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Vpliv manjšega dodatka legirnih elementov na aluminijeve livarske zlitine

Influence of Minor Alloying Element Addition on Aluminium Casting Alloys

Izvleček

Standardni materiali ne izpolnjujejo strogih zahtev za kompleksne aplikacije. Članek obravnava modeliranje inovativnih aluminijevih zlitin z boljšimi lastnostmi za visokotemperaturne aplikacije. Za analizo vpliva dodatka cirkonija in molibdena na strjevanju zlitine Al-Si-Mg-Mn, smo uporabili termodinamične izračune, enostavno termično analizo in diferencialno kalorimetrijo. Optična mikroskopija in elektronska vrstična mikroskopija z energijsko disperzijsko spektroskopijo sta služili za določanje razvoja mikrostrukture preiskovanih zlitine.

Analizirali smo kemično sestavo, vrsto in količino nastalih faz, preučili ravnotežne in neravnotežne procese ter značilne temperature strjevanja za laboratorijske in industrijske aluminijeve zlitine. Ko smo v zlitino dodali cirkonij, se je izoblikovala nova igličasta faza. Molibden v zlitini je vključen v fazo AlFeMnSi, pri čemer v nekaterih primerih delno zamenja železo in oblikuje novo fazo AlFeMnMoSi z drugačno morfologijo bolj zaokrožene kitajske pisave.

Ključne besede: aluminijeve livarske zlitine, manjši legirni dodatki, termodinamika, strjevanje, mikrostruktura

Abstract

Standard materials do not satisfy the rigorous requirements for complex applications. The paper represents the modeling of innovative aluminium alloys with better properties for high temperature applications. Thermodynamic equilibrium calculations, simple thermal analysis and differential scanning calorimetry were used in order to analyse the influence of joint micro- addition of zirconium and molybdenum on solidification of Al-Si-Mg-Mn alloy, whereas the optical microscopy and scanning electron microscopy as well as the energy dispersive spectroscopy were employed to investigate the microstructure development of investigated experimental alloys.

An analysis of chemical composition and types of phases, the amount of phase and study of equilibrium and non-equilibrium processes and the characteristic solidification temperatures for laboratory and industrial aluminium alloys were made. When zirconium was added to the alloy, a needle-like phase formed. Molybdenum in the alloy is incorporated into the AlFeMnSi phase, and in some cases completely replaced iron, and formed a new AlFeMnMoSi phase with a different morphology in a more roundish Chinese script.

Keywords: Aluminium casting alloys, Minor alloying addition, Thermodynamics, Solidification, Microstructure

1 Uvod

V avtomobilski industriji se pojavlja potreba po novih aluminijevih zlitinah, ki imajo optimalno kombinacijo trdnosti, odpornosti proti utrujanju, preoblikovalnosti in korozijske obstojnosti[1]. Zaradi zahtev po hitrem napredku tehnologije je veliko raziskav usmerjenih v razvoj novih aluminijevih zlitin. Sistem zlitin Al-Zn-Mg-Cu vzbuja največ zanimanja za nove zlitine, saj je osnovni sistem za razvijanje preoblikovalne zlitine tipa AA7075, ki ima najvišjo trdnost. Med vsemi novimi zlitinami je predvsem zlitina (6,5–7,5 wt.% Zn, 2–2,8 wt.% Mg, in 1–1,5 wt.% Cu) industrijsko uporabna. Povprečna vrednost natezne trdnosti takšne zlitine v T6 stanju znaša 570 MPa[2]. K zlitini se dodajajo tudi drugi elementi, kot so Cr, Mn in Zr, ki vplivajo na strukturo zrn in podzrn ter pripomorejo k izboljšanju trdnosti. Za optimizacijo mehanskih lastnosti aluminijevih zlitin se lahko dodaja prehodni element Zr (0,1 – 0,15 mas. %), ki vpliva na enakomerno razporeditev delcev znotraj mikrostrukture[3]. Dodatek silicija in železa zniža topnost mangana, pospešuje hitrost precipitacije sekundarnih faz, ki vsebujejo mangan, kot npr. Al_6(Fe,Mn) ter poveča število nastalih Al_3Zr delcev[4]. Glede na literaturo[5], sta, poleg aluminija in silicija, v aluminijevem kotu sistema Al-Fe-Mn-Si, v ravnotežju tudi fazi Al_6(Fe,Mn) in α-AlFeMnSi. V aluminijevem kotu sistema Al-Mn-Zr ni bilo odkritih ternarnih faz[6].

