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Vpliv molibdena in cirkonija na aluminijeve livarske zlitine

Effect of Molybdenum and Zirconium on Aluminium Casting Alloys

Povzetek

Modeliranje razvoja mikrostrukture med izdelavo omogoča globlje razumevanje sinergijskega vpliva različnih obdelovalnih parametrov, ki vplivajo na razvoj mikrostrukture. Cilj je bil razviti aluminijevo livarsko zlitino, ki ima izboljšane mehanske lastnosti, hkrati pa zmanjšuje težo končnega izdelka, ki se uporablja v avtomobilski industriji. Raziskane so bile mikrostruktura in mehanske lastnosti zlitine AlSi9Cu3(Fe) ob prisotnosti različnih kombinacij dodatkov Zr in Mo. Lite eksperimentalne zlitine so bile izpostavljene toplotni obdelavi T6. Natezne preizkuse smo izvedli za vse eksperimentalne zlitine pri 25 °C. Za proučevanje nastanka različnih intermetalnih faz smo uporabili optično mikroskopijo in elektronski mikroanalizator. Ugotovljeno je bilo, da lahko optimalna kombinacija dodatka Zr in Mo rahlo izboljša mehanske lastnosti preiskovane zlitine v litem stanju in znatno v toplotno obdelanem stanju T6.

Ključne besede: Al-livarske zlitine, prehodne kovine, mikrostruktura, toplotna obdelava, mehanske lastnosti

Abstract

Modelling of the evolution of microstructure during processing enables the deeper understanding of synergetic influence of various processing parameters that influences on the evolution of microstructure. The aim was to develop aluminium casting alloy, which have improved mechanical properties, while reducing the weight of the finished product used in the automotive industry. The microstructure evolution and mechanical properties of AlSi9Cu3(Fe) die casting alloy were investigated in the presence of various combinations of Zr and Mo additions. The cast experimental alloys were exposed to T6 heat treatment. Tensile tests were made for all experimental alloys at 25 °C. Optical microscopy and electron micro-analyzer were used to study the formation of different intermetallic phases. It was established that the optimal combination of Zr and Mo addition to investigated Al-casting alloy can slightly improve the mechanical properties in as-cast state and significantly in T6 heat treated state.

Key words: Al-casting alloys, Transition metals, Microstructure, Heat treatment, Mechanical properties

0 Uvod

Mikrostrukturne komponente zlitin iz sistema Al-Si odločilno vplivajo na mehanske in tehnološke lastnosti ulitkov. Izboljšanje mehanskih lastnosti dosežemo z udrobnjevanjem α-Al in/ali modifikacijo evtektika (α-Al + β-Si) in visoke hitrosti ohlajanja. Pomembna lastnost precipitacije sistemov strjevanja zlitin Al-Si je tudi odvisnost od ravnovesja topljivosti bakra in magnezija v zmesnih kristalih α-Al v povezavi s temperaturo. Baker v zlitini AlSi9Cu3 med termalnim kaljenjem zmanjšuje odpornost proti koroziji in izboljšuje mehanske lastnosti [1]. Železo povečuje odpornost proti razpokam v vročem in zmanjšuje verjetnost sprijetja ulitka v formo. Železo pri Al-livarskih zlitinah zmanjšuje voljnost. Tvori netopne faze Al_3Fe, Al_6FeMn in Al_5FeSi, ki izboljšujejo trdnost, zlasti pri višjih temperaturah. Z zvečanjem koncentracije železa in posledično netopnih faz se livnost in zmožnost dovajanja zmanjšata. Magnezij je osnova za trdnost in trdoto pri termalno kaljenih zlitinah Al-Si in se pogosto uporablja pri kompleksnih zlitinah Al-Si, ki vsebujejo baker, mangan, nikelj in druge elemente. Mangan je pri litih zlitinah običajno obravnavan kot nečistoča, v zelo majhnih koncentracijah pa ga lahko najdemo v zlitinah za gravitacijsko litje. Mangan je pomemben legirni element pri gnetnih Al zlitinah. Če zlitina ni pozneje oblikovana, mangan ne igra tako pomembne vloge. Večji volumski odstotek faze Al_6Mn lahko zveča trdnost ulitka. [2]

Ob tako širokem razponu uporabe aluminijevih zlitih za najrazličnejše namene na zlitine vplivajo sestava, udrobnjevanje in ustrezna toplotna obdelava. Z izbiro ustrezne toplotne obdelave lahko dosežemo želene mikrostrukture in posledično potrebne mehanske lastnosti. Za toplotno obdelavo se odločimo, ko želimo pri določeni sestavi doseči maksimalno trdnost

0 Introduction

The microstructural components of alloys from Al-Si system have a decisive influence on the mechanical and technological properties of castings. The increase in mechanical properties is achieved by the grain-refining of α-Al and/or modification of eutectic (α-Al + β-Si) and high cooling rate. An important feature of the precipitation hardening systems of Al-Si alloys is also the dependence of the equilibrium solubility of the copper and magnesium in the solid solution α-Al regarding the temperature. Copper in alloy AlSi9Cu3 reduces corrosion resistance and increases mechanical properties by thermal hardening [1]. The iron increases the resistance to cracks in hot and reduces the tendency of sticking the casting to the die. Iron in Al-casting alloys reduces ductility. It forms the insoluble phases Al_3Fe, Al_6FeMn and Al_5FeSi, which improve strength, especially at elevated temperatures. By increasing the concentration of iron and thus the insoluble phases, the castability and the feeding ability are reduced. Magnesium is the basis for strength and hardness in heat-treated Al-Si alloys and is widely used in complex Al-Si alloys containing copper, manganese, nickel and other elements. Manganese is usually treated as impurity in cast alloys and it can be found in very low concentrations in alloys for gravity casting. Manganese is an important alloying element in the wrought Al-alloys. If the alloy is not subsequently formed, it does not play such an important role. A larger volume fraction of Al_6Mn phase may increase the casting strength. [2]

