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Načini izboljšanja mehanskih lastnosti recikliranih aluminijevih zlitin

Ways to Improve Mechanical Properties of Recycled Aluminium Alloys

Izvleček

Poraba aluminija in aluminijevih zlitin po svetu narašča, ti materiali pa se uporabljajo na vedno nove načine. Aluminij se lahko proizvaja iz surovine, imenovane boksit, ali z recikliranjem odpadnega aluminija. Pri recikliranju aluminija je trdnost materiala odvisna od kakovosti staljene kovine ter legirnih elementov in elementov v sledeh v odpadnem aluminiju. Od trdnosti materiala litih izdelkov se veliko pričakuje in trg nenehno povprašuje po materialu, ki ima pravo in zanesljivo kakovost.

V tem prispevku smo želeli raziskati načine za izboljšanje mehanskih lastnosti recikliranih aluminijevih zlitin, osnova katerih je zlitinski sistem Al-Si. Proučili smo vpliv vsebnosti vodika na notranjo poroznost materiala in učinek legirnega elementa silicija (Si) na mehanske lastnosti materiala.

Vsebnost vodika smo med procesom recikliranja na določenih mestih merili z indeksom gostote (v talilnici) in z različnimi razplinjevalnimi metodami. Indeks gostote je merilo za merjenje in primerjavo vzorcev ob upoštevanju notranje poroznosti. Ker zrak vsebuje vlago, to vpliva na topnost vodika v talini in temperaturo taline. Rezultati nateznih preizkusov in mikroskopske raziskave jasno razkrivajo, da razlike v vsebnosti zlitinskih elementov vodijo v izjemne razlike v mehanskih lastnostih.

Ključne besede: aluminij, recikliranje, legirni elementi, litje, strjevanje, vodik, mehanske lastnosti, mikrosturktura

Abstract

The aluminium and aluminium alloys consumption in the world is increasing and continues to find new applications. Aluminium can be produced from the raw material bauxite or by recycling aluminium scrap. When aluminium is being recycled the material strength is depending on the molten metal quality as well as the alloying and trace elements in the aluminium scrap. High demands are put on the material strength of cast products and the market is continuously asking for a material with the right and reliable quality.

This paper aims to investigate ways to improve the mechanical properties of recycled aluminium alloys based upon the Al-Si alloy system. The influence of hydrogen content on internal porosity and the sole effect of the alloying element Si on the mechanical properties have been studied.

The hydrogen content has been measured by Density Index at specific locations in the recycling process (at the smelter) and with different degassing methods. Density Index is a

measure for measuring and comparing the samples with respect to the internal porosity. As the air contains moisture, along with the melt temperature, the solubility of hydrogen in the melt is affected. Furthermore, the tensile test results and microscopic investigations reveal clearly that the variations within the alloying element range lead to remarkable differences in the mechanical properties.
Keywords: Aluminium, recycling, alloying elements, casting, solidification, hydrogen, mechanical properties, microstructure

1 Uvod

V zadnjih letih se je število različnih vrst uporabe aluminijevih ulitkov povečalo zaradi njihove lahkosti, visoke trdnosti glede na težo, prožnosti in izjemne vsestranskosti. Toda ena lastnost je še posebej cenjena. Aluminij lahko recikliramo v nedogled. Ne glede na to, kolikokrat ga obdelamo in uporabimo, ostane tako rekoč nespremenjen. Zato je aluminij material s trajnimi lastnostmi, material, ki ni potrošen, ampak ga lahko uporabljamo vedno znova brez izgube njegovih najpomembnejših lastnosti. Za pretaljevanje aluminija potrebujemo malo energije: v procesu recikliranja je potrebne le 5 % energije, ki je potrebna za proizvodnjo primarne kovine [1–3].

Zahteve glede kakovosti aluminijevih zlitin pri pretaljevanju opredeljuje evropski standard EN 1676:2010. Ta standard razvršča in določa te lastnosti, proizvodne pogoje, njihove lastnosti in identifikacijske oznake [4]. Standard določa omejitve glede kemijske sestave aluminijevih zlitin za litje in mehanske lastnosti posameznih poskusnih litih vzorcev teh zlitin [5]. Ti standardi predstavljajo referenčne smernice za sektor, ki se ukvarja z litjem aluminijevih zlitin in s proizvodnjo ulitkov.

Kakovost aluminijevih ulitkov je v veliki meri odvisna od procesa litja in parametrov, kot so hitrost strjevanja, vendar pa tudi kemijska sestava pomembno vpliva na njihove mehanske lastnosti [6].

1 Introduction

The use of aluminium cast components in so many different applications has increased in recent years thanks to their light weight, high strength to weight aspect ratio, flexible and very versatile. But there’s one quality that is particularly most valuable. Aluminium is infinitely recyclable. It remains essentially unchanged no matter how many times it is processed and used. Therefore, aluminium be considered as a material with permanent characteristics, one that is not consumed, but used over and over again, without the loss of its essential properties. The remelting of aluminium requires little energy: no more than 5 % of the energy required to produce the primary metal initially is needed in the recycling process [1-3].