Aluminijeve zlitine imajo širok spekter uporabnosti na katerega vplivajo kemijska sestava, udrobnjevanje in toplotna obdelava. Z ustrezno izbiro kemijske sestave in toplotne obdelave, je dosežena želena mikrostruktura ter posledično ustrezne mehanske lastnosti. Zaporedje toplotnih obdelav (raztopno žarjenje, gašenje in precipitacijsko utrjevanje, ki je

1 Introduction

New aluminium alloys with an optimal combination of strength, fatigue resistance, formability, and corrosion resistance, are desired in the automotive industry[1]. Demands of rapidly evolving technology dictate the development of a novel aluminium casting alloys. The average value of ultimate tensile strength (UTS) for the strongest aluminium AA7075 alloys in the T6 temper is 570 MPa[2], which has found some industrial applications. Other alloying elements, such as Cr, Mn, and Zr are added to these type of alloys in order to control the grain and subgrain structures, which also contribute to the strengthening. To optimize mechanical properties of Al alloys, the addition of the transition element Zr (0.1 – 0.15 wt. %) was suggested in order to enhance the formation of small dispersions[3]. The addition of Si and Fe decreases solubility of Mn, accelerates precipitation rate of secondary Mn-bearing phases, such as Al_6(Fe,Mn), as well as increases formation of Al_3Zr particles[4]. According to the literature[5], two main phases beside α-Al and β-Si are in equilibrium in the Al-rich corner of the Al-Fe-Mn-Si system: Al_6(Fe,Mn) and α-AlFeMnSi. No ternary compounds have been reported in the Al-rich corner of the Al- Mn-Zr system[6].

The use of aluminium alloys is influenced by composition, grain-refining and corresponding heat treatment. By selecting the appropriate heat treatment, the desired microstructure and, consequently, the required mechanical properties may be achieved. Heat treatment is used when maximum strength is desired in a given composition by means of a solution annealing, quenching and precipitation hardening.

Al-Si alloy modification studies for high temperature applications have been

lahko naravno ali umetno) se uporabi, ko je potrebno doseči najvišjo trdnost z obstoječo kemijsko sestavo. V namen razumevanja modifikacij zlitin Al-Si za visokotemperaturno uporabo je bilo narejenih veliko raziskav[7, 8, 9, 10]. Mikrolegiranje aluminijevih zlitin iz sistema Al-Si-Cu-Mg s Cr, Ti, V ali Zr, poviša mehanske lastnosti po T6 toplotni obdelavi. Napetost tečenja se lahko v primerjavi z osnovno zlitino poviša za 30 %, natezna trdnosti pa za 5 %[11]. Ti/Zr/V z aluminijem in silicijem tvorijo Al(ZrTiV)Si fazo, ki poviša natezne lastnosti zlitine AlSi7Cu1 za 20-40 % in ima v primerjavi s komercialno A380 zlitino 11.5-15 x boljšo duktilnost[12].

Toplotna obdelava zlitine AlSi7Cu1Mg0,5 z dodatki 0,21 mas. % Ti, 0,3 mas. % V in 0,47 mas. % Zr povzroči raztapljanje bakra, magnezijevih faz in Si-evtektika, med tem ko je $(AlSi)_x(TiZrV)$ faza s tetragonalno kristalno strukturo odporna proti raztapljanju do temperatur med 696-705 °C, kar poviša temperaturno stabilnost preiskovanih zlitin[13]. Trdota zlitine po T6 toplotni obdelavi znaša 96 HRF. V zlitini AlSi7Cu1Mg0.5 z dodatki titana, vanadija in cirkonija, lahko nastanejo faze $Cu_{15}Al_{43}Si$, $Al_5Mg_9Si_8Cu_2$ in $Al_{14}FeMg_4Si_6$ ter intermetalne faze $Al_3Si_{26}TiV_{10}Fe$ in $Al_{13}Si_2Ti_3Zr$. Med T6 toplotno obdelavo pride do raztapljanja $Cu_{15}Al_{43}Si$ in $Al_5Mg_9Si_8Cu_2$ faz, železove faze (AlSiCuFe in $Al_9Mg_{12}Si_6Fe$) pa ostanejo neraztopljene. Intermetalne faze $Al_{27}SiTiZr_9$ in AlSiTiVFe ostanejo v mikrostrukturi v majhnih količinah[14], z dodatkom 0.2 mas. % Zr in 0.2 mas. % Ni, pa nastanejo intermetalne faze $(Al,Si)_3(Zr,Ti)$, Al_3CuNi in Al_9NiFe. Z višanjem temperature pada natezna trdnost teh zlitin, kar je posledica višanja deleža nikljevih in cirkonijevih faz. Pri 300 °C pride do približno 30 % povišanja natezne trdnosti in napetosti tečenja, v primerjavi z osnovno zlitino. Skupna vsebnost niklja in cirkonija ne sme presegati 0.4 mas. %[15].