On such a wide range of use of aluminium alloys for various purposes, the composition, the grain-refining and the corresponding heat treatment influences the properties. By selecting the appropriate heat treatment, the desired microstructure s pomočjo žarjenja, gašenja raztopine ter strjevanja s precipitacijo, ki lahko poteka po naravnem postopku ali umetno. Z ustrezno toplotno obdelavo ulitkov lahko dosežemo naslednje: večjo trdnost in posledično obdelovalnost materiala, večjo trdoto, stabilnejše mehanske in fizične lastnosti, dimenzijsko stabilnost, odpravo preostale obremenitve, povzročene med ulivanjem, tempranjem, obdelavo itd. [3, 4, 5, 6]

Natezna trdnost zlitine AlSi9Cu3 je 240–310 N/mm^2, raztezek pa približno 4 %. Trdota po Brinellu znaša 80–120 HB. [7]

Modifikacije zlitine Al-Si pri uporabi na visoki temperaturah so bile že velikokrat predmet raziskav. [8, 9, 10, 11] Pri legiranju livarskih Al-litin za uporabo pri visokih temperaturah morajo biti izpolnjeni štirje pogoji [12]: legirni element mora biti (i) zmožen oblikovati toplotno stabilno fazo strjevanja, (ii) izkazovati nizko topnost v matriki Al, (iii) imeti nizko prevodnost v matriki Al in (iv) ohranjati zmožnost litine za klasično strjevanje. Aluminijeve zlitine iz sistema Al-Si-Cu-Mg z mikrododatkom Cr, Ti, V in Zr izboljšujejo mehanske lastnosti po toplotni obdelavi T6, pri čemer se meja teženja poveča za 30 %, natezna trdnost pa za 5 % glede na osnovno zlitino pod enakimi pogoji [13]. Ti/Zr/V skupaj z Al in Si tvorijo fazo Al(ZrTiV)Si, ki povečuje trdnostne lastnosti zlitine AlSi7Cu1 za 20 do 40-krat in kaže na 11,5 do 15-kratno boljšo prevodnost v primerjavi s komercialno zlitino A380. [14]

Pri toplotni obdelavi zlitine AlSi7Cu1Mg0,5 z dodatkom 0,21 wt.% Ti, 0,3 wt.% V in 0,47 wt.% Zr, se faze Cu in Mg z evtektičnim Si raztopijo, medtem ko faza $(AlSi)_x(TiVZr)$ s tetragonalno kristalno strukturo ostane odporna do temperature 696–705 °C, kar poveča temperaturno stabilnost preiskovanih zlitin. [15] Trdota tovrstne zlitine po toplotni obdelavi T6 znaša 96 HRF. Pri takšni zlitini AlSi7Cu1Mg0,5

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 process of solution annealing, quenching and precipitation hardening, which may be natural or artificial. By appropriate heat treatment of castings, the following can be achieved: improved strength and consequently machinability of the material, increase in hardness, stabilized mechanical and physical properties, ensured dimensional stability, eliminated residual stresses caused during casting, tempering, treatment ... [3, 4, 5, 6].

The tensile strength of the AlSi9Cu3 alloy is 240-310 N/mm2, and the elongation is about 4 %. The hardness measured according to Brinell is 80-120 HB. [7]

Al-Si alloy modification studies for high temperature applications have been the subject of numerous studies. [8, 9, 10, 11] For the alloying of foundry Al-alloys for use at high temperatures, four conditions should be met [12]: the alloying element must (i) be able to form a thermally stable hardening phase, (ii) exhibit low solubility in the Al matrix, (iii) has low diffusivity in the Al-matrix, and (iv) retain the ability of the alloy for conventional solidification. Aluminium alloys from the Al-Si-Cu-Mg system with micro-addition of Cr, Ti, V and Zr elements increase the mechanical properties after the T6 heat treatment, whereas yield strength increases for 30 % and tensile strength for 5 % regarding to the base alloy under the same conditions [13]. Ti/Zr/V together with Al and Si form Al (ZrTiV) Si phase, which increases the tensile properties of AlSi7Cu1 alloy by 20-40 % and shows by 11.5-15 times better ductility compared to the commercial alloy A380. [14]

During the heat treatment of the alloy AlSi7Cu1Mg0.5 with the addition of 0.21 wt. % Ti, 0.3 wt. % V and 0.47 wt. % Zr, Cu-z dodatkom Ti, V in Zr se lahko tvorijo naslednje 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 $Al_{13}Si_2Ti_3Zr$, pri čemer se med topilnim žarjenjem faze $Cu_{15}Al_{43}Si$ in $Al_5Mg_9Si_8Cu_2$ raztopijo, železove faze pri AlSiCuFe in $Al_9Mg_{12}Si_6Fe$ pa ostanejo neraztopljene. Intermetalne faze $Al_{27}SiTiZr_9$ in AlSiTiVFe ostanejo v mikrostrukturi v majhnih količinah. [16] Če zlitini A354 dodamo 0,2 wt.% Zr in 0,2 wt.% Ni, se v mikrostrukturi tvorijo intermetalne faze $(Al,Si)_3(Zr,Ti)$, Al_3CuNi in Al_9NiFe. Z dvigom temperature se natezna trdnost teh zlitin zmanjša zaradi večjega deleža faz Ni in Zr, medtem ko so pri 300 °C napetostne lastnosti (končna natezna trdnost in meja teženja) 30 % višje v primerjavi z osnovno zlitino. Skupna koncentracija Ni in Zr ne sme preseči 0,4 wt.%. [17]

Trdnostne lastnosti zlitine Al7Si0,5Cu0,3Mg z dodatkom Mo (0,3 wt.%) se ohranijo kljub izpostavljenosti visokim temperaturam. Z lezenjem povezane lastnosti pri tovrstni zlitini se izboljšajo. Meja plastičnosti, natezne trdnosti in raztezka se z dodatkom Mo zveča za 25, 15 in 35 %. V tem primeru se tvorijo precipitati Al-(Fe, Mo)-Si, ki so stabilni pri 300 °C in zavirajo dislokacijske ovire, ki strjujejo matriko. [18] V kombinaciji z Mn (<0,5 wt.%) se koncentracija precipitatov poveča, velikost precipitatov pa se zmanjša. [19] Mo zavira tudi tvorbo škodljive faze β-Al5FeSi in tvori fazo Al- (Fe,Mo)-Si kubične strukture. [18, 19].

