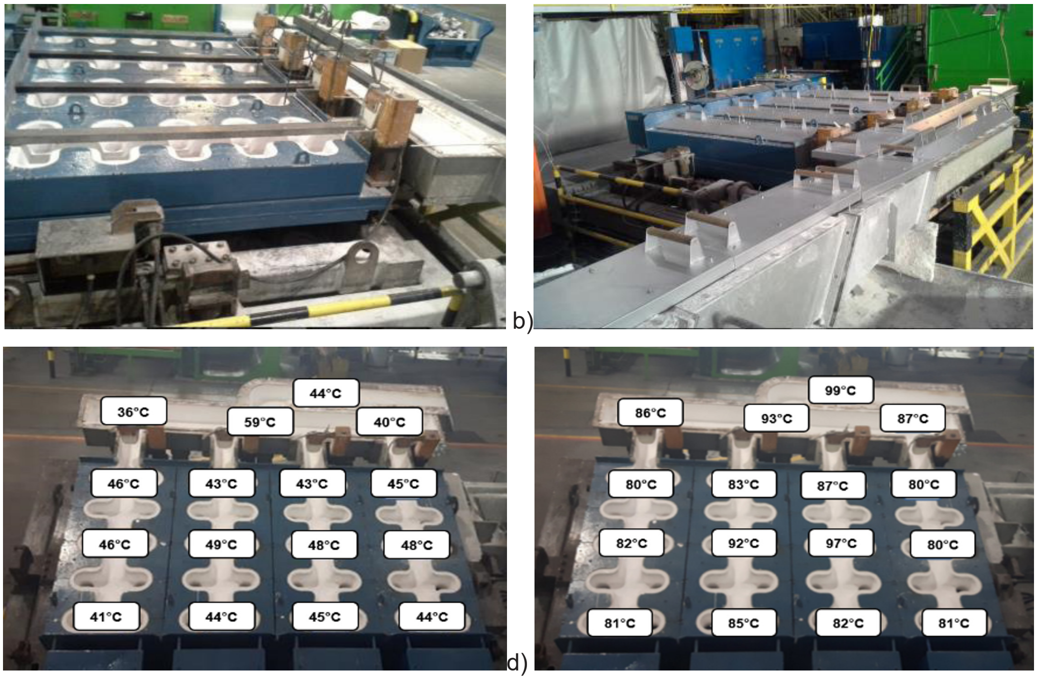
a) b) c) d)



Slika 1. Gretje livne garniture brez izolacijskih pokrovov (a), lokacije in rezultati meritev livne garniture v °C pred litjem šarže A (b) ter gretje livne garniture z izolacijskimi pokrovi (c) in lokacije in rezultati meritev livne garniture v °C pred litjem šarže B (d).

Figure 1. Heating of the casting die without insulating covers (a), locations and results of measurements of the casting die in °C before casting batch A (b) and heating of the casting die with insulating covers (c) and locations and results of measurements of the casting die in °C before casting of batch B (d).

705 °C in v zadnji najbolj oddaljeni kokili livne garniture Φ 228 mm 658 °C.

Načrtovano sestavo zlitine EN AW-6082 smo izdelali z mešanjem taline primarnega in sekundarnega aluminija, približno v razmerju 1:1, v 40 t električni peči. Doseganje ustrezne kemijske sestave smo izvedli z dodajanjem legirnih elementov. Talino v peči smo legirali s čistim magnezijem in silicijem. Preiskave kemijske sestave so bile narejene pri pripravi taline na livni peči tik pred pričetkom litja drogov. Obe kemijski sestavi sta bili ustrezni in sta podani v tabeli 1.

Analiza kemijske sestave smo naredili tudi na šestih vzorcih iz ulitega droga

3 Results and Discussion

Temperature measurements were first carried out on the casting launder and casting die (molds) before and after the casting system was reconstructed. It was found that the insulating covers significantly contribute to the heating of the casting system before the start of casting. After reconstruction the casting system, the temperature of the melt at the beginning of casting was higher (Figure 1), which has a favourable effect on the microstructure of the EN AW-6082 alloy billet.

The measurement of the temperature of the melt before reconstruction of casting

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Tabela 1. Kemijska sestava šarže A in B pred litjem.

Table 1. Chemical composition of batches A and B before casting.

Šarža / Batch	Element [mas. %]											Nečistoče / Impurities	
	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Hg	Pb	Cd	Posamezno / Individually	Skupaj / Together
A	0,84	0,26	0,01	0,47	0,67	0,01	0,02	0,02	<0,001	<0,01	<0,001	<0,05	0,84
B	0,85	0,24	0,02	0,49	0,69	0,03	0,02	0,01	<0,001	<0,01	<0,001	<0,05	<0,15

Tabela 2. Kemijska sestava preiskovanih vzorcev iz diskov.