the subject of numerous studies[7, 8, 9, 10]. Aluminium alloys from the Al-Si-Cu-Mg system with micro-additions of Cr, Ti, V and Zr increase the mechanical properties after the T6 heat treatment. The yield strength increases for 30 % and tensile strength for 5 % in comparison to the base alloy under the same conditions[11]. Ti/Zr/V together with Al and Si form Al(ZrTiV)Si phase, which increases tensile properties of AlSi7Cu1 alloy by 20-40 % and exhibits 11.5-15 times better ductility compared to the commercial alloy A380[12]. Heat treatment of the alloy AlSi7Cu1Mg0.5 with additions of 0.21 wt. % Ti, 0.3 wt. % V and 0.47 wt. % Zr, causes dissolution of Cu- and Mg-phases along with the eutectic Si, while $(AlSi)_x(TiVZr)$ phase with tetragonal crystal structure is resistant to dissolution up to 696-705 °C, which increases high-temperature stability of examined alloys[13]. Hardness of the alloy after the T6 heat treatment is 96 HRF. In AlSi7Cu1Mg0.5 alloy with the addition of Ti, V and Zr following phases may form: $Cu_{15}Al_{43}Si$, $Al_5Mg_9Si_8Cu_2$ and $Al_{14}FeMg_4Si_6$ and intermetallic phases $Al_3Si_{26}TiV_{10}Fe$ and $Al_{13}Si_2Ti_3Zr$, whereas during the T6 heat treatment, soluble annealing phases $Cu_{15}Al_{43}Si$ and $Al_5Mg_9Si_8Cu_2$ dissolve, while Fe-phases AlSiCuFe and $Al_9Mg_{12}Si_6Fe$ remain undissolved. The intermetallic phases $Al_{27}SiTiZr_9$ and AlSiTiVFe remain in the microstructure in small quantities[14]. With addition of 0.2 wt. % Zr and 0.2 wt. % Ni, intermetallic phases $(Al,Si)_3(Zr,Ti)$, Al_3CuNi and Al_9NiFe are formed in the microstructure. By raising the temperature, the tensile strength of these alloys decreases as a result of increasing proportion of Ni and Zr-phases, while at 300 °C tensile properties (ultimate tensile strength and yield strength) are for about 30 % higher as compared to the base alloy. The total concentrations of Ni and Zr should not exceed 0.4 wt %[15].

Z dodatkom molibdena (0.3 mas. %) zlitini Al7Si0.5Cu0.3Mg dosežemo, da material ohrani trdnost pri povišanih temperaturah ter ima višjo odpornost proti lezenju. Za 20, 15 in 35 % se povišajo tudi meja plastičnosti, natezna trdnosti in raztezek. V teh primerih se tvorijo Al-(Fe,Mo)-Si precipitati, ki so stabilni pri 300 °C in preprečujejo premik dislokacij, s čimer utrdijo matrico[16]. S kombinacijo mangana (<0.5 mas. %) se precipitati zmanjšajo, njihova množina pa se poviša[17]. Molibden prav tako preprečuje nastanek škodljive β-Al_5FeSi faze in tvori Al-(Fe,Mo)-Si, ki ima kubično strukturo.

V okviru tega dela, smo z namenom identifikacije mikrostrukturnih komponent iz predhodno omenjenih aluminijevih zlitin, uporabili termodinamske izračune (Thermo-Calc), različne termične analize ter optično in elektronsko mikroskopijo.

2 Eksperimentalno delo

V članku je bila obravnavana zlitina AlSi10MnMg, ki je bila legirana z Zr in/ali Mo. Izračuni termodinamskih ravnotežij so bili izvedeni s pomočjo programske opreme Thermo-Calc 2017a, uporabljena je bila podatkovna baza SSOL5. Kemijske sestave, ki so bile uporabljene za izračune izopletnih faznih diagramov zlitin, so podane v Tabeli 1. Vzorci so bili izdelani v indukcijski peči, kjer smo za taljenje uporabili jeklen lonček. Med ulivanjem so bile izvedene tudi enostavne termične analize (ETA). Izrisane so bile ohlajevalne krivulje, ki smo jih dobili s pomočjo ETA, in izračunani prvi odvodi, s pomočjo katerih smo določili karakteristične točke preiskovanih zlitin. Diferenčna vrstična kalorimetrija (DSC) je bila izvedena na napravi Netzsch STA 449C Jupiter. Vzorce za DSC analizo smo ustrezno pripravili in jih postavili v korundne

The strength of the alloy Al7Si0.5Cu0.3Mg with addition of Mo (0.3 wt. %) are maintained despite exposure to an elevated temperature, whereas the creep properties of the alloy improve. The plasticity limit, tensile strength and elongation increase by 25, 15 and 35 % with addition of Mo. In this case Al-(Fe,Mo)-Si precipitates are formed, which are stable at 300 °C, and inhibit dislocations barriers which hardens the matrix[16]. In combination with Mn (<0.5 wt. %), the precipitation concentration increases, whereas the size of precipitates reduces[17]. Mo also inhibits the formation of the harmful β-Al_5FeSi phase and forms Al-(Fe,Mo)-Si phase of cubic structure[18].

In this article, equilibrium thermodynamic calculations (Thermo-Calc), various thermal analyses and optical and scanning electron microscopy were used in order to identify the influence of Mo and Zr addition on the course of the solidification and the generated microstructures of aluminium system Al-Si-Mg-Mn.