Skladno s predhodnimi raziskavami je bila opravljena analiza dodatka Zr in/ali Mo k zlitini AlSi9Cu3, pri čemer je bila opravljena analiza vpliva dodatka Zr in/ali Mo na mikrostrukturo in mehanske lastnosti zlitine AlSi9Cu3 v litem stanju in toplotno obdelanem stanju.

and Mg-phases along with the eutectic Si dissolve, while the $(AlSi)_x(TiVZr)$ phase of tetragonal crystal structure stays resistant up to 696 to 705 °C, which increases the temperature stability of the examined alloys. [15] The hardness of such an alloy after the T6 heat treatment is 96 HRF. In such an 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 $Al_{13}Si_2Ti_3Zr$, where in during the T6 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. [16] In the case that in the alloy A354 are added 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 rising the temperature tensile strength of these alloys decrease as a result of increasing proportion of Ni and Zr-phases, while at 300 °C the tensile properties (ultimate tensile strength and yield strength) are for 30 % higher as compared with the base alloy. The total Ni and Zr concentrations should not exceed 0.4 wt. %. [17]

The strength properties of the alloy Al7Si0.5Cu0.3Mg with the addition of Mo (0.3 wt. %) are maintained despite exposure to an elevated temperature. The creep properties in such an alloy improve. The limit of plasticity, tensile strength and elongation increases by 25, 15 and 35 % with the 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. [18] In combination with Mn (<0.5 wt. %), the precipitation concentration increases, whereas the size of precipitations is reduced. [19] Mo also inhibits the formation

1 Eksperimetano delo

Raziskovali smo hipoevtektične zlitine AlSi9Cu3 brez (osnove) in z dodatkom prehodnih elementov Zr in/ali Mo. Oznake eksperimentalnih zlitin in njihove kemijske sestave so predstavljene v Preglednici 1. Zlitine smo stopili v indukcijski peči, kjer smo po načrtih kot predzlitinama AlZr10 in AlMo5 dodali dodatek Zr in Mo. Za izdelavo visokokakovostne taline smo talino z mešalom vsaj 10 minut razplinjevali z Ar, indeks gostote (IG) pa smo izmerili pred litjem. Ko je indeks gostote padel pod vrednost 2, smo lahko začeli z ulivanjem.

Iz vsake eksperimentalne zlitine smo izdelali serije po pet ulitkov v formah za ulivanje preizkušancev za natezni preizkus (Sl. 1a). Po rezanju ulitkov v preizkušance za natezne preizkuse smo vse vzorce označili, kot je prikazano na Sliki 1b. Preizkušance smo pripravili skladno s standardom DIN 50125, natezne preizkuse pa opravili z napravo INSTRON 8802 skladno s standardom EN ISO 6892-1 A224.

Za primerjavo litega in toplotno obdelanega stanja preiskovanih zlitin smo na šestih vzorcih iz vsake eksperimentalne zlitine izvedli toplotno obdelavo T6. Toplotna obdelava T6 je potekala po naslednjem postopku:

of the harmful β-Al5FeSi phase and forms Al- (Fe,Mo)-Si phase of cubic structure. [18, 19].

According to previous researches, an analysis of Zr and/or Mo addition to AlSi9Cu3 alloy was made, whereas the impact analysis of Zr and/or Mo addition on the microstructure and mechanical properties of the AlSi9Cu3 alloy in cast and heat-treated state was made.

1 Experimental Work

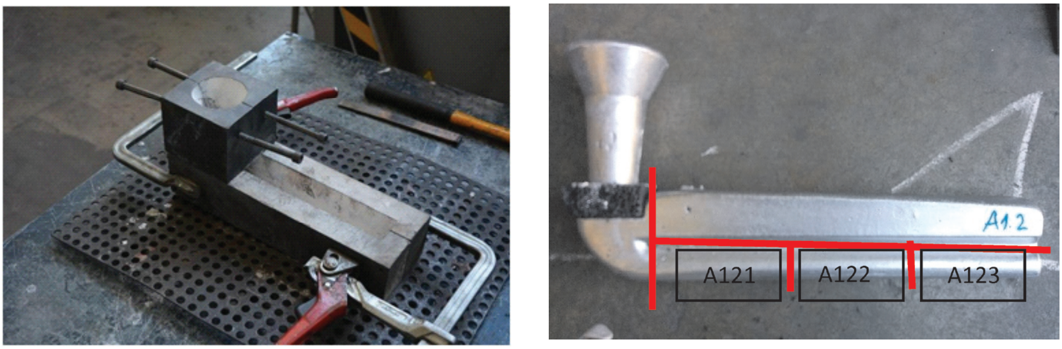
Hypoeutectic AlSi9Cu3 die casting alloys, without a base and in addition of the transition elements Zr or/and Mo, were investigated. The experimental alloy designations and its chemical compositions are presented in Table 1. The alloys were melted in an induction furnace, whereas various planned additions of Zr and Mo were added as master alloys AlZr10 and AlMo5. In order to produce a high quality melt, the melt was degassed using Ar for at least 10 min with the Impeller, whereas the density index (DI) was measured before casting. When the DI was below 2, the casting could start.

From each experimental alloy the series of five castings were casted into the die for casting the tensile samples (Fig.