The quality requisites of aluminium alloys intended for remelting is defined by European Standard EN 1676:2010. This standard specifies the classification and designation that apply to these qualities, manufacturing conditions, their features and identification markings [4]. The standard specifics the chemical composition limits of aluminium alloys for casting and the mechanical features of the separate casting test specimens for said alloys [5]. These standards are reference guidelines in the world of foundry aluminium alloys and casting manufacturing.

The quality of aluminium components mainly depends on casting process and parameters, such as solidification rate, Ena od največjih težav, povezanih z litjem aluminijevih zlitin, je mikroporoznost. O soodvisnosti poroznosti in mehanskih lastnosti litih aluminijevih zlitin je pisalo veliko avtorjev [7–10]. Za določanje te soodvisnosti v večini študij uporabljajo parameter globalne volumetrične poroznosti. Med procesom litja in strjevanja nastajajo plini, ki povzročajo mikroporoznost. Plini so lahko posledica reakcije med formo iz peska in kovino ali pa se med strjevanjem sproščajo plini, raztopljeni v tekoči kovini. Najpomembnejši plin, ki je precej topen v aluminiju in njegovih zlitinah, je vodik. Topnost vodika v aluminiju se spreminja neposredno s temperaturo in kvadratnim korenom tlaka – topnost hitro narašča z naraščanjem temperature nad likvidusom. Škodljive učinke poroznosti na mehanskih lastnosti litih aluminijevih zlitin je veliko avtorjev proučevalo več let [11–17].

Izvedli so veliko študij, v katerih so raziskovali učinek posameznih spremenljivk na lastnosti litih zlitin Al-Si-Mg in predvsem vsebnost bakra (Cu), magnezija (Mg) in železa (Fe). V nekaterih študijah [18, 19] poudarjajo, da je zaradi trojne evtektične reakcije pri približno 525 °C vsebnost bakra v evtektični talini visoka, kar poveča volumetrično krčenje med strjevanjem in poroznost ter tako zmanjša trdnost izdelkov. Druge študije [20, 21] kažejo, da se trdnost teh zlitin izboljšuje z dodajanjem bakra do 5 %.

Učinek legirnih elementov silicija, bakra, magnezija, mangana in železa na mehanske lastnosti reciklirane aluminijeve zlitine EN AB-46000 je proučeval Dugic in sod. [22] s proizvajanjem usmerjeno strjenih vzorcev z malo napakami. V tej študiji rezultati nateznih preizkusov in mikroskopskih raziskav jasno odkrivajo, da razlike v količini zlitinskih elementov vodijo v izjemne razlike v mehanskih lastnostih, ki znašajo do 73 MPa v natezni trdnosti

but also chemical composition, obviously, significantly affects the mechanical properties [6].

One of the most serious problems associated with the casting of aluminium alloys is the micro porosity. The correlation between the porosity and mechanical properties of cast aluminium alloys have been discussed by many authors [7-10]. Most of these studies use the parameter of global volumetric porosity to determine this correlation. During the casting and solidification process, the evolutions of gases cause the micro porosity. The gases may be the result of a reaction between the casting sand mould and the metal, or they may result from the evolution of gases dissolved in the liquid metal during solidification. The most important gas that is appreciably soluble in aluminium and its alloys is hydrogen. The solubility of hydrogen in aluminium varies directly with temperature and the square root of pressure; solubility increases rapidly with increasing temperature above the liquidus. The detrimental effects of porosity on the mechanical properties of cast aluminium alloys have been studied for many years and by many authors [11-17].

Many studies have been carried out in order to investigate the effect of single variables on the properties of cast Al-Si-Mg alloys and especially the Cu, Mg and Fe content. Some studies [18,19] emphasize that due to ternary eutectic reaction at about 525°C, the Cu content in the eutectic melt is high which increases volumetric shrinkage during solidification and porosity and thus decreasing the strength of components. Other studies [20,21] reveal that the strength of these alloys are improved as Cu is added up to level of 5%.

The sole effect of the alloying element range of Si, Cu, Mg, Mn and Fe on the mechanical properties of the recycled in 49 MPa v meji plastičnosti. Raztezek do razpoke je prav tako posledica legirnih elementov, in sicer zaradi večje vsebnosti intermetalnih spojin.

Cilj tega prispevka je proučiti vpliv vsebnosti vodika na nastajanje notranje poroznosti in učinek legirnega elementa silicija, brez vpliva bakra, železa ali drugih sestavin, ki jih najdemo v sekundarnih zlitinah, na mehanske lastnosti zlitin na osnovi Al-Si.