Table 2. Chemical composition of the investigated samples from discs.

Vzorec / Sample	Element [mas. %]											Nečistoče / Impurities	
	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Hg	Pb	Cd	Posamezno / Individually	Skupaj / Together
A1S	0,83	0,25	0,01	0,47	0,64	0,01	0,02	0,02	<0,001	<0,01	<0,001	<0,05	<0,15
A1R	0,85	0,26	0,01	0,47	0,65	0,01	0,02	0,02	<0,001	<0,01	<0,001	<0,05	<0,15
A2S	0,83	0,25	0,01	0,47	0,64	0,01	0,02	0,03	<0,001	<0,01	<0,001	<0,05	<0,15
A2R	0,85	0,26	0,01	0,47	0,65	0,01	0,02	0,02	<0,001	<0,01	<0,001	<0,05	<0,15
A3S	0,84	0,26	0,01	0,47	0,64	0,01	0,02	0,03	<0,001	<0,01	<0,001	<0,05	<0,15
A3R	0,83	0,25	0,01	0,47	0,64	0,01	0,02	0,03	<0,001	<0,01	<0,001	<0,05	<0,15
B1S	0,83	0,24	0,01	0,50	0,65	0,03	0,02	0,02	<0,001	<0,01	<0,001	<0,05	<0,15
B1R	0,85	0,24	0,01	0,50	0,65	0,03	0,02	0,02	<0,001	<0,01	<0,001	<0,05	<0,15
B2S	0,83	0,23	0,01	0,50	0,64	0,03	0,02	0,02	<0,001	<0,01	<0,001	<0,05	<0,15
B2R	0,85	0,24	0,01	0,50	0,65	0,03	0,02	0,02	<0,001	<0,01	<0,001	<0,05	<0,15
B3S	0,83	0,23	0,01	0,50	0,64	0,03	0,02	0,02	<0,001	<0,01	<0,001	<0,05	<0,15
B3R	0,84	0,24	0,01	0,50	0,65	0,03	0,02	0,02	<0,001	<0,01	<0,001	<0,05	<0,15

šarže A, ki je bil lit pred predelavo livnega sistema in šestih vzorcih ulitega droga šarže B, ki je bil lit po predelavi livnega sistema. Kemijska analiza je bila narejena na šestih diskih obeh ulitih šarž zlitine EN AW-6082 iz sredine in roba diska. Rezultati kemijske analize iz označenih vzorcev, ki so bili odvzeti iz diskov šarže A in šarže B, so prikazani v tabeli 2. Oznake vzorcev so: A - podaja šaržo, številke 1, 2 in 3 - mesto odvzema diska na 5900, 6500 in 7000 mm dolžine droga ter S in R-sredina ali rob droga. Kemijska analiza preiskanih vzorcev je prikazala, da je na robu droga pri obeh šaržah večja koncentracija Si, Fe in Mg. Iz kemijske analize prikazane v tabeli 2 smo ugotovili prisotnost makroizcej, delež

system the continuous casting die was carried out at the beginning of the casting and then at a length of 150 mm of the cast billet. The temperature of the melt was measured with a thermo-probe at the outlet of the casting furnace and was 722 °C. The temperature of the melt was also measured in the casting launder and was 695 °C. The temperature of the melt in the outermost mold of the Φ 228 mm casting die was 650 °C. After reconstruction the casting die, the temperature of the melt at the outlet of the casting furnace was 722 °C, 705 °C in the casting launder and 658 °C in the outermost mold of the casting die Φ 228 mm.

The planned composition of the EN AW-6082 alloy was produced by mixing legirnih elementov na robu diska je večji kot v sredini diska.

Za termodinamične simulacije so bili izbrani štirje elementi, ki so v zlitini aluminija zastopani v največjih deležih (Si, Fe, Mg in Mn). Na sliki 2 je razvidno, da se ravnotežno strjevanje preiskovane zlitine prične, ko se iz taline začnejo strjevati primarni zmesni kristali α-Al pri temperaturi 651 °C (likvidus temperatura). Z zniževanjem temperature se pri temperaturi 633 °C začne strjevati evtektska faza $Al_{15}Si_2Mn_2$. Strjevanje se konča pri temperaturi 601 °C. Pri nadaljnjem ohlajanju se pri temperaturi 510 °C prične izločanje faze Mg_2Si. Ko temperatura taline pade na 437 °C se začne izločanje faze $Al_9Fe_2Si_2$. Glede na termodinamični izračun se pri temperaturi 441 °C izloči še faza β-Si.

V tabeli 3 so prikazane faze in temperature pri katerih se faze strjujejo oz. izločajo, ter ravnotežni delež le-teh pri sobni temperaturi odčitanih iz ravnotežnega faznega diagrama prikazanega na sliki 2.