2 Experimental Work

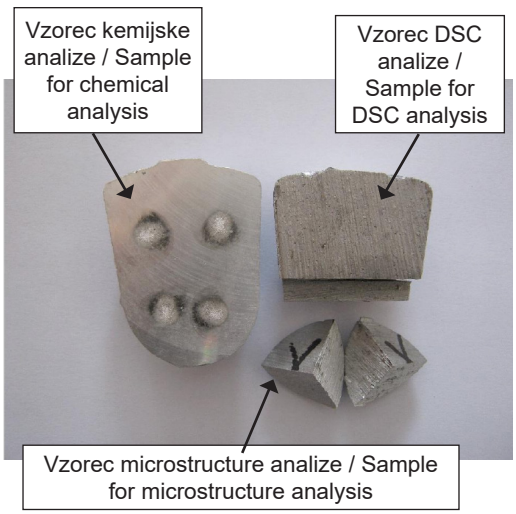
In this research AlSi10MnMg alloy (named Silafont 36 by Rheinfelden) was used and alloyed with various combinations of Zr and Mo. Thermodynamic calculations were performed with Thermo-Calc 2017a software in combination with the SSOL5 database. Chemical compositions of alloys given in Table 1 were used in order to calculate isopleth phase diagrams of experimental alloys. Samples were melted in an induction furnace using steel crucible, whereas simple thermal analysis (STA) was performed, from which data cooling curves and their derivatives were plotted and characteristic temperatures were determined. Differential scanning calorimetry (DSC) was performed

Table 1. Chemical composition of experimental alloys /wt. %.

Tabela 1. Kemijska sestava preiskovanih zlitin v mas. %.

Alloy	Mo	Zr	Fe	Mn	Cr	Ti	Si	Mg	Al
A1	0	0	0.11	0.52	0.20	0.092	10.89	0.64	rest
A2	0	0.18	0.12	0.49	0.18	0.063	10.68	0.65	rest
A3	0.11	0.21	0.12	0.48	0.21	0.069	10.02	0.65	rest
A4	0.22	0.19	0.12	0.45	0.21	0.054	9.56	0.65	rest

lončke, v katerih smo jih nato ogrevali in ohlajali s hitrostjo 10 K/min v zaščitni Ar atmosferi. Za mikrostrukturno analizo smo vzorce najprej metalografsko pripravili in jih nato analizirali s pomočjo optičnega mikroskopa Olympus BX61, ki je opremljen z DP70 kamero. Hkrati je bila opravljena tudi vrstična elektronska mikroskopija s pomočjo JEOL JSM-5610 elektronskega



Slika 1. STA vzorec, v katerem imamo prikazana mesta, iz katerih so bili narejeni vzorci za nadaljnje analize (kemijska analiza, DSC in mikrostukturna analiza)

Figure 1. Samples after STA and sampling method for chemical composition analysis, DSC and microstructure investigations

using Netzsch STA 449c Jupiter apparatus. A sample for DSC was put in a corundum crucible and heated and cooled at a constant rate of 10 $Kmin^{-1}$ in an Ar protective atmosphere. Samples for microstructural examination were prepared by conventional metallographic procedure and examined using Olympus BX61 optical microscope with DP70 camera. In order to do the electron microscopy and identification of phases present in these experimental alloys a Scanning electron microscope JEOL JSM-5610 with attached EDS was used. Samples and sampling method for STA, DSC and microstructure investigations are presented in Fig. 1.

3 Results and Discussion

3.1 Thermodynamic Calculations

From the chemical composition given in Table 1 the course of equilibrium solidification and the equilibrium phases were calculated for all experimental alloys in order to predict equilibrium phase formation. Fig. 2 is showing Scheil-Gulliver solidification calculated for all investigated alloys. According to the thermodynamic equilibrium calculation, solidification of the primary α-Al with additions of Zr or/and Mo moves to a higher temperature (A2 – A4 in Fig. 2). Solidification temperature interval increases, agreeing with STA

vrstičnega mikroskopa, ki je opremljen z energijsko disperzijskim spektrometerom (EDS). S pomočjo EDS analize smo analizirali in identificirali prisotne faze v preiskovanih zlitinah. Vzorci, ki so bili uporabljeni za STA, DSC in mikrostrukturne preiskave so prikazani na Sliki 1.