2 Materiali in metode

Za proučevanje vsebnosti vodika in razplinjevanja smo izbrali dve različni vrsti zlitin (EN AB-46000 in EN AB-43400) skladno z evropskim standardom EN 1676:2010. Sestavi obeh zlitin sta navedeni v preglednici A.1 v dodatku A. Vsebnost vodika smo na določenih mestih v različnih stopnjah procesa ocenjevali z indeksom gostote, kakovost taline pa smo spreminjali z različnimi metodami razplinjevanja. Indeks gostote je merilo za merjenje in primerjavo vzorcev ob upoštevanju njihove notranje poroznosti. V merjenje smo vključili dva vzorca. Prvi vzorec iz vsake skupine smo postavili v vakuumski stroj, kjer se je strdil v vakuumu (označen z V). Stroj je nastavljen tako, da deluje štiri minute pri znižanem tlaku 80 mbar. Drugi vzorec se je strdil na zraku pod atmosferskim tlakom (označen z A). Indeks gostote smo izračunali po enačbi 1.

$$DI = \frac{D_A - D_V}{D_A} \times 100 \ [\%] \qquad (1)$$

DI = indeks gostote, [%]
D_A = gostota vzorca, ki se je strdil pod atmosferskim tlakom, [kg/dm^3]
D_V = gostota vzorca, ki se je strdil v vakuumu, [kg/dm^3].

aluminium alloy EN AB-46000 by producing directional solidified samples with low defect levels have been investigated by Dugic et al [22]. In this study the tensile test results and microscopic investigations reveal clearly that the variations within the alloying element range lead to remarkable differences in the mechanical properties, that can be quantified to 73 MPa in tensile strength and 49 MPa in yield strength. The elongation to failure was also affected as a function of the alloying elements which is due to increased levels of intermetallics.

The aim of this paper is to discuss the influence of hydrogen content on the internal porosity formation and the sole effect of the alloying element Si, without any interaction from Cu, Fe and other constituents found in secondary alloys, on the mechanical properties of Al-Si based alloys.

2 Materials and Methods

Two different types of alloys (EN AB-46000 and EN AB-43400) regarding to the European Standard EN 1676:2010 were selected for the investigations of the hydrogen content and degassing. The compositions of the both alloys are given in Appendix A, table A.1. The hydrogen content was evaluated by Density Index (DI) at specific locations, at different stages in the process and the melt quality has been been varied with different degassing methods. DI is a measure for measuring and comparing the samples with respect to the internal porosity. A measurement includes two samplings. The first sample in each group is placed in a vacuum machine, where it solidifies during vacuum (labelled with V). The machine is set to run at 80 mbar reduced pressure for four minutes. The second sample solidifies free in air, during

Pri procesu razplinjevanja v livarni uporabljajo tradicionalno mešanico dušika in klora. Danes so na trgu zelo razširjene soli klorovih in fluorovih spojin, ki se v livarnah uporabljajo zelo pogosto. Za merjenje učinkovitosti te soli v procesu razplinjevanja smo po običajnem procesu razplinjevanja uporabili še razplinjevalno sol na osnovi klora ($MgCl_2$). Sol proizvaja družba Hoersch GmbH pod trgovskim imenom Dursalite.

Da bi proučili učinek silicija na mehanske lastnosti zlitin Al-Si brez neposrednega vpliva poroznosti, oksidov in/ali intermetalnih spojin, smo uporabili tehniko usmerjenega strjevanja. Osnovni material za to študijo je bil Al-7%Si-0,4%Mg, pri čemer smo ulili šest zlitin z različnimi koncentracijami silicija, modificiranimi s približno 100–150 ppm Sr. Kemijsko sestavo posamezne zlitine smo določili z uporabo optične emisijske spektometrije SPECTROMAXx in je prikazana v preglednici 1.

Preglednica 1: Kemijska sestava

Table 1: Chemical composition

Element	Si	Mg	Fe	Sr	Ti	Al
AIA	6,55	0,40	0,1	0,0150	0,13	Bal.
AIB	10,09	0,40	0,2	0,0104	0,13	Bal.
AIC	11,40	0,39	0,2	0,0100	0,13	Bal.
AID	12,50	0,39	0,2	0,0140	0,12	Bal.
AIE	13,03	0,39	0,2	0,0090	0,12	Bal.
S	14,46	0,38	0,2	0,0117	0,12	Bal.

Vzorce, cilindrične palice (dolžina 20 cm, premer 1 cm), smo ulili v stalno bakreno formo. Lite palice smo nato pretalili in segreli do 710 °C za 30 minut v argonski atmosferi (Ar) s tehniko postopnega strjevanja (slika 1) v Bridgmanovi peči ter usmerjeno strjevali, tako da smo dobili vzorce z mikrostrukturo, ki je enaka kot pri tlačnem litju, s širino sekundarnih dendritnih vej (SDAS) 8–10 µm. Povprečno vrednost SDAS iz 10 meritev z

atmospheric pressure (labelled with A). The DI was calculated according to eq 1.

$$DI = \frac{D_A - D_V}{D_A} \times 100\ [\%] \quad (1)$$

DI = Density Index, [%]