S pomočjo atlasa mikrostruktur aluminijevih zlitin smo kvalitativno določili značilne faze v izrezu diska zlitine EN AW-6082 (slika 3). Mikrostruktura zlitine EN AW-6082 sestoji iz večkomponentne trdne raztopine α-Al. Ločimo lahko faze AlFeMnSi, ki se pojavljajo v različnih

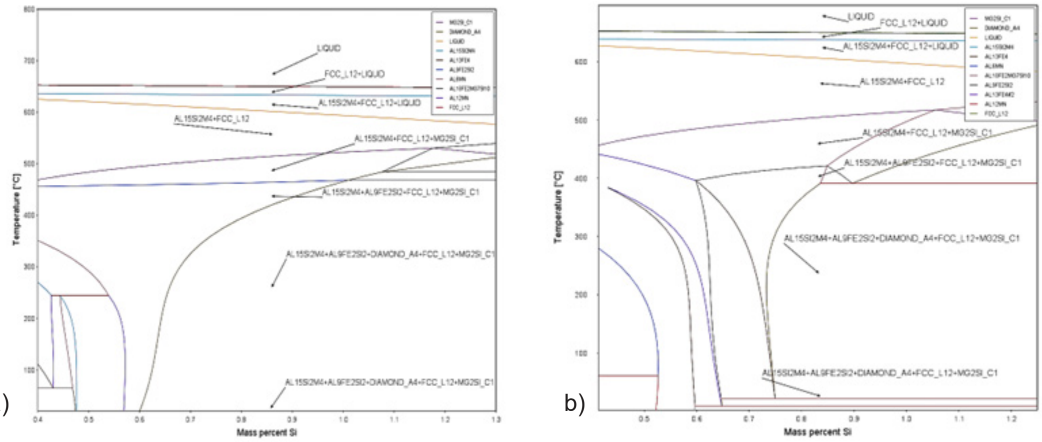
primary and secondary aluminium melt, approximately in a 1:1 ratio, in a 40 t electric furnace. The appropriate chemical composition was achieved by adding alloying elements. The melt in the furnace was alloyed with pure magnesium and silicon. Investigations of the chemical composition were made during the preparation of the melt in the casting furnace just before the start of casting the bars. Both chemical compositions were adequate.

The chemical composition analysis was also performed on six samples from the cast billet of batch A, which was cast before reconstruction of the casting system, and six samples of the cast billet of batch B, which was cast after reconstruction the casting system. Chemical analysis was done on six discs of both cast batches of EN AW-6082 alloy from the centre and edge of the disc. The results of the chemical analysis from the labeled samples taken from the discs of batch A and batch B are shown in Table 2. Sample labels are A-indicates the batch, numbers 1, 2 and 3-place of the disc withdrawal at 5900, 6500 and 7000 mm of billet length and S and R - middle or edge of the disc. The chemical analysis of the examined samples presented in Table 2 showed that there is a higher concentration of Si, Fe and Mg at the edge of the billet in

Tabela 3. Ravnotežne faze ter temperature nastanka faz, ki se pojavijo v zlitini EN AW-6082.

Table 3. Equilibrium phases and phase formation temperatures that occur in the EN AW-6082 alloy.

Faza / Phase	Šarža / Batch A		Šarža / Batch B	
	Temperatura / Temperature [°C]	Delež faze pri 20 °C / Phase fraction at 20 °C [mas. %]	Temperatura / Temperature [°C]	Delež faze pri 20 °C / Phase fraction at 20 °C [mas. %]
α-Al	651	96,077	649	96,352
$Al_{15}Si_2Mn_2$	633	1,605	636	1,670
solidus	601	/	607	/
Mg_2Si	510	1,057	504	1,020
$Al_9Fe_2Si_2$	437	1,001	421	0,872
β-Si	441	0,260	388	0,279



Slika 2. Ravnotežni izopletni fazni diagram šarže A (a) in šarže B (b).

Figure 2. Equilibrium isopleth phase diagram of batch A (a) and batch B (b).

oblikah »kitajske pisave« in intermetalno fazo Mg_2Si [11]

Na vseh preiskovanih vzorcih smo naredili tudi kvantitativno analizo mikrostrukturnih sestavin. Na ta način se je analiziralo število faz (Mg2Si >1 µm/0,51 mm^2), poroznost se je analizirala na podlagi internih etalonov in analiziralo se je število vključkov (/cm^2). Poroznost se je analizirala

both batches. From the chemical analysis was found the presence of microsegregates; the proportion of alloying elements at the edge of the disc is greater than in the middle of the disc.

Four elements were chosen for the thermodynamic simulations, which are represented in the largest proportions in the aluminium alloy (Si, Fe, Mg and Mn). It

Tabela 4. Vrednosti analize preiskanih vzorcev pred predelavo livnega sistema.