Preglednica 1. Oznaka zlitine in kemijska sestava eksperimentalnih zlitin / wt.%

Table 1. Alloy designation and chemical composition of experimental alloys / wt. %.

AlSi9Cu3	Si	Fe	Cu	Mn	Mg	Zn	Ti	Zr	Mo	Al
A1	8,284	0,258	3,076	0,172	0,309	0,078	0,073	0,004	0,001	preostanek / rest
A2	8,198	0,262	3,028	0,172	0,313	0,078	0,074	0,095	0,006	preostanek / rest
A3	7,895	0,263	2,951	0,168	0,300	0,075	0,068	0,110	0,110	preostanek / rest
A4	7,684	0,274	2,844	0,165	0,290	0,072	0,066	0,107	0,180	preostanek / rest
A5	8,203	0,258	3,029	0,172	0,308	0,078	0,078	0,002	0,008	preostanek / rest
A6	8,512	0,291	3,524	0,179	0,370	0,082	0,067	0,189	0,016	preostanek / rest
A7	7,895	0,280	2,942	0,168	0,301	0,075	0,068	0,179	0,113	preostanek / rest
A8	7,887	0,302	2,991	0,166	0,302	0,074	0,065	0,176	0,190	preostanek / rest



a) b)

Slika 1. Forma za ulitke za natezne preizkuse (a) in ulitek iz forme z oznako preseka in vzorca (b): številka pomeni vrsto zlitine, prva številka pomeni sestavo zlitine, druga serijo ulitka iz eksperimentalne litine, zadnja pa vzorec iz ulitka za natezni preizkus

Figure 1. The die for the tensile castings (a) and the casting from the die where the cutting and the sample marking is marked (b): letter means the type of the alloy, first number means the alloy composition, second number means the serial casting from the experimental alloy and the last number means the sample from the casting for the tensile test

1. žarjenje raztopine pri 520 °C 2 uri,
2. kaljenje v vodi do sobne temperature,
3. umetno staranje pri 180 °C 5 ur,
4. hlajenje na zraku do sobne temperature.

Po toplotni obdelavi T6 smo za natezni preizkus pripravili po pet vzorcev vsake eksperimentalne zlitine. En preostali vzorec smo uporabili za analizo mikrostrukture. Popolno mikrostrukturno analizo smo opravili z optično mikroskopijo. Metalografske vzorce smo pripravili skladno s standardnim metalografskim postopkom: prvo brušenje (brusni papir z granulacijami 80, 320 in 1.200), sledilo je poliranje približno 5 minut s suspenzijo iz diamantnih zrnc 3 µm (CT Diamond Suspension Mono) in končno poliranje približno 20 sekund z alkalno suspenzijo iz koloidnega kremena 0,5 µm (Colloidal Silica Suspension 50nm Alkaline). S svetlobnim mikroskopom ZEISS AXIO Imager A1m smo z različnimi povečavami fotografirali mikrostrukturo vseh eksperimentalnih vzorcev v litem in

1a). Afterwards the castings were cut into the samples for the tensile tests, whereas all the samples were marked as shown in Fig. 1b. The tensile samples were prepared according to standard DIN 50125 and the tensile tests were made on INSTRON 8802 according to standard EN ISO 6892-1 A224.

To compare the as-cast state and heat treated state of the investigated alloys, T6 heat treatment was conducted on six samples from each experimental alloy. T6 heat treatment was conducted as follows:

1. Solution annealing at 520 °C for 2h
2. Quenching in water to room temperature
3. Artificial ageing at 180 °C for 5h
4. Cooling in air to room temperature

After the T6 heat treatment five samples from each experimental alloy were prepared for the tensile test. One sample, that was left, was used for the microstructure analysis. In order to do complete microstructure analysis, optical microscopy was used.

toplotno obdelanem stanju. Kvantitativno in kvalitativno analizo mikrostrukture štirih vzorcev (A823, B823, A843 in B843) v litem in toplotno obdelanem stanju smo opravili z vrstičnim elektronskim mikroskopom (SEM) JEOL 7200F-JSM, opremljenim s spektometroma EDS in WDS, ki omogoča analizo sestave faze.