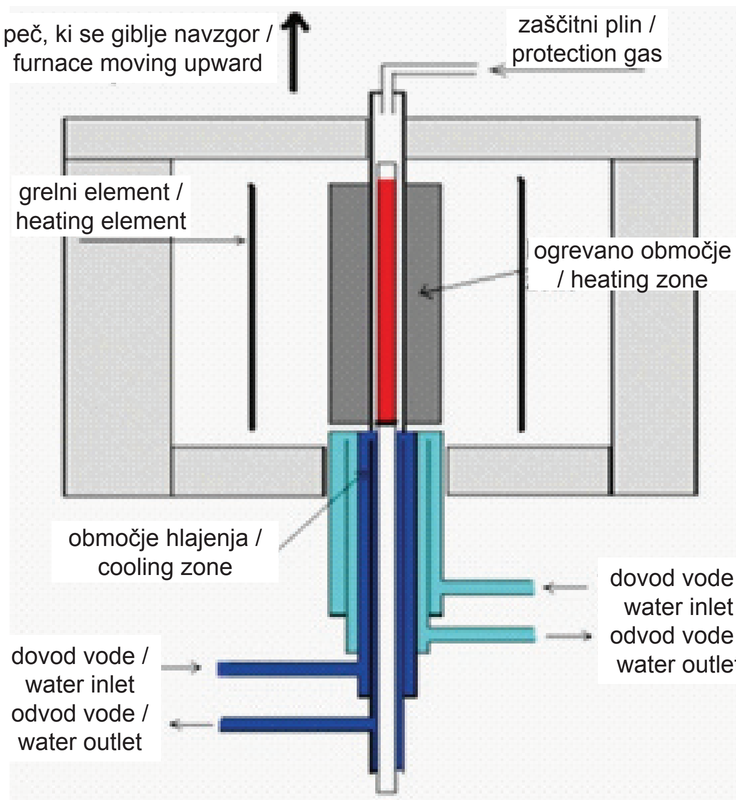
D_A = the density of the sample which solidified during atmospheric pressure, [kg/dm^3]

D_V = the density of the sample which solidified during vacuum pressure, [kg/dm^3].

The degassing process used in the cast house is a traditional gas blend of nitrogen and chlorine gas. In the market today salt of chlorine and fluorine compounds are widely spread and is the one commonly used among cast houses. In order to measure the efficiency of such salt in the degassing process, chlorine based degassing salt ($MgCl_2$) was carried out after the normal degassing process. The salt is manufactured as Dursalite from Hoersch GmbH.

In order to investigate the sole effect of Si on the mechanical performance of Al-Si alloys without any direct impact of porosity, oxides and/or intermetallics, the directional solidification technique has been employed. The base material for this study was Al-7%Si-0.4%Mg where six alloys with variation of Si concentration were cast, modified with approximately 100-150 ppm Sr. The chemical composition of each alloy were obtained using SPECTROMAXx optical emission spectroscopy, see table 1.

Samples, initial cylindrical rods (length 20 cm, diameter 1 cm) were cast in a permanent copper mold. The cast rods were then re-melted remelted and heated to 710°C for 30 minutes under Ar-atmosphere in the gradient solidification technique, see figure 1, using a Bridgman



Slika 1. Shema peči za usmerjeno strjevanje

Figure 1. A scheme of the directional solidification furnace

usmerjenim strjevanjem smo izvedli v vseh pogojih.

3 Rezultati in razprava

3.1 Meritve indeksa gostote taline v rotacijski peči

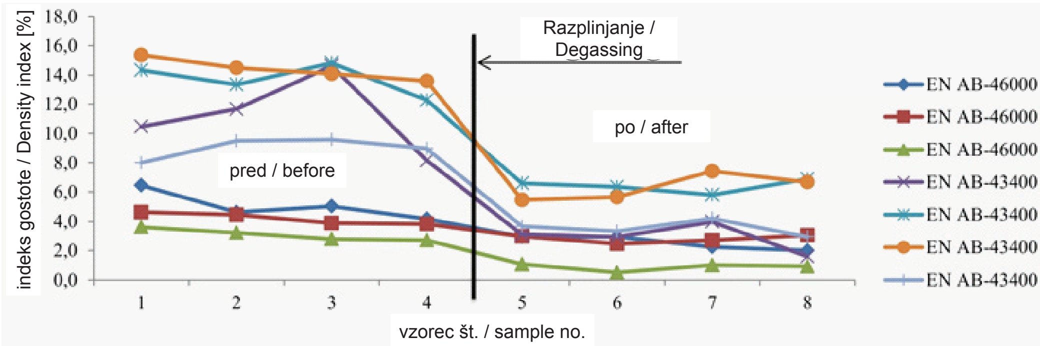
Indeks gostote pred procesom razplinjevanja in po njem je osvetljen na sliki 2. Različne krivulje predstavljajo tri različne ulitke zlitine EN AB-46000, poimenovane C1–C3, in štiri različne ulitke (C1–C4) zlitine EN AB-43400.

furnace and directionally solidified in a way to produce samples with microstructures corresponding to high pressure die cast ones with a secondary dendrite arm spacings (SDAS) of 8-10 µm. An average SDAS offrom 10 measurements offrom the directional solidification direction has been carried out in all conditions.