Table 4. The analysis values of the examined samples before recostructing the casting system.

Vzorec / Sample	Število / Number Mg_2Si > 1 µm / 0,51 mm^2	Poroznost / Porosity	Število vključkov / Number of inclusions / cm^2	
			< 20 µm	20–50 µm
A1S	176	5,0		
A1R	198	4,0	1	1
A2S	169	4,5	1	1
A2R	189	3,5	2	2
A3S	157	5,0	1	1
A3R	179	5,0	2	1
B1S	145	3,0		
B1R	171	2,5	1	
B2S	153	4,0		
B2R	173	3,0		
B3S	170	4,5		1
B3R	186	4,0	2	

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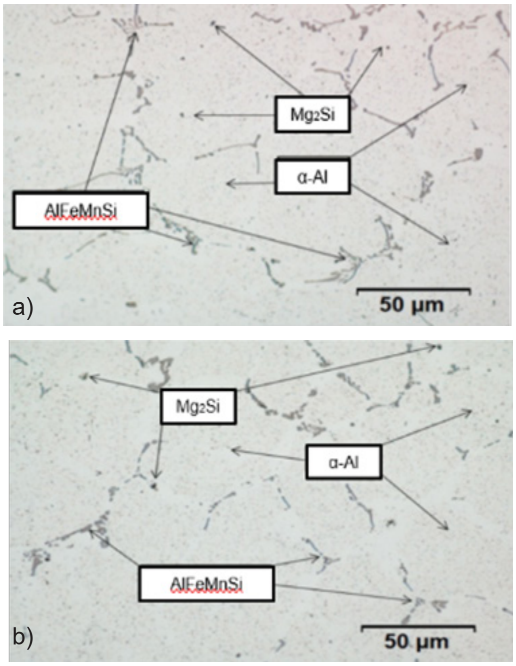


Slika 3. Mikroposnetek vzorca iz šarže A, odvzetega na dolžini droga 7000 mm iz sredine (a) ter vzorca iz šarže B, odvzetega na dolžini droga 7000 mm iz sredine (b).

Figure 3. Micrograph of a sample from batch A taken at a billet length of 7000 mm from the centre (a) and a sample from batch B taken at a billet length of 7000 mm from the centre (b).

kvalitativno na podlagi primerjalnih etalonov. Vrednosti analize vzorcev so razvidne v tabeli 4. Vzorci so bili velikosti cca 4 cm^2. Iz kvantitativne analize mikrostrukturnih sestavin smo ugotovili, da je po predelavi livnega sistema število faz Mg_2Si, ki so večje od 1 mikrometra, manjše. Zmanjšala se je poroznost in število vključkov.

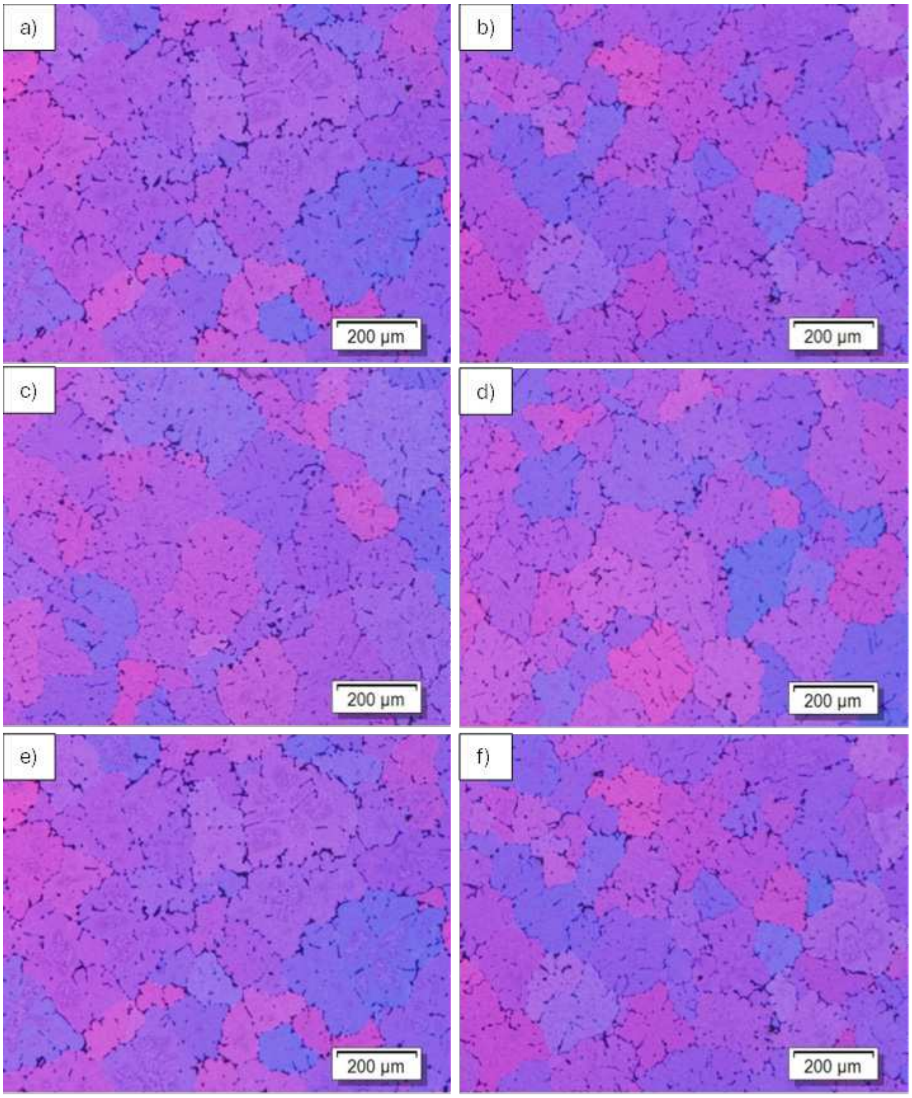
S primerjavo velikosti kristalnih zrn smo potrdili, da so zrna ob robu diska manjša kot na sredini diska, zaradi večje ohlajevalne hitrosti na robu drogov (sliki 4 in 5). Ugotovili smo, da je v obeh ulitih šaržah iz zlitine EN AW-6082 makrostruktura finozrnata, kar je posledica dodajanja udrobnjevalca AlTi5B1. Opazimo lahko tudi, da so zrna