3 Rezultati in diskusija

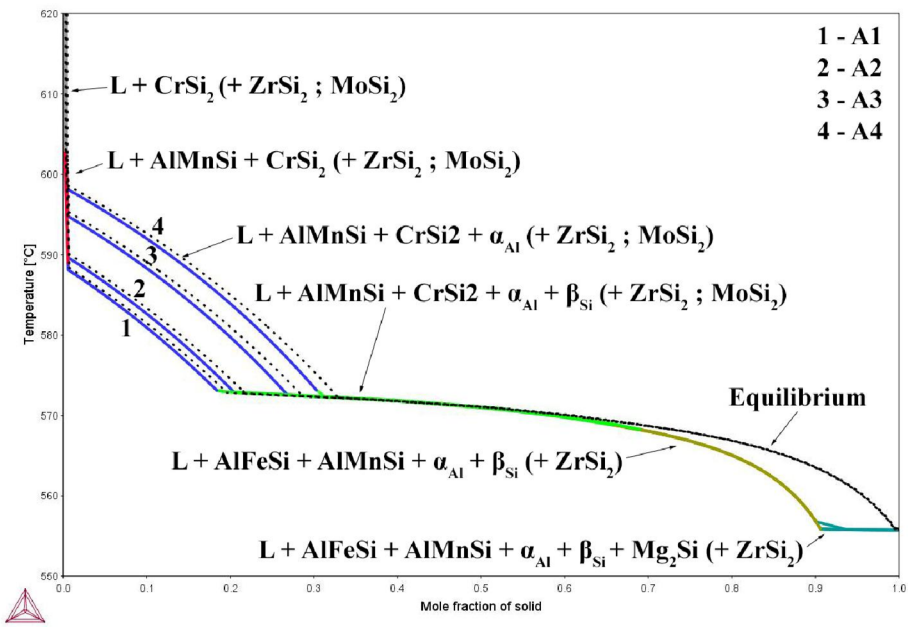
3.1 Termodinamični izračuni

Za vse preiskovane zlitine s kemijskimi sestavami, ki so podane v Tabeli 1, so bili narejeni termodinamični izračuni ravnotežnega strjevanja in določene ravnotežne faze, ki se pojavljajo. Na Sliki 2 imamo predstavljen Sheil-Gulliverjev diagram strjevanja izračunan za vse analizirane zlitine.. Glede na termodinamični ravnotežni izračun, se strjevanje primarnega

measurements, presented hereafter. New phases ($ZrSi_2$, $MoSi_2$, $Al_{12}Mo$) were predicted and are attributed to the Zr or/ and Mo. The SSOL5 databases does not contain multi-component phases with Zr and Mo, which are according to the microstructural examination and literature definitely present.

3.2 Simple Thermal Analysis

Fig. 3 shows cooling curves of investigated alloys. It can be seen that during solidification, liquidus temperature of the A1 alloy without additives is lower compared to alloys containing Zr or/and Mo. Liquidus recalescence decreases or even disappears with addition of Zr or/and Mo. With addition of Mo to the alloy Silafont 36, solidification of Mo-eutectic immediately after start of the primary solidification can be detected,



Slika 2. Sheil-Gulliverjev diagram strjevanja izračunan za vse analizirane zlitine

Figure 2. Scheil-Gulliver solidification simulation, calculated for all investigated alloys

α-Al z dodatkom Zr in/ali Mo pomakne k višjim temperaturam. Prav tako se razširi strjevalno območje, kar smo potrdili tudi s pomočjo STA analize, rezultati le-te bodo predstavljeni v nadaljevanju. Pojavijo se tudi nove faze (Al_3Zr, $MoSi_2$ in $Al_{12}Mo$), ki smo jih predvideli in so posledica dodatka Zr in/ali Mo. Uporabljena podatkovna baza SSOL5 ne vsebuje več komponentnih faz, ki se tvorijo z Zr, ter Mo in so prisotne, kar potrjujeta tako mikrostrukturna analiza, kot tudi literatura.

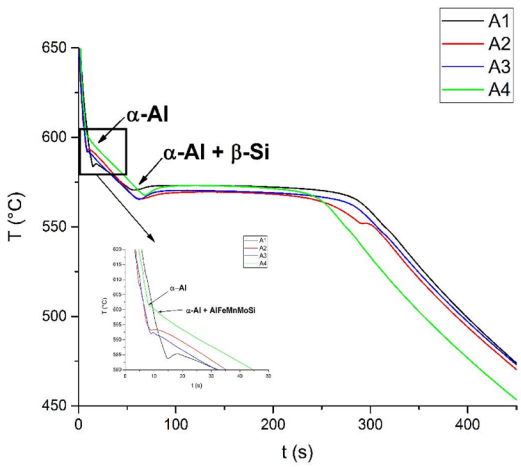
3.2 Enostavna termična analiza

Na Sliki 3 imamo predstavljene ohlajevalne krivulje preiskovanih zlitin. Iz diagrama je razvidno, da se likvidus temperatura z dodatkom Zr in/ali Mo zvišuje v primerjavi z vzorcem S1, ki je brez dodatka omenjenih legirnih elementov. Z dodatkom Zr in/ali Mo se likvidus rekalescenca zmanjšuje in lahko tudi izgine. Z dodatkom Mo zlitini AlSi10MnMg, se začne evtektik na osnovi Mo strjevati takoj za primarnim strjevanjem, kar je posledica modificiranega (α-Al + AlFeMnSi) evtektika. Temperaturni interval strjevanja preiskovane zlitine (S2) se poveča z dodatkom Zr. Med tem, ko nam dodatek Zr zmanjša časovni interval strjevanja, dodatek Mo nima bistvenega vpliva.

3.3 Diferenčna vrstična kalorimetrija

Na Sliki 4 imamo predstavljene rezultate DSC analize za preiskovane zlitine (S1 – S4). Razvidno je, da se entalpija izločanja (povečano območje na sliki 4a) poveča z dodatkom Zr in se tudi pomakne k višjim temperaturam, kjer je izločevanje bolj intenzivno. Prav tako je evidentno, da se potek taljenja z dodatkom Zr in/ali Mo močno

which was attributed to the modified (α- Al + AlFeMnSi) eutectic. The solidification temperature interval for the investigated alloy (A2) is increased when the alloy was modified with Zr. Zr in the investigated alloy reduces the solidification time interval, whereby Mo does not have any significant influence.