3 Results and Discussion

3.1 The Density Index Measurements from the Melt in The Rotary Furnace

The density index before and after the degassing process are highlighted in figure 2. The various curves illustrate three



Slika 2: Povprečne vrednosti indeksa gostote iz štirih preizkusnih serij pred razplinjevanjem sedmih različnih posameznih šarž in po njem

Figure 2: The average density index values from four test series before and four after degassing of seven individual charges of metal

Kot lahko vidimo, zlitina EN AB 46000 izkazuje povprečno nižji indeks gostote kot EN AB 43400. Višji indeks gostote je lahko posledica višje prvotne vsebnosti vodika, višje ravni vključkov in/ali oksidov. Rezultati razplinjevanja jasno kažejo na učinkovitost tega procesa. Indeks gostote se je po razplinjevanju s 16 % znižal na 6–8 % za zlitino EN AB 43400 in s 7 % na 1–2 % za zlitino EN AB 46000. V tem primeru lahko talilnica do neke mere zagotovi visoko kakovost taline v ingotih po ustreznem razplinjevanju.

Glavne razlike v kemijski sestavi med zlitinama EN AB-43400 in EN AB-46000 so 2,5 % Cu, 0,8 % Zn, 0,6 % Si, 0,1 % Mg, 0,1 % Fe, 0,08 % Mn, vendar so razlike tudi v drugih elementih, ki so različno uravnavani. Silicij je edini zgoraj omenjen element, za katerega je znano, da niža topnost vodika v aluminijevih zlitinah. Drugih pet omenjenih elementov poveča topnost vodika in najverjetneje predstavlja dejavnik, zaradi katerega se razlikuje topnost med obema vrstama zlitin.

Baker je zlitinski element, katerega delež se med sestavama (2,5 wt. %) obeh zlitin najbolj razlikuje, kar v največji meri

different charges of an EN AB-46000 type of alloy, named C1-C3 and four different charges (C1-C4) of EN AB-43400.

As can be observed, the EN AB 46000 alloy exhibits generally lower DI than the EN AB 43400 alloy. The higher DI could be due to higher initial hydrogen content, higher level of inclusions and/or oxides. The degassing however clearly demonstrates its effectiveness; the DI after the degassing operation drops from approximately 16% down to 6-8 % for the EN AB 43400 alloy and from approximately 7 % down to 1-2 % for EN AB 46000. Hereby the smelter can in this case to some extent guarantee a high level of melt quality in the ingots after a proper degassing.

The main differences in the chemical composition between alloys EN AB-43400 and EN AB-46000 are 2.5 % Cu, 0.8 % Zn, 0.6 % Si, 0.1 % Mg, 0.1 % Fe, 0.08 % Mn, but also the other elements that are regulated differently. Corresponding to the hydrogen solubility [17], Si is the only element mentioned above, that is known to decrease the solubility of Hydrogen in aluminium alloys. The other five mentioned elements increase the hydrogen solubility prispeva k zmanjšanju topnosti vodika v zlitini EN AB-46000. Obdelava aluminijevih zlitin v livarnah je danes pogosto standardizirana, ne glede na vrsto zlitine ali druge dejavnike, kot je vlažnost. Likvidus temperature je v veliki meri odvisen od vsebnosti silicija v aluminijevi zlitini, topnost vodika pa je odvisna tudi od koncentracij drugih elementov. Ta prispevek potrjuje teorijo o topnosti vodika in daje predloge za različne načine obdelave aluminijevih zlitin v odvisnosti od dejavnikov, ki vplivajo na vsebnost vodika.

Po tradicionalnem postopku razplinjevanja in s pridobljenimi rezultati, ki so razvidni iz slike 2, smo izvedli dodatno obdelavo, da bi ugotovili, ali je mogoče

and are likely the factor that differ the solubility between the two types of alloy.

Between the two alloys, Cu is the alloying element that has the greatest difference in percentage between the compositions (2.5 wt %), which contributes the most to the decrease of the hydrogen solubility for the EN AB-46000 alloy. The metal treatment of aluminium alloys in a cast house are today often standardized no mater of the type of alloy or other factors as the humidity. The liquidus temperature is much dependent of the Si content in an aluminium alloy, but the hydrogen solubility is also depending on other element concentrations. This article sates the theory of the hydrogen solubility and gives suggestions on how to work with

Slika 3. Izhodni podatek meritve indeksa gostote za vrsto zlitine EN AB-46000 je prikazan na sliki a), na sliki b) pa indeks gostote za zlitino EN AB 43400

Figure 3. The output from the DI measurement for the EN AB-46000 type of alloy in a) while b) demonstrates the DI for the EN AB 43400 alloy

indeks gostote še nekoliko znižati. Uporabili smo razplinjevalno sol $MgCl_2$ in rezultate predstavili na sliki 3 za obe vrsti zlitine (EN AB-46000 in EN AB-43400) posebej. Rezultati na slikah 3 a in b prikazujejo štiri meritve po prvem postopku razplinjevanja in štiri meritve po obdelavi s soljo $MgCl_2$.