2 Rezultati in razprava

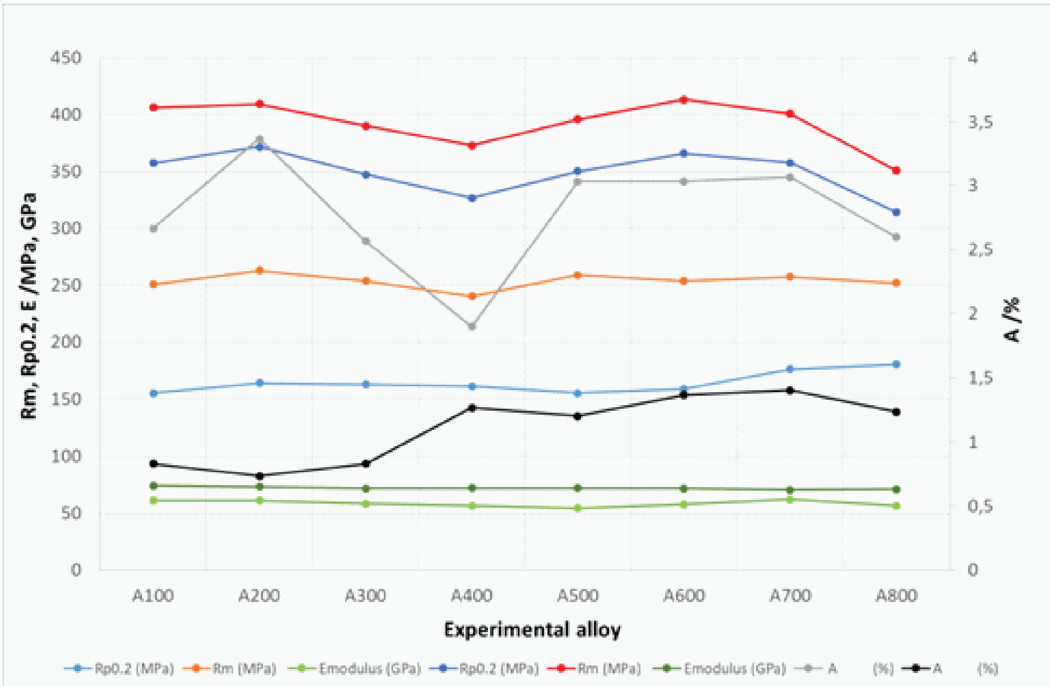
Pri vsaki raziskovani zlitini smo preizkusili pet vzorcev v litem in toplotno obdelanem stanju. Pridobljene podatke, obdelane kot maksimume in minimume, smo odstranili iz izračunov povprečja. Pridobljeni rezultati vseh nateznih preizkusov so predstavljeni v Preglednici 2. Na Sliki 2 je prikazana primerjava nateznih lastnosti za eksperimentalne zlitine A (AlSi9Cu3), svetle barve prikazujejo rezultate pri litem stanju, temne pa stanje pri toplotno obdelanem stanju. Sklepamo lahko, da dodatek 0,2 wt.% Mo (zlitina A4 in A8) ni primeren; mehanske lastnosti so slabše kot pri manjšem dodatku Mo. Toplotna obdelava poveča Rm, $Rp_{0,2}$ in E, zmanjša pa raztezek. Dodatka Zr in Mo ugodno vplivata na raztezek pri toplotno obdelanem stanju. Pri toplotno obdelanem stanju smo najvišji vrednosti Rm (~420 MPa) in $Rp_{0,2}$ (~ 375 MPa) dosegli pri zlitinah A2 in A6, medtem ko smo samo Zr dodali v zlitino AlSi9Cu3.

Z namenom analize mikrostrukturnih komponent, tvorjenih na osnovi Zr in Mo, smo na vseh eksperimentalnih vzorcih opravili optično analizo mikrostrukture. Slika 3 predstavlja svetlobnomikroskopski posnetek vzorcev A1 (osnovna zlitina), A2 (zlitina z 0,1 wt.% Zr) in A8 (zlitina z 0,2 wt.% Zr in 0,2 wt.% Mo) v litem in toplotno obdelanem stanju pri 1.000-kratni povečavi. Na svetlobnomikroskopskih posnetekih so označene glavne komponente

Metallographic samples were prepared according to standard metallographic procedure: first grinding (80, 320 and 1200 grinding paper), followed by polishing with 3μm CT Diamond Suspension Mono for approximately five minutes and finished by polishing with 0.5 μm Colloidal Silica Suspension 50nm Alkaline for approximately 20 s. Using light microscope ZEISS AXIO Imager A1m the microstructure of all experimental samples in as-cast and heat treated state were photographed at various magnification. The quantitative and qualitative microstructure analysis of four samples (A823, B823, A843 and B843) in as-cast and heat treated state were made using Scanning electron microscope (SEM) JEOL 7200F-JSM equipped with EDS and WDS- spectrometers, which enables the analysis of phase composition.

2 Results and Discussion

From each investigated alloy five samples were tested in as-cast and heat treated state. Gained data were processed as the maximum and minimum results were eliminated from the average calculations. The collected results from all tensile tests are presented in Table 2. Fig. 2 presents the comparison of tensile properties for experimental alloys A (AlSi9Cu3), whereas light colours present the results in as-cast state and dark colours after the heat treatment. It can be concluded, that the addition of 0.2 wt.% Mo (alloy A4 and A8) is not suitable; the mechanical properties are lower as at the lower additions of Mo. Heat treatment increases Rm, $Rp_{0.2}$ and E, whereas it lowers elongation. The additions of Zr and Mo have favourable impact on the elongation in heat treated state. In heat treated state the maximum Rm (~ 420 MPa) and $Rp_{0.2}$ (~ 375 MPa) were achieved in



Slika 2. Grafična predstavitev vseh rezultatov nateznega preizkusa za eksperimentalno zlitino A v litem stanju (svetle barve) in po toplotni obdelavi T6 (temne barve)

Figure 2. Graphical presentation of all results from the tensile test for experimental alloy A in as-cast state (light colours) and after T6 heat treatment (dark colours)

Preglednica 2. Natezne lastnosti za vse eksperimentalne zlitine v litem in toplotno obdelanem stanju

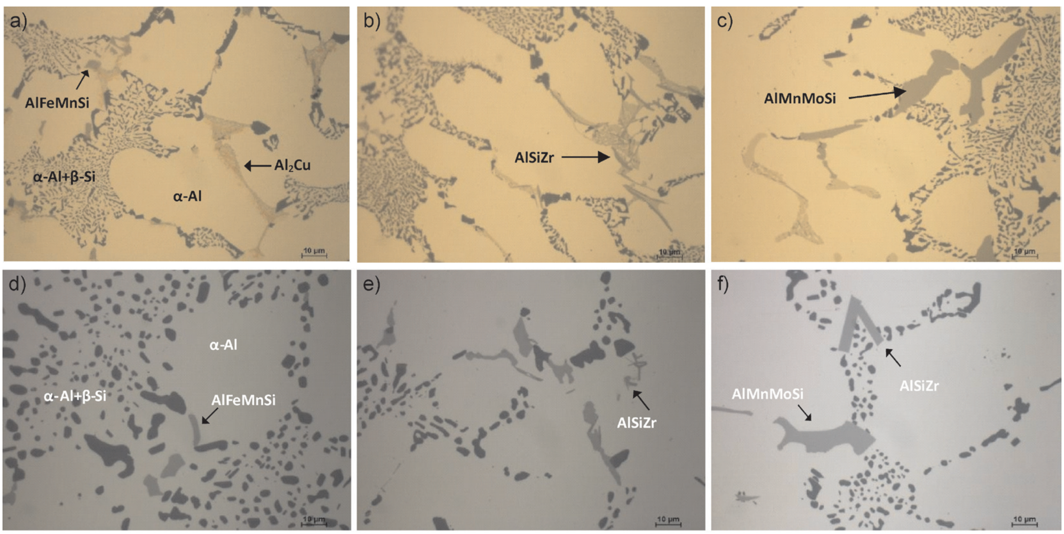
Table 2. Tensile properties for all experimental alloys in as-cast and heat treated state

