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Vpliv Cu na razvoj mikrostrukture zlitine AlSi7MgCu

Influence of Cu on the microstructure development of AlSi7MgCu alloy

Izvleček

Snovanje in karakterizacija zlitine AlSi7Mg(Cu) z dodatkom Cu (do 1,435 wt.%) predstavlja izziv na poti k doseganju naprednih mehanskih lastnosti že pri običajnih, torej neobdelanih ulitkih. Mikrostrukturna raziskava zlitine AlSi7MgCu odkriva širok razpon zapletenih reakcij in možnih intermetalnih faz zaradi interakcije legirnih elementov in elementov v sledovih. Dodatek Cu (do 1,435 wt.%) kot sekundarni legirni element sproža dodatno interakcijo s prehodnimi elementi Fe, Mn in sekundarnim legirnim elementom Mg. Razvoj mikrostrukture in določitev zaporedja strjevanja zagotavljajo podroben vpogled v poti strjevanja tako neobdelanih kot toplotno obdelanih ulitkov. Obogatitev procesa strjevanja s kompleksnimi intermetalnimi fazami odkriva naslednje sestavine: dendritna mreža; železna iglasta formacija Al_5SiFe in/ali kompleksna formacija, podobna kitajskim pismenkam $Al_{15}(Fe,Mn,Cu)_3Si_2$; glavna evtektska $(\alpha_{Al}+\beta_{Si})$; kompleksen evtektski klaster faze $Al_8Mg_3(Fe,Mn,Cu)Si_6$ in faze $Al_5(Fe,Mn,Cu)_2Mg_8Si_6$ ter precipitat sekundarne evtektske faze $\alpha_{Al}+Mg_2Si$ in $\alpha_{Al}+Al_2(Fe,Mn,Cu)$. Infiltracija pogostih prehodnih elementov, npr. Fe in Mn v fazah, ki prenašajo Cu, je privedla do visoke vsebnosti prehodnih elementov (Fe+Mn+Cu). Mikrostrukturne raziskave so pokazale tudi trajno interakcijo Fe, Mn in Cu pri tvorbi širokega razpona intermetalnih faz skozi celoten proces strjevanja.

Narava (morfologija in interakcije legirnih elementov) tvorjenih intermetalnih faz ustreza razvoju nateznih in mehanskih lastnosti zaradi močnih vezi in interakcije med celotnim procesom strjevanja.

Ključne besede: zlitina AlSi7MgCu, baker, mikrostruktura, prehodni elementi

Abstract

Designing and characterisation of AlSi7MgCu alloy with extra addition of Cu (up to 1.435 wt.%) represents a challenge in order to achieve advanced mechanical properties already in as- cast state. Microstructural investigation of AlSi7MgCu alloy reveals a wide range of complex reactions and possible intermetallic phases due to the interaction of alloying and trace elements. An extra addition of Cu (up to 1,435 wt.%) as a secondary alloying element initiates an additional interaction with transition elements Fe, Mn and secondary alloying element Mg. Evolution of microstructure and determination of solidification sequence enables a detailed overview of the solidification path in both states, as-cast and heat-treated. Enrichment of solidification process with complex intermetallic phases reveals the following constituents: dendrite network; iron-based needle-like Al_5SiFe and / or complex Chinese script formation $Al_{15}(Fe,Mn,Cu)_3Si_2$; main eutectic $(\alpha_{Al}+\beta_{Si})$; complex eutectic clusters of $Al_8Mg_3(Fe,Mn,Cu)Si_6$ and $Al_5(Fe,Mn,Cu)_2Mg_8Si_6$ phase and secondary eutectic phase precipitations α_{Al}+Mg_2Si and α_{Al}+$Al_2(Fe,Mn,Cu)$. Infiltration of common transition elements such as Fe and Mn in Cu bearing phases resulted in high total content of transition elements (Fe+Mn+Cu). Microstructural investigation also indicates continuous interaction of Fe, Mn and Cu in formation of wide range of intermetallic phases through the whole solidification process.

The nature (morphology and alloying elements interaction) of formed intermetallic phases comprehends to the tensile mechanical properties' development due to strong connections and interactions during solidification process as a whole.

Keywords: AlSi7MgCu alloy, copper, microstructure, transition elements

1 Uvod

Vse večje povpraševanje po lahkih aluminijastih zlitinah zaradi učinka racionalizacije in posledičnega zmanjšanja emisij CO_2 prihaja tudi iz avtomobilske industrije [1, 2, 3]. Varnostno kritični ulitki iz aluminijeve zlitine so bili - kar se tiče dolgoročne stabilnosti v agresivnem strojnem okolju - izpostavljeni visokim zahtevam na tržišču. Mehanske lastnosti, dovzetnost za toplo pokanje in druge kakovostne lastnosti aluminijastih komponent so močno odvisne od kemične sestave [4, 5, 6]. Zato postaja inovativen pristop k zasnovi spremenjene kemične sestave aluminijastih zlitin z večjo natezno trdnostjo, toplotno stabilnostjo, odpornostjo proti koroziji pomemben dejavnik za strukturne komponente v avtomobilski industriji.

Zaradi odlične livnosti, primernosti za recikliranje, nizkostroškovne proizvodnje, visoke specifične trdnosti in dobrega razmerja med trdnostjo in težo, zlasti v primeru toplotno obdelanih ulitkov, je tradicionalna zlitina AlSi7Mg pogosta