3.2 Spreminjanje indeksa gostote kot dejavnika prenosa kovine

Slika 4 prikazuje spremembe indeksa (slika 2 na desni strani) gostote od razplinjevalne postaje do zadrževalne peči tik pred litjem ingotov. V talilni peči smo po razplinjevanju kot prvi postaji izvedli tri merilne postaje. Po prvi postaji smo kovino izpustili v naslednji vsebnik in nato v zadrževalno peč, preden smo jo končno ulili v ingote. Diagram na sliki 4 prikazuje šest krivulj, ki predstavljajo tri zlitine vrste EN AB-46000 in tri zlitine vrste EN AB-43400.

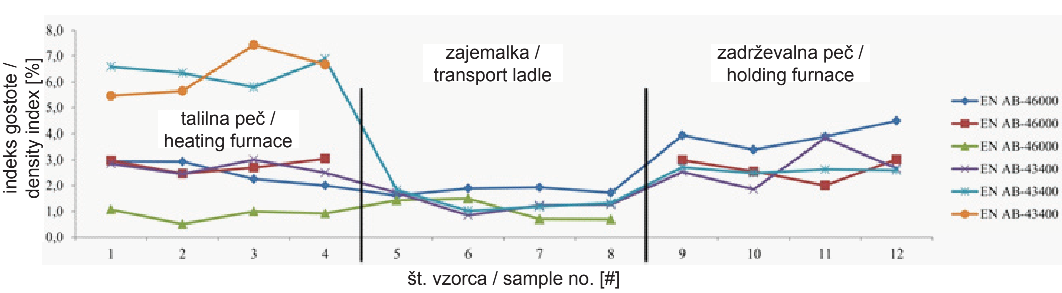
Ker je indeks gostote povezan z nastajanjem notranje poroznosti, proces nastajanja poroznosti pa je povezan z vsebnostjo vodika in oksidov, ki služijo kot nukleacijska mesta za poroznost, jasno opažamo, da se indeks gostote po večkratnem izpustu taline poveča. Izpuščanje taline in čas pospešita proces

aluminium alloys differently depending on factors that affect the hydrogen content.

After traditional degassing and the outcomes declared in figure 2, an additional treatment was performed to investigate whether it is possible or not to reduce the DI further. The use of $MgCl_2$ degassing salt after the traditional degassing process was performed and is presented in figure 3 for the EN AB-46000 and EN AB-43400 type of alloy respectively. The results shown in figure 3 a and b, correspond to four measurements before the second degassing process and four with the $MgCl_2$ treatment.

3.2 Variation of the Density Index as a Function of Metal Transport

Figure 4 shows the changes in DI from the degassing station, reported in figure 2 (right hand side), to holding furnace, just prior to casting of ingots. Three measurement stations were carried out with the heating furnace after degassing as the first station. After the first station the metal was tapped to the next container and after a second tap in the holding furnace before the final casting into ingots. The diagram in figure 4 shows six curves representing three alloys



Slika 4: Sprememba v indeksu gostote med razplinjevalno postajo (postaja 1), transportnim loncem (postaja 2) in zadrževalno pečjo (postaja 3)

Figure 4: The change in density index from the degassing station (station 1), the transport container (station 2) and the holding furnace (station 3)

nastajanja vodika v talini in oksidov/oksidnih filmov zaradi izpuščanja; celo oksidi sčasoma postanejo grobi.

3.3 Vpliv silicija na mikrostrukturo in mehanske lastnosti

Mikrostruktura

Po [17] silicijevi dodatki ne bi smeli povzročati dodatne poroznosti, saj silicij pravzaprav pomeni zmanjšano topnost vodika v talinah zlitin na osnovi Al-Si. Edina večja sprememba v mikrostrukturi, ki se pojavi, ko se vsebnost silicija približuje 14 %, je v deležu primarnih aluminijevih dendritov, ki je skoraj nič. Pri skoraj 7 wt. % silicija mikrostrukturo sestavljajo α-dendriti in spremenjena evtektična zlitina Al-Si, kot na sliki 5. Če vsebnost silicija povečamo do 11 wt. %, se delež α-dendritov in evtektična zlitina Al-Si pomembno spremenita. Mikrostrukturo z vsebnostjo silicija 12,5 wt. % izkazuje predvsem evtektična zlitina Al-Si z nekaj α-dendriti manjše velikosti. V primerjavi z zlitino s 13,0 wt. % silicija, za katero je značilna povsem evtektična struktura Al-Si, iz katere raste dendritska struktura, v mikrostrukturi nismo našli α-dendritov. Vzrok za ta prehod je najverjetneje dejstvo, da je rast evtektične strukture Al-Si v sklopljenem območju hitrejša od rasti α-dendritov. Dodajanje več silicija pa povzroči spremembo mikrostrukture. V evtektični zlitini Al-Si se je dendritska rast spremenila v stebričasto rast. Zaradi nastajanja dolgotrajnega mejnega sloja pred trdnim strjevanjem robovi okoli evtektične zlitine Al-Si vsebujejo intermetalne spojine in grob silicij. Pri uporabi usmerjenega strjevanja v hiperevtektičnih zlitinah presenetljivo nismo opazili primarnega silicija.