Zlitina / Alloy	V litem stanju / cast state				V toplotno obdelanem stanju T6 / T6 As-heat treated state			
	$Rp_{0,2}$ (MPa)	Rm (MPa)	A (%)	Modul elastičnosti / (GPa)	$Rp_{0,2}$ (MPa)	Rm (MPa)	A (%)	Modul elastičnosti / Emodulus (GPa)
A100	155,0	250,7	2,7	60,7	357,3	406,3	0,8	73,8
A200	164,0	262,7	3,4	60,9	371,7	409,3	0,7	73,0
A300	162,7	253,7	2,6	58,2	347,3	390,3	0,8	71,5
A400	161,3	240,3	1,9	56,2	326,7	372,7	1,3	71,7
A500	155,0	258,7	3,0	54,2	350,0	396,0	1,2	71,8
A600	158,7	253,7	3,0	57,5	365,7	413,3	1,4	71,4
A700	176,0	257,3	3,1	61,8	357,7	401,0	1,4	70,2
A800	180,3	251,7	2,6	56,3	314,3	350,7	1,2	70,9

mikrostrukture. Pri osnovni zlitini A smo opazili naslednje mikrostrukturne komponente (Sl. 3a): α-Al, evtektik (α-Al + β-Si), evtektična faza Al_2Cu in evtektična faza AlFeMnSi (predvidoma $Al_{15}(Fe,Mn)_3Si_2$). Ko smo v zlitino dodali Zr, je prišlo do faze z iglasto formacijo, kar smo pozneje analizirali kot fazo AlSiZr (Sl. 3b). Po drugi strani Mo v zlitini ni tvoril nove intermetalne faze, pač pa se je vdelal v fazo AlFeMnMoSi, včasih je nadomestil Fe in tvoril novo fazo AlFeMnMoSi z drugačno morfologijo (Sl. 3c). Tvoril je tudi formacijo, podobno kitajskim pismenkam, le da je bila ta bolj zaobljene oblike, kar bi lahko bil vzrok za izboljšane mehanske lastnosti. Po toplotni obdelavi T6 v mikrostrukturi nismo zaznali nobene evtektične faze Al_2Cu (Sl. 3d). Evtektična faza Si in AlFeMnSi je bila v mikrostrukturi nekoliko bolj zaobljena in fragmentirana, ravno tako faza AlFeMnSi (Sl. 3f). Toplotna obdelava T6 ni vplivala na fazo Zr (Sl. 3e).

alloy A2 and A6, where only Zr was added in the alloy AlSi9Cu3.

In order to analyze the microstructure components formed on base of Zr and Mo all experimental samples were exposed to optical microstructure analysis. Fig.3 presents micrographs of samples A1 (base alloy), A2 (alloy with 0.1 wt. % Zr) and A8 (alloy with 0.2 wt.% Zr and 0.2 wt.% Mo) in as-cast and heat treted state at 1000x magnification. On the micrographs the main microstructure components are marked. In base alloy A following microstructure components were detected (Fig. 3a): α-Al, eutectic (α-Al + β-Si), eutectic Al_2Cu-phase and eutectic AlFeMnSi-phase (presumably $Al_{15}(Fe,Mn)_3Si_2$). When Zr was added in the alloy needle-like phase occurred, which was later analysed as AlSiZr-phase (Fig. 3b). On the other hand, Mo in the alloy did not form new intermetallic phase, but it incorporated into AlFeMnSi-phase, sometimes replaced Fe and formed new AlFeMnMoSi phase



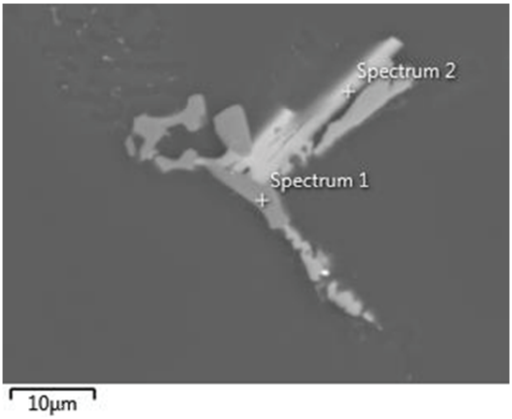
Slika 3. Mikrostruktura nekaterih eksperimentalnih vzorcev. A123 (a), A223 (b) in A823 (c) v litem stanju ter A143 (d), A243 (e) in A843 (f) po toplotni obdelavi T6 pri 1.000-kratni povečavi

Figure 3. Microstructure of some experimental samples: A123 (a), A223 (b) and A823 (c) in as cast state and A143 (d), A243 (e) and A843 (f) in T6 heat treated state at 1000x magnifications

Na Slikah 4 in 5 sta predstavljeni in analizirani fazi Zr in Mo. S preslikavanjem smo potrdili, da je Zr tvoril skupaj z Al, Ti in Si, Mo pa skupaj z Al, Fe, Mn in Si (Sl. 5). Po toplotni obdelavi so bile faze Al_2Cu, AlSiZr in AlFeMnMoSi tesneje povezane in bolj zaobljene, kot je prikazano na Sliki 5.

with a different morphology (Fig. 3c). It formed also in a shape of a chinese-script, only more roundish, which could be the reason for improvement in mechanical properties. After T6 heat treatment no Al_2Cu-eutectic phase could be detected in the microstructure (Fig. 3d). Eutectic Si and AlFeMnSi phase appeared more roundish and fragmented in the microstructure, the same as AlFeMnMoSi-phase (Fig.3f). T6 heat treatment have no impact on Zr-phase (Fig.3e).