can be seen in Figure 2 that the equilibrium solidification of the investigated alloy begins when the primary crystals of α-Al begin to solidify from the melt at a temperature of 651 °C (liquidus temperature). As the temperature decreases, the $Al_{15}Si_2Mn_2$ eutectic phase begins to solidify at a temperature of 633 °C. Solidification ends at a temperature of 601 °C. During further cooling, at a temperature of 510 °C, the precipitation of the Mg_2Si phase begins. When the temperature of the melt drops to 437 °C, the $Al_9Fe_2Si_2$ phase begins to precipitate. According to the thermodynamic calculation, the β-Si phase also precipitates at a temperature of 441 °C.

Table 3 shows the phases and temperatures at which the phases solidify or precipitate, and their equilibrium fraction at room temperature read from the equilibrium phase diagram shown in Figure 2.

With the help of the atlas of microstructures of aluminium alloys, qualitatively the characteristic phases in the EN AW-6082 alloy disc (Figure 3) were determined. The microstructure of the EN AW-6082 alloy consists of a multicomponent α-Al solid solution. The AlFeMnSi phases were distinguished, which appear in various “Chinese script” forms, and the Mg_2Si intermetallic phase [11].

A quantitative analysis of microstructural components on all investigated samples was also performed. In this way, the number of phases was analyzed (Mg_2Si >1 μm/0.51 mm^2), the porosity was analyzed based on internal standards and the number of inclusions (/cm^2). Porosity was analyzed qualitatively based on comparative standards. The values of the sample analysis can be seen in Table 4. The samples were approximately 4 cm^2 in size. From the quantitative analysis of the microstructural components was found that after reconstruction of the casting system,



Slika 4. Mikrostruktura šarže A v polarizirani svetlobi: A1S (a), A1R (b), A2S (c), A2R (d), A3S (e), A3R (f).