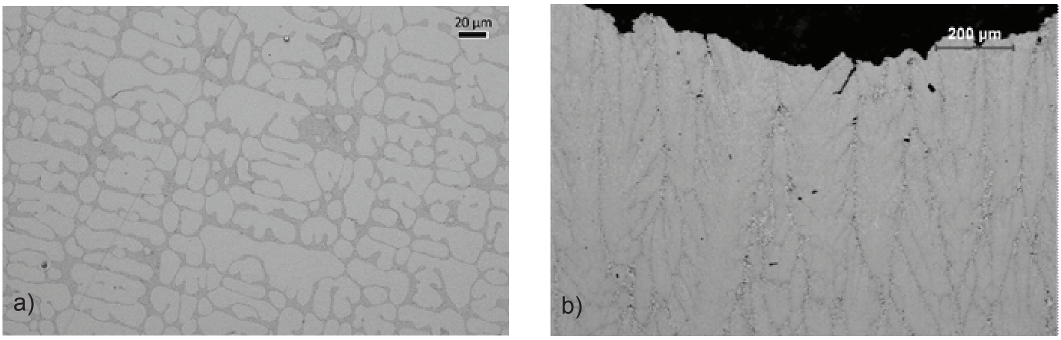
of the EN AB-46000 type of alloy and three the EN AB-43400.

Since DI is linked to internal porosity formation, and the formation process of porosity is linked to the hydrogen level and oxides that serve as nucleation sites for porosity, it is clearly observed that the DI is increasing after tapping a couple of times. Melt tapping and time accelerate the hydrogen pick-up process in the melt as well as oxides/oxide films formations due to the tapping; even the oxides are getting coarser with time.

3.3 The Influence of Si on the Microstructure and Mechanical Properties

Microstructure

According to [17], the Si additions should not lead to any further porosity formations since the Si actually leads to reduced solubility of hydrogen in the molten Al-Si based alloys. The only remarkable change in the microstructure, when approaching 14% of Si, is the fraction of primary aluminium dendrites that is nearly zero. At around 7 wt. % Si the microstructure is composed of α-dendrites and modified Al-Si eutectic, see figure 5. Increasing the Si level up to 11 wt. % the fractions of α-dendrites and Al-Si eutectic are remarkably changed. The microstructure of the alloy with Si level of 12.5 wt. % exhibit mostly Al-Si eutectic with few and smaller size of the α-dendrites. Compared to the alloy with Si of 13.0 wt. % that is characterized by a fully Al-Si eutectic structure growing with a dendritic structure; no α-dendrites however is is found in the microstructure. This transition is probably due to the fact that the Al-Si eutectic growth in the coupled zone is more rapid then α-dendrites growth. Adding more Si lead to change in the microstructure; the Al-Si eutectic changed from dendritic

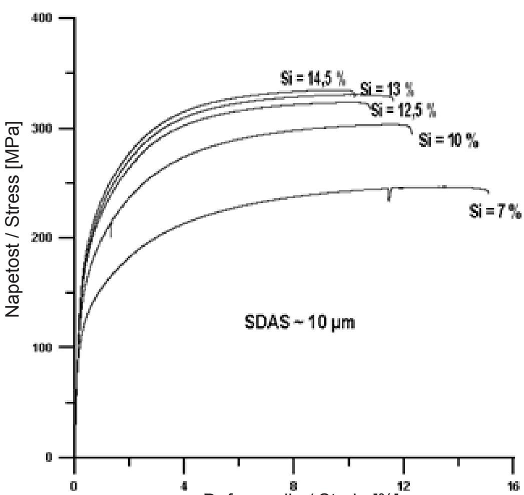


Slika 5. Slika a) prikazuje zlitino s 7 % silicija, b) pa prikazuje zlitino s 14,5 % silicija

Figure 5. While a) is illustrating the alloy with 7% Si, b) illustrates the alloy with 14.5 % Si

Mehanske lastnosti

Na mehanske lastnosti zlitin na osnovi Al-Si neposredno vplivajo dejavniki, kot so hitrost strjevanja, napake in zlitinski elementi. Da bi se izognili vsem drugim vplivom na vsebnost silicija, smo izdelali usmerjeno strjene vzorce. Kot je razvidno s slike 6, imajo silicijevi dodatki pomemben vpliv na mejo plastičnosti in končno natezno trdnost zaradi disperzijskega utrjanja. Vendar lahko opazimo majhen padec raztezka do razpoke, ki znaša približno 10 % za zlitino, ki vsebuje 14,5 % silicija. Razlog za takšno



growth to columnar growth. Due to long range boundary layer build up ahead of solid interface the boarders around the A-Si eutectic contains intermetallics as well as coarser Si. Surprisingly no primary Si in the hyper eutectic alloys was observed when employing directional solidification.