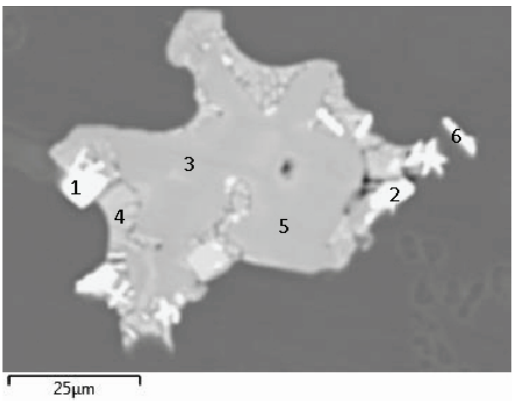
In Fig. 4 and 5 Zr- and Mo-bearing phases are presented and analyzed. Mapping confirmed, that Zr formed together



Slika 4. Mikrograf SEM vzorca A823 z analizo EDS

Figure 4. SEM micrograph of sample A823 with the corresponding EDS analysis

Element	Al	Si	Mn	Fe	Cu	Mo	Mg	Ti	Zr	
Spectrum 1	58.45	9.31	7.1	16.52	4.19	4.43				AlFeMnMoSi
Spectrum 2	43.44	10.24			6.23		2.41	0.61	37.07	AlSiZr



Slika 5. Mikrograf SEM vzorca A843 z analizo EDS

Figure 5. SEM micrograph of sample A843 with the corresponding EDS analysis

Element	Al	Si	Ti	Cu	Zr	Mn	Fe	Mo	Mg	
Spekter 1	4,58	33,25	2,74	0,76	58,66					AlSIZr
Spekter 2	29,68	26,09	1,89	2,6	39,75					AlSiZr
Spekter 3	74,2	4,35	0,09	0,48		2,58	0,54	17,75		AlMnMoSi
Spekter 4	67,9	6,43		25,68						Al_2Cu
Spekter 5	54,98	9,25	0,04	5,03	0,56	5,83	14,45	9,86		AlFeMnMoSi
Spekter 6	12,24	31,97	1,91	2,19	51,22				0,47	AlSiZr

Sestava faz je podobna kot pri zlitini v litem stanju.

3 Sklepi

Iz dobljenih rezultatov lahko sklepamo naslednje:

- toplotna obdelava poveča Rm, $Rp_{0,2}$ in E, zmanjša pa raztezek zlitine AlSi9Cu3. Dodatka Zr in Mo ugodno vplivata na raztezek pri toplotno obdelanem stanju. Pri toplotno obdelanem stanju smo dosegli najvišji vrednosti Rm (~420 MPa) in Rp0,2 (~375 MPa), medtem ko smo samo Zr dodali v zlitino AlSi9Cu3. Dodatek 0,2 wt.% Mo ni primeren; mehanske lastnosti so slabše kot pri manjšem dodatku Mo.
- Pri osnovni zlitini AlSi9Cu3 smo zaznali naslednje mikrostrukturne komponente: α-Al, evtekt (α- Al + β-Si), evtektična faza Al_2Cu in evtektična faza AlFeMnSi ($Al_{15}(Fe,Mn)_3Si_2$) skladno s pričakovanji. Pri dodatku Zr v zlitino se je tvorila faza z iglasto formacijo. Mo v zlitini se je vdelal v fazo AlFeMnMoSi, v nekaterih primerih je nadomestil Fe in tvoril novo fazo AlFeMnMoSi z drugačno morfologijo v podobi nekoliko zaobljene kitajske pismenke. Pri toplotni obdelavi T6 nismo zaznali evtektične faze Al_2Cu, pri evtektični fazi Si in AlFeMnSi (AlFeMnMoSi) pa se je v mikrostrukturi pojavila nekoliko bolj zaobljena in fragementirana oblika.
- Z analizo SEM smo potrdili, da je Zr združil z Al, Ti in Si, Mo pa z Al, Fe, Mn in Si. Po toplotni obdelavi so bile faze Al_2Cu, AlSiZr in AlFeMnMoSi tesneje povezane in bolj zaobljene.

4 Zahvale

Avtorji se zahvaljujemo Avstrijski akademiji znanosti za priložnost sodelovanja pri

with Al, Ti and Si and Mo together with Al, Fe, Mn and Si (Fig. 5). After the heat tretment phases Al_2Cu, AlSiZr and AlFeMnMoSi formed more together and more roundish, as it is shown on Fig. 5. The composition of phases is similar as in the alloy in as-cast state.

3 Conclusion

From the presented results it can be concluded:

- Heat treatment increases Rm, $Rp_{0.2}$ and E, whereas it lowers elongation of AlSi9Cu3 alloy. The additions of Zr and Mo have favorauble impact on the elongation in heat treated state. In heat treated state the maximum Rm (~ 420 MPa) and $Rp_{0.2}$ (~ 375 MPa) were achieved, where only Zr was added in the alloy AlSi9Cu3. The addition of 0.2 wt.% Mo is not suitable; the mechanical properties are lower as at the lower additions of Mo.
- In base AlSi9Cu3 alloy following microstructure components were detected: α-Al, eutectic (α- Al + β-Si), eutectic Al_2Cu phase and eutectic AlFeMnSi phase ($Al_{15}(Fe,Mn)_3Si_2$), as it was expected. When Zr was added in the alloy needle-like phase formed. Mo in the alloy incorporated into AlFeMnSi phase, in some cases replaced Fe, and formed new AlFeMnMoSi phase with a different morphology in a more roundish Chinese script. At T6 heat treated state no Al_2Cu-eutectic phase could be detected, whereas eutectic Si and AlFeMnSi (AlFeMnMoSi) phase appeared more roundish and fragmented in the microstructure.
- SEM analysis confirmed that Zr formed together with Al, Ti and Si and Mo together with Al, Fe, Mn and Si. After the heat treatment phases Al_2Cu,

projektu Joint Excellence in Science and Humanities, ki podpira sodelovanje znanstvenikov iz različnih držav. To delo sta podprla tudi Ministrstvo za izobraževanje, znanost in šport ter Evropski sklad za regionalni razvoj v okviru Evropske komisije. To delo je bilo opravljeno v okviru programa Materiali in tehnologije za nove aplikacije (MARTINA, št. zahtevka: C3330-16-529008) in programa P2-0344(B), funkcionalno ocenjeni materiali.