Slika 3. Ohlajevalne krivulje preiskovanih zlitin

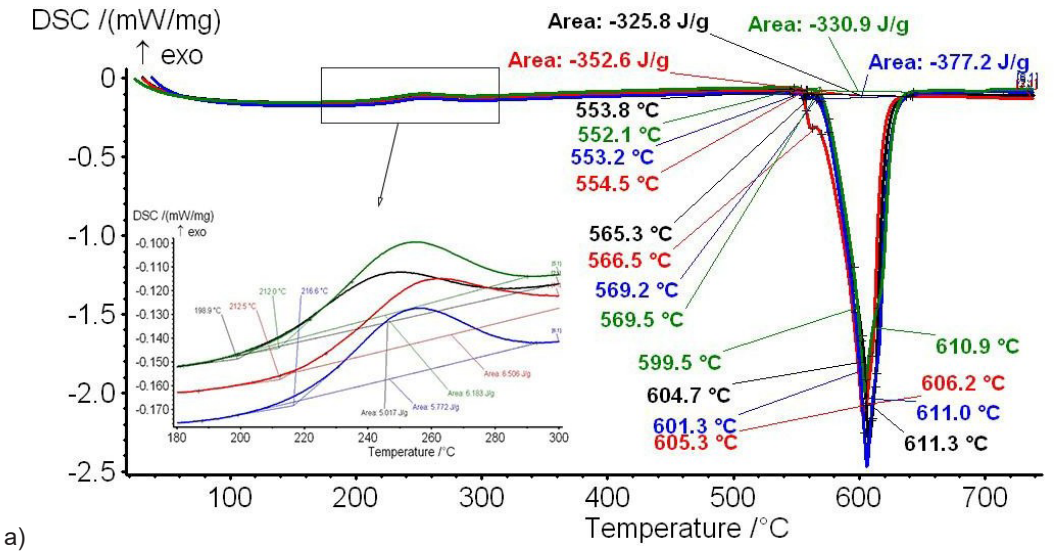
Figure 3. Cooling curves of investigated alloys

3.3 Differential scanning calorimetry

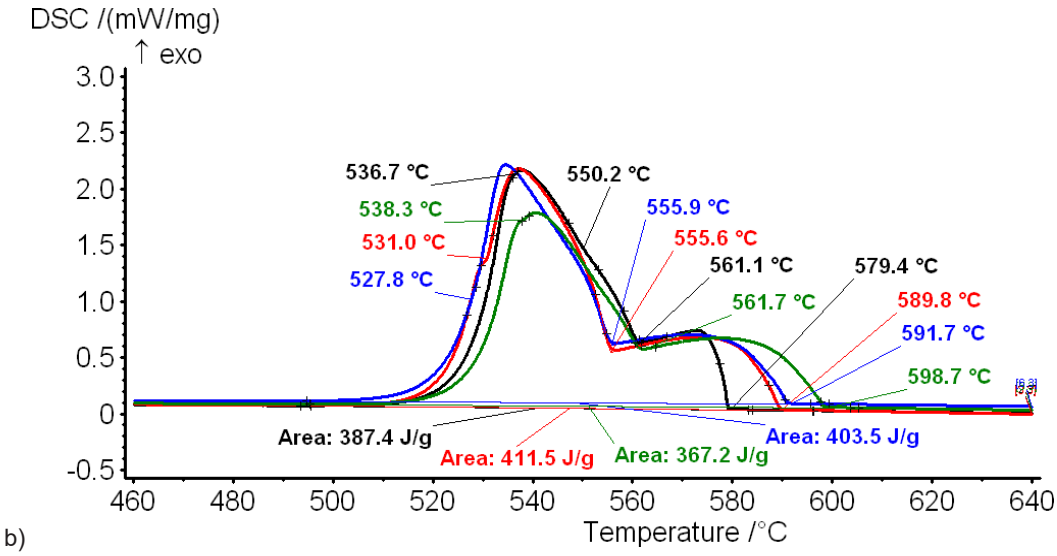
Results obtained from DSC analysis of alloys A1 – A4 are shown in Fig. 4. It is evident that the enthalpy of precipitation (magnified section in Fig. 4a) increases when Zr is added, and begins at a higher temperature, whereas the precipitation is more intense. Furthermore, the melting course of alloys with Zr or Mo additions differs significantly in comparison to the alloy A1 with no additions. Melting enthalpy also indicates on the differences, whereas it increases with the addition of Zr or Mo. Fig. 4b shows a relatively equilibrium solidification process. As already noted by thermodynamic calculations and STA, it can be seen that the addition of 0.2 wt. %

razlikuje od poteka taljenja osnovne zlitine brez dodatkov (S1). Hkrati se spremeni tudi talilna entalpija, ki se z dodatkom Zr in/ali Mo poveča. Na Sliki 4b je predstavljeno

Zr or/and 0.2 wt. % Mo increases liquidus temperature.



a)



b)

Slika 4. Ogrevna DSC krivulja s povečanim območjem izločevanja a) in ohlajevalna DSC krivulja b) vseh preiskovanih vzorcev: S1 – črna, S2 – rdeča, S3 – zelena in S4 – modra krivulja

Figure 4. Heating DSC curves, where the precipitation section is magnified (a) and cooling DSC curves (b) of all experimental samples: A1 – black, A2 – red, A3 – blue and A4 – green

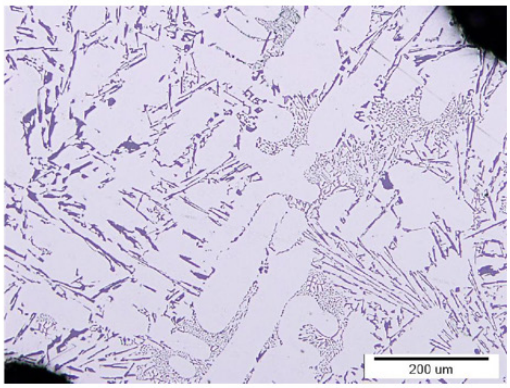
ravnotežno strjevanje. Kot je že bilo ugotovljeno s pomočjo termodinamičnih izračunov in DSC analize, nam dodatek 0,2 mas.% Zr in/ali 0,2 mas.% Mo zviša likvidus temperaturo.