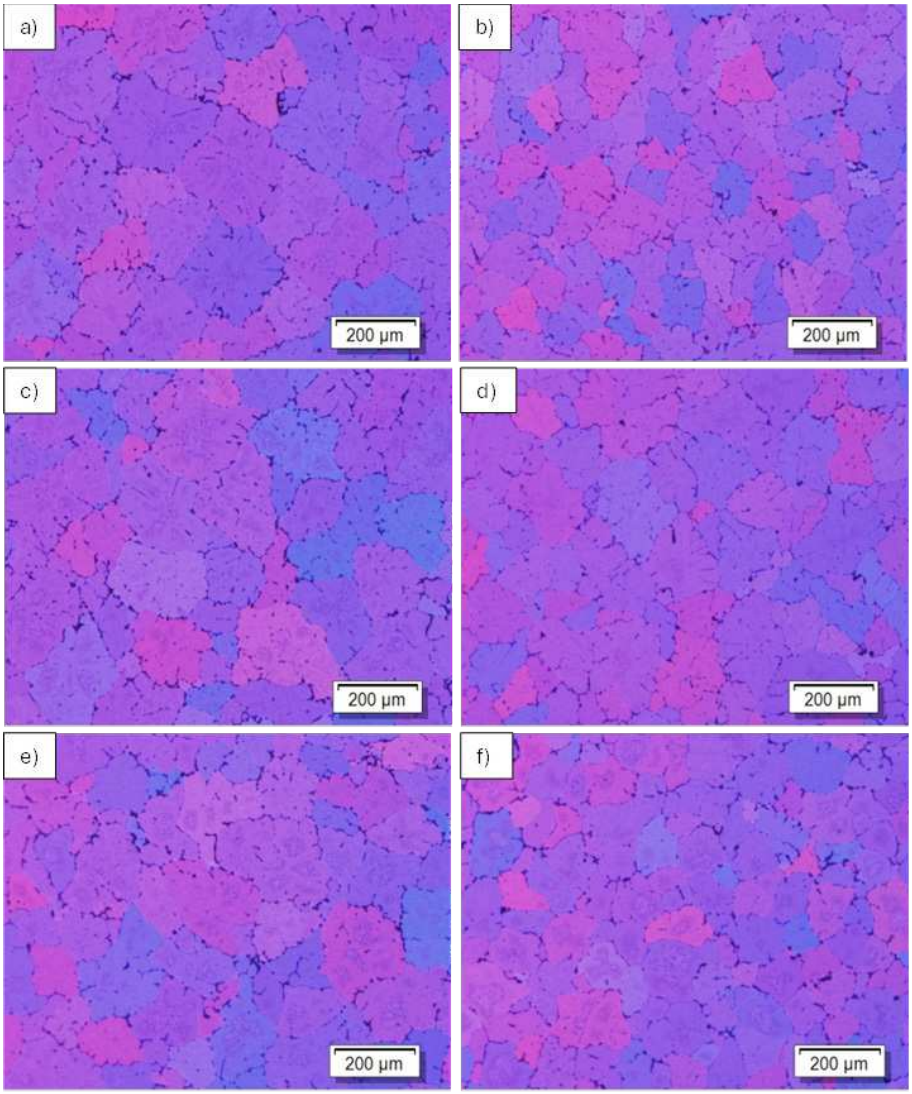
Figure 4. Microstructure of batch A in polarized light: A1S (a), A1R (b), A2S (c), A2R (d), A3S (e), A3R (f).

na vseh preiskanih mestih droga manjša po predelavi livnega sistema (tabela 5).

Elektronska mikroanaliza vzorcev (SEM) je bila narejena na šestih diskih zlitine EN AW-6082 iz roba diska. V mikrostrukturi smo potrdili in karakterizirali

the number of Mg_2Si phases that are larger than 1 micrometer is smaller. Porosity and the number of inclusions decreased.

By comparing the size of the crystal grains, it was confirmed that the grains at the edge of the disc are smaller than in the

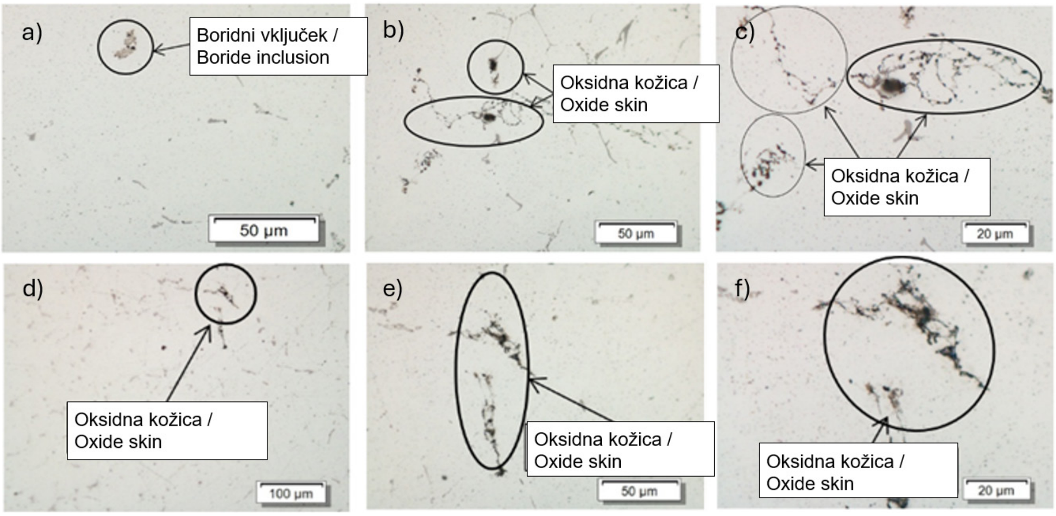


Slika 5. Mikrostruktura šarže B v polarizirani svetlobi: B1S (a), B1R (b), B2S (c), B2R (d), B3S (e), B3R (f).