AlSiZr and AlFeMnMoSi formed more connected and more roundish.

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5 Viri / References

1 BAKER H., Alloy Phase Diagrams. ASM Handbook – Volume 3. ASM International, Materials Park. Ohio, 1992.
2 ASM Metals HandBook Volume 15 – Casting, objavljeno leta 1988.
3 DAVIS J. R., ASM Specialty Handbook, Aluminium and Aluminium Alloys. ASM International, 1993, str. 220–224.
4 ASM HANDBOOK, Volume 4, Heat Treating, ASM International, The Materials Information Company, 1991.
5 S. C. Weakley-Bollin, W. Donlon, C. Wolverton, W. J. Jones, in J. E. Allison, Modelling the Age-Hardening Behaviour of Al-Si-Cu Alloys, Metallurgical and Materials Transactions A, 35a (2004), str. 2407–2418.
6 O. R. Myhr, Ø. Grong, S. J.Andersen, Modelling of the age hardening behaviour of Al-Mg-Si alloys, Acta mater. 49 (2001) str. 65–75.
7 http://www.limatherm.com/img/fck/8910041/limatherm/File/Technical%20information/Aluminium%20specification.pdf
8 S.K. Shaha, F. Czerwinski, W. Kasprzak, D.L. Chen, Work hardening and texture during compression deformation of the Al–Si–Cu–Mg alloy modified with V, Zr and Ti, J. Alloy. Compd. 593 (2014), str. 290–299.
9 T. Gao, X. Zhu, Q. Sun, X. Liu, Morphological evolution of ZrAlSi phase and its impact on the elevated-temperature properties of Al–Si piston alloy, J. Alloy. Compd. 567 (2013), str. 82–88.
10 S.K. Shaha, F. Czerwinski, W. Kasprzak, D.L. Chen, Tensile and compressive

deformation behavior of the Al–Si–Cu–Mg cast alloy with additions of Zr, V and Ti, Mater. Des. 59 (2014), str. 352–358.
11 S.K. Shaha, F. Czerwinski, W. Kasprzak, J. Friedman, D.L. Chen, Effect of Zr, V and Ti on hot compression behavior of the Al–Si cast alloy for powertrain applications, J. Alloy. Compd. 615 (2014), str. 1019–1031.
12 K.E. Knipling, Development of a Nanoscale Precipitation-strengthened Creepresistant Aluminum Alloy Containing Trialuminide Precipitates, Northwestern University, Evanston, IL, 2006.
13 S.K. Shaha, F. Czerwinski, W. Kasprzak, J. Friedman, D.L. Chen, Ageing characteristics and high-temperature tensile properties of Al–Si–Cu–Mg alloys with micro-additions of Cr, Ti, V and Zr, Materials Science & Engineering A, A 652 (2016), str. 353–364
14 S.K. Shaha, F. Czerwinski, W. Kasprzak, J. Friedman, D.L. Chen, Microstructure and mechanical properties of Al–Si cast alloy with additions of Zr–V–Ti, Materials & Design 83 (2015), str. 801–812
15 S.K. Shaha, F. Czerwinski, W. Kasprzak, J. Friedman, D.L. Chen, Thermal stability of (AlSi)x(ZrVTi) intermetallic phases in the Al–Si– Cu–Mg cast alloy with additions of Ti, V, and Zr, Thermochimica Acta 595 (2014), str. 11–16
16 W. Kasprzak, B. S. Amirkhiz, M. Niewczas, Structure and properties of cast Al–Si based alloy with Zr–V–Ti additions and its evaluation of high temperature performance, Journal of Alloys and Compounds 595 (2014) , str. 67–79
17 A.M.A. Mohamed, F.H. Samuel, Saleh Al Kahtani, Microstructure, tensile properties and fracture behavior of high temperature Al–Si–Mg–Cu cast alloys, Materials Science & Engineering A577 (2013), str. 64–72
18 A.R. Farkoosh, X. Grant Chen, M. Pekguleryuz, Dispersoid strengthening of a high temperature Al–Si–Cu–Mg alloy via Mo addition, Materials Science & Engineering A 620 (2015), str. 181–189
19 A.R. Farkoosh, X. Grant Chen, M. Pekguleryuz, Interaction between molybdenum and manganese to form effective dispersoids in an Al–Si–Cu–Mg alloy and their influence on creep resista

AKTUALNO / CURRENT

Koledar livarskih prireditev 2018

Datum dogodka	Ime dogodka	Lokacija
26.- 27. 04. 2018	Grosse Giessereitechnische Tagung (Osterreich, Schweiz, Deutschland)	Salzburg, Avstrija
16.-18.05. 2018	17th International Foundrymen Conference	Opatija, Hrvaška
04.- 05.06.2018	10. Industrijski forum IRT	Portorož, Slovenija
12. - 14. 09. 2018	58. IFC - mednarodno livarrsko posvetovanje Portorož	Portorož, Slovenije
23.- 27. 09. 2018	73rd World Foundry Congress »Creative Foundry« in Generalna skupščina WFO	Krakow, Poljska
11..10.2018	IFF- International Foundry Forum	Amsterdam, Nizozemska