Mechanical properties

Several factors such as solidification rate, defects and alloying elements impart directly on the mechanical performance of Al-Si based alloys. In order to avoid any other impacts than the Si level, directionally solidified samples were produced. As observed in figure 6, the additions of Si have a significant influence on yield strength and ultimate tensile strength due to dispersion hardening. However, a small drop in elongation to failure may be observed but the drop is from a high level and maintained at around 10 % for the alloy containing 14.5% Si. The reasons for that retained high level

Slika 6. Vpliv silicijevih dodatkov na natezno trdnost litih zlitin Al-Si

Figure 6. The influence of Si additions on the tensile behaviour of Al-Si cast alloys

ohranitev visoke ravni voljnosti je lahko poleg spreminjanja morfologije silicija, ki je zlasti vlaknasta, proizvodna metoda. Z usmerjenim strjevanjem običajno dobimo dobro napolnjene vzorce, ki vsebujejo malo napak.

4 Sklepi

Z ocenjevanjem rezultatov smo pokazali, da so vrednosti indeksa gostote odvisne od vrste zlitin. Sestava zlitine pomembno vpliva na absorpcijo vodika v talino ali njegovo izločanje. Baker je zlitinski element, katerega delež se med sestavama (2,5 wt %) zlitin EN AB-43400 in 46000 najbolj razlikuje, kar v največji meri prispeva k zmanjšanju topnosti vodika v zlitini EN AB-46000.

Količine silicija, ki smo jih povečali s 7 na 14 %, so povsem spremenile mikrostrukturo – od aluminijevih dendritov in evtektične strukture Al-Si do povsem evtektične strukture Al-Si. Evtektična struktura Al-Si je prispevala k pomembnemu izboljšanju trdnosti na račun voljnosti, ki je padla z že tako visokih vrednosti – s 16 % pri vsebnosti silicija 7 % na 10 % za zlitine s 14 % silicija.

4.1 Zahvale

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of ductility behaviour may be, besides the modification of Si morphology being mostly fibrous, the production method; directional solidification that usually produces well fed samples that contain low amount of defects.

4 Conclusions

The evaluation of the results shows that the Density Index values are depending upon the type of alloy. The alloy composition has great significance on the hydrogen absorption of the melt or removal from the melt. Between the alloys EN AB-43400 and 46000, Cu is the alloying element that has the greatest difference in percentage between the compositions (2.5 wt %), which contributes the most to the decrease of the hydrogen solubility for the EN AB-46000 alloy.

The additions of Si from approximatley 7% to 14% changed the microstructure fully; from Al-dendrites and Al-Si eutectic to a fully Al-Si eutectic. The Al-Si eutectic structure contributed to a significant strength improvment on the expense of ductility that drops from already high values; around 16% at Si content of 7% down to around 10% for alloys with 14% Si.

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Dodatek A / Appendix A

Preglednica A.1. Kemijska sestava merjenih šarž kovine. Izračunali smo srednje vrednosti za vsako vrsto zlitine (Mv) in razlike v povprečnih koncentracijah med obema vrstama zlitine (ΔMv).

Table A.1. The chemical composition of the measured charges of metal. The mean values for each type of alloy are calculated (Mv) as well as the difference in the average concentrations between the two types of alloy (ΔMv).

EN AB 43400	Alloy Composition [wt.%]											
	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Pb	Sn	Ti	Na
1	9,885	0,821	0,059	0,343	0,350	0,010	0,006	0,049	0,005	0,001	0,036	0,000
2	9,055	0,799	0,056	0,338	0,359	0,007	0,007	0,051	0,006	0,005	0,038	0,000
3	9,370	0,826	0,055	0,325	0,375	0,009	0,006	0,085	0,010	0,002	0,036	0,000
4	9,555	0,863	0,059	0,369	0,352	0,008	0,006	0,061	0,006	0,001	0,033	0,000
5	9,802	0,536	0,060	0,142	0,325	0,007	0,006	0,069	0,009	0,002	0,039	0,000
M_v	9,533	0,769	0,058	0,303	0,352	0,008	0,006	0,063	0,007	0,002	0,037	0,000
EN AB 46000	Alloy Composition [wt.%]											
	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Pb	Sn	Ti	Na
1	8,720	0,878	2,954	0,296	0,258	0,020	0,023	0,860	0,050	0,039	0,025	0,000
2	8,711	0,958	2,972	0,306	0,290	0,028	0,028	0,767	0,040	0,039	0,022	0,000
3	8,205	0,660	2,233	0,221	0,225	0,020	0,026	0,857	0,048	0,028	0,030	0,000
4	8,791	1,064	2,196	0,327	0,273	0,038	0,040	0,910	0,067	0,060	0,026	0,000
5	8,768	0,844	2,379	0,223	0,165	0,034	0,017	0,810	0,045	0,022	0,021	0,000
6	9,617	1,050	2,619	0,230	0,218	0,038	0,031	0,764	0,053	0,048	0,027	0,000
7	9,079	1,097	2,667	0,273	0,220	0,049	0,040	0,835	0,088	0,060	0,019	0,000
M_v	8,841	0,936	2,574	0,268	0,236	0,033	0,029	0,829	0,056	0,042	0,024	0,000
ΔM_v	-0,69	0,17	2,52	-0,04	-0,12	0,02	0,02	0,77	0,05	0,04	-0,01	0,00