Figure 5. Microstructure of batch B in polarized light: B1S (a), B1R (b), B2S (c), B2R (d), B3S (e), B3R (f).

prisotnost intermetalnih faz, vključkov in nečistoč (slika 6). Namen raziskave je bil doseganje ustrezne mikrostrukture na drogovih dolžine 7000 mm, ki so namenjeni za visoko kakovostne profile iz aluminija s čim manjšim odrezom (izmetom).

middle of the disc, due to the higher cooling rate at the edge of the billets (Figures 4 and 5). It was found that in both batches cast from the EN AW-6082 alloy, the macrostructure is fine-grained, which is a result of the addition of AlTi5B1 grain refiner. It can also



Slika 6. Vzorec A1R: TiB_2 - boridni vključek (a), vzorec A2R: $MgAl_2O_4$ - oksidna kožica (b, c), vzorec B3R: Mg-oksid (d, e, f).

Figure 6. Sample A1R: TiB_2 - boride inclusion (a), sample A2R: $MgAl_2O_4$ - oxide skin (b, c), sample B3R: Mg-oxide (d, e, f).

Tabela 5. Primerjava velikosti zrn preiskanih vzorcev iz šarže A in šarže B.

Table 5. Comparison of the grain size of the investigated samples from batch A and batch B.

Vzorec / Sample	Velikost zrn / Grain size [µm]	Šarža / Sample	Velikost zrn / Grain size [µm]
A1S	159	B1S	152
A1R	121	B1R	116
A2S	155	B2S	147
A2R	122	B2R	114
A3S	150	B3S	139
A3R	117	B3R	109

S SEM analizo smo ugotovili, da so v drogovih, ki so bili uliti pred in po predelavi livnega sistema v mikrostrukturi prisotni vključki in nečistoče na osnovi Al, Ti, Ca, Mg in O. Prisotnost O bi lahko bila povezana s prekomerno uporabo tehničnih plinov, ki se

be observed that the grains are smaller in all investigated locations of the billet after reconstructing the casting system (Table 5).

Scanning electron microanalysis (SEM) of samples was performed on six discs of EN AW-6082 alloy from the edge of the disc. The presence of intermetallic phases, inclusions and impurities in the microstructure was confirmed and characterized (Figure 6). The purpose of the work was to achieve an appropriate microstructure on 7000 mm long billets, which are intended for high-quality aluminium profiles with the smallest possible cut (discharge).

Through SEM analysis, it was found that in the billets that were cast before and after reconstruction of the casting system, there are inclusions and impurities based on Al, Ti, Ca, Mg and O in the microstructure. The presence of O could be related to the excessive use of technical gases, which are used when casting billets on a Hot Top casting machine.

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uporabljajo pri litju drogov na livnem stroju Hot Top.

4 Zaključki

Namen raziskve je bil doseči ustrezno mikrostrukturo drogov dolžine 7000 mm iz zlitine EN AW-6082, ki je namenjena za visoko kakovostne profile iz aluminija. V delu smo analizirali strjevanje in mikrostrukturne sestavine pred in po predelavi livnega sistema. Iz opravljenih preiskav smo prišli do naslednjih zaključkov:

1. Pri merjenju temperature sistema livnih žlebov in livne garniture pred in po predelavi livnega sistema smo ugotovili, da so temperature v povprečju za 45 °C višje, če je livni sistem pokrit z izolacijskimi pokrovi.
2. Kljub temu, da je na začetku ulivanja drogov pred in po predelavi livnega sistema bila pri obeh šaržah temperatura taline na livni peči enaka, smo pri litju izmerili različne temperature taline na istih mestih livnega sistema. Temperatura se je glede na oddaljenost od livnega sistema do droga nekoliko spreminjala oz. ni bila konstantna. Temperatura taline na najbolj oddaljenem mestu livne garniture je bila višja za 8 °C, ko je bila livna garnitura pokrita s pokrovi.
3. Iz kemijske analize smo ugotovili prisotnost makroizcej, delež legirnih elementov na robu diska je večji kot v sredini diska.
4. Z računalniškim programom Thermo-Calc je bila izvedena simulacija termodinamičnih ravnotežij preiskovane zlitine EN AW-6082. Ugotovljena je prisotnost naslednjih mikrostrukturnih sestavin: α-Al, $Al_{15}Si_2Mn_2$, Mg_2Si, $Al_9Fe_2Si_2$ in β-Si.
5. Primerjava mikrostruktur pred in po predelavi livnega sistema je dokazala

4 Conclusions

The aim of the investigation was to achieve the appropriate microstructure of the 7000 mm long billets made of EN AW-6082 alloy, which is intended for high-quality aluminium profiles. In the investigation, solidification and microstructural components before and after reconstruction of the casting system were analyzed. From the conducted investigations, the following conclusions can be drawn:

1. When measuring the temperature of the casting launder system and the casting die before and after reconstructing the casting system, it was found that the temperatures are in average 45 °C higher if the casting system is covered with insulating covers.
2. Despite the fact that at the beginning of the casting of the billets before and after reconstructing the casting system, the temperature of the melt on the casting furnace was the same in both batches, during casting different temperatures of the melt at the same places of the casting system were measured. The temperature varied slightly depending on the distance from the casting system to the billet or was not constant. The temperature of the melt at the farthest point of the casting die was 8 °C higher when the casting die was covered with covers.
3. From the chemical analysis, the presence of microsegregates was found, whereas the proportion of alloying elements at the edge of the disc is greater than in the middle of the disc.
4. The Thermo-Calc computer program was used to simulate the thermodynamic balances of the investigated EN AW-6082 alloy. The presence of the following microstructural components was found: α-Al, $Al_{15}Si_2Mn_2$, Mg_2Si,

večjo prisotnost nekovinskih vključkov v mikrostrukturi droga na dolžini 7000 mm, ki je bil ulit pred predelavo livnega sistema.

6. Ugotovili smo, da je v mikrostrukturi zlitine EN AW-6082 število faz Mg_2Si, ki so večje od 1 μm na drogu dolžine 7000 mm manjše, če je livni sistem pokrit z izolacijskimi pokrovi.
7. S primerjalno analizo smo dokazali, da je poroznost v mikrostrukturi zlitine EN AW-6082 v drogu dolžine 7000 mm manjša, če je livni sistem pokrit z izolacijskimi pokrovi.
8. Ugotovili smo, da livni sistem, ki je pokrit z izolacijskimi pokrovi, vpliva na velikost kristalnih zrn. V mikrostrukturi drogov, ki so bili liti po predelavi livnega sistema, so zrna na dolžini droga 7000 mm manjša za cca 5 %.
9. Z vrstično elektronsko mikroskopijo (SEM) je v mikrostrukturi dokazana prisotnost vključkov in nečistoč različnih oblik in velikosti na osnovi O, Al, Mg, Ca in Ti.

Glede na dobljene rezultate smo ugotovili, da je potrebno zagotoviti čim bolj enakomerne pogoje litja skozi celotno litje posamezne šarže. Na začetku litja je za uspešen pričetek litja potrebno zagotoviti ustrezno temperaturo taline na najbolj oddaljenem delu livne garniture, ki odločilno vpliva na mikrostrukturo zlitine EN AW-6082. Dokazali smo, da je razdelilne žlebove pred SIR filtrom bolje toplotno izolirati. To zaradi zmanjšanja temperaturnega gradienta taline med začetkom in koncem litja prispeva k izboljšanju mikrostrukture drogov zlitine EN AW-6082 na dolžini 7000 mm in s tem se zmanjša izmet oz. odrez drogov po litju.

Ugotovitve raziskave so že bile vpeljane v redno proizvodnjo. Dosegli so zmanjšanje tehnološkega izmeta, kar predstavlja boljšo

$Al_9Fe_2Si_2$ and β-Si.

5. The comparison of the microstructures before and after the reconstruction of the casting system proved the greater presence of non-metallic inclusions in the microstructure of the billet with a length of 7000 mm, which was cast before the reconstruction of the casting system.
6. It was found that in the microstructure of the EN AW-6082 alloy, the number of Mg_2Si phases larger than 1 μm on a 7000 mm long billet is smaller if the casting system is covered with insulating covers.
7. Through a comparative analysis, the smaller porosity in the microstructure of the EN AW-6082 alloy in a 7000 mm long billet was proved if the casting system is covered with insulating covers.
8. We found that the casting system, which is covered with insulating covers, affects the size of the crystal grains. In the microstructure of billets that were cast after reconstruction of the casting system, the grains on the billet length of 7000 mm are smaller by approx. 5%.
9. The presence of inclusions and impurities of various shapes and sizes based on O, Al, Mg, Ca and Ti is proven by electron microscopy (SEM).

Based on the obtained results, it can be concluded that it is necessary to ensure the most uniform casting conditions throughout the entire casting of each batch. At the beginning of casting, for a successful start of casting, it is necessary to ensure the appropriate temperature of the melt at the farthest part of the casting die, which decisively affects the microstructure of the EN AW-6082 alloy. It was proved that it is better to thermally insulate the runners before the SIR filter. The reduction of the temperature gradient of the melt between stroškovno učinkovitost in konkurenčnost na trgu.

the beginning and the end of casting, contributes to the improvement of the microstructure of the billets of the EN AW-6082 alloy at a length of 7000 mm, thereby reducing the rejection or cutting of billets after casting.

The findings of the investigation have already been introduced into regular production. They have achieved a reduction in technological waste, which represents better cost efficiency and competitiveness in the market.

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