3.4 Optična in elektronsko vrstična mikroskopija

Na Sliki 5 imamo predstavljeno mikrostrukturo DSC vzorcev v litem stanju. V nadaljevanju so prikazane fotografije mikrostruktur, ki so bile posnete s svetlobnim optičnim mikroskopom in elektronskim vrstični mikroskopom. Oblika in porazdelitev mikrostrukturnih sestavin

3.4 Optical end Electron Microscopy

Microstructure of samples from STA in as-cast state are shown in Fig. 5. Optical micrographs, where shape and distribution of microstructural components were observed (Fig. 5a, c, e, g) and images from electron microscopy of investigated alloys, where EDS analysis was made (Fig. 5b, d, f, h), are presented. From the optical micrographs can be concluded that the addition of Zr or/ and Mo causes a formation of a smaller microstructure components, which is most evident for the eutectic (α-Al + β-Si). Furthermore, microstructure of the alloy A2 exhibit needles belonging to the Zr-phase, and in the alloy A3 and A4 the modified



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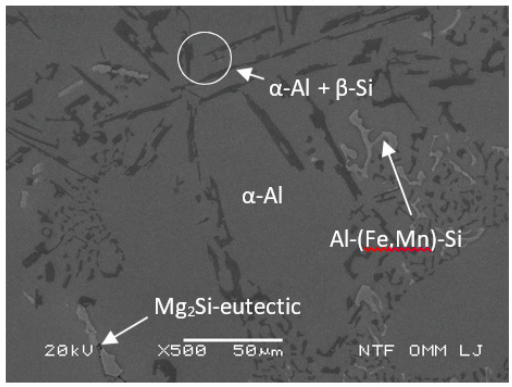
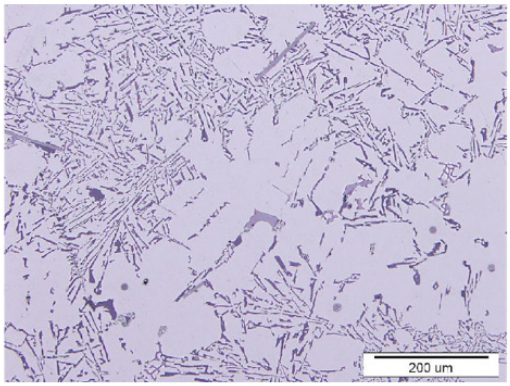
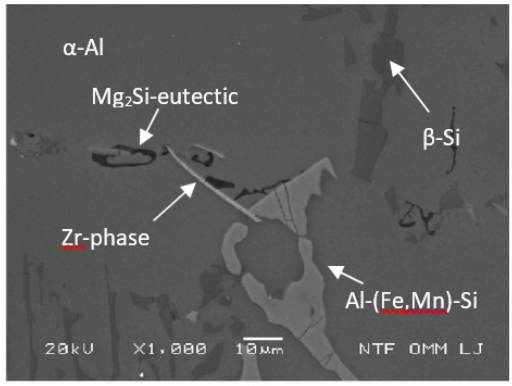


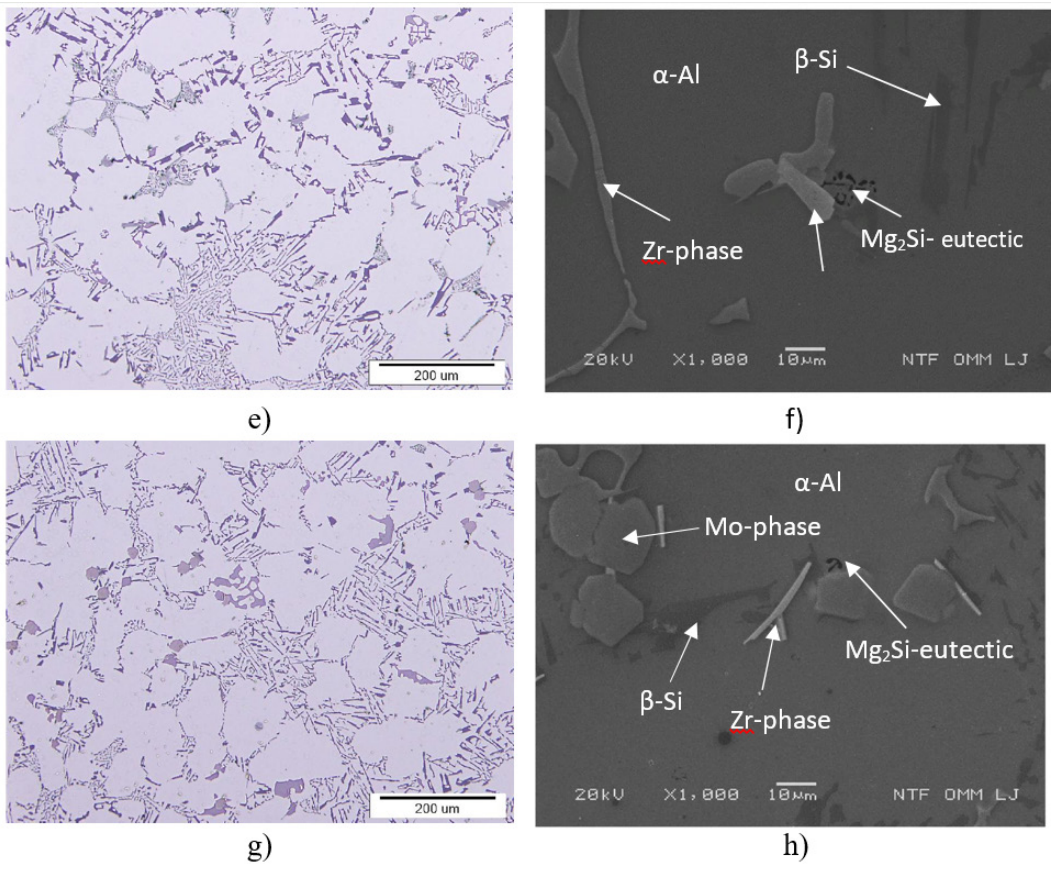
b)



c)



d)



Slika 5. Fotografije mikrostruktur posnete z optično mikroskopijo (a, c, e in g), vrstično elektronsko mikroskopijo in pripadajočimi območji EDS analize (b, d, f in h) za preiskovane vzorce S1 (a, b), S2 (c, d), S3 (e, f) in S4 (g, h)

Figure 5. Optical micrographs (a, c, e, g) and SEM images, where EDS analysis of marked phases was made (b, d, f, h) of experimental AlSi10MgMn alloy A1 (a, b), A2 (c, d), A3 (e, f) and A4 (g, h)

je bila analizirana s pomočjo optičnega svetlobnega mikroskopa. Med tem, ko smo s pomočjo elektronskega vrstičnega mikroskopa analizirali kemijsko sestavo faz preiskovanih zlitin z ali brez dodatka Zr in/ali Mo. Iz mikrostruktur na Slikah 5a, c, e in g lahko ugotovimo, da dodatek Zr in/ali Mo povzroči nastanek manjših mikrostrukturnih sestavin, kar je najbolj opazno pri evtektiku (α-Al + β-Si). V mikrostrukturi vzorca S2

AlFeMnSi phase due to Mo can be seen. In the alloy A4 both newly formed phases belonging to added alloying elements were detected. The morphology of the Zr- phase in the investigated alloys is similar to the phase morphology $(AlSi)_3(ZrTi)$ [10,11] and the morphology of Mo-phase is similar to the phase Al(Fe,Mo)Si, according to the literature.

opazimo faze v obliki iglic, ki pripadajo Zr fazam, med tem ko pri zlitini S3 opazimo modificirano fazo AlFeMnSi, ki je posledica dodatka Mo. Pri zlitini S4 imamo v mikrostrukturi obe novo nastali fazi, ki sta posledica dodatka Mo in Zr. Morfologija Zr in Mo faz v preiskovanih zlitinah je glede na literaturo podobna morfologiji faze $(AlSi)_3(ZrTi)$ [10,11] in Al(Fe,Mo)Si.

4 Zaključki

Glede na literaturne vire in trenutne raziskave vpliva Zr in/ali Mo na potek strjevanja, razvoj mikrostrukture in mehanskih lastnosti, lahko povzamemo naslednje zaključke:

Začetek strjevanja preiskovanih zlitin se z dodatkom Zr in/ali Mo prestavi k višjim temperaturam, istočasno se likvidus rekalescenca zmanjša ali celo izgine, med tem, ko se temperaturni interval strjevanja poveča.

Z dodatkom Zr preiskovanim zlitinam se začnejo tvoriti igličaste Zr faze. Po drugi strani pa se dodani Mo vgrajuje v AlFeMnSi fazo in v nekaterih primerih zamenja Fe in tako tvori novo AlFeMnMoSi fazo z drugačno morfologijo, ki je podobna kitajski pisavi, ampak s to razliko, da je okroglih oblik.

4 Conclusion

According to the literature sources and current research results, the influence of Zr or/and Mo on the course of solidification and the microstructure development, the following conclusion can be made:

The start of solidification of the investigated alloys with the addition of Zr or/and Mo shifts to a higher temperature, while the liquidus recalescence decreases or even disappears and the solidification temperature interval increases.

Zr and/or Mo causes the formation of a smaller microstructure components. When Zr was added in the alloy, a needle-like phase formed. Mo in the alloy is incorporated into AlFeMnSi phase, and in some cases replaced Fe, and formed new AlFeMnMoSi phase with a different morphology in a more roundish Chinese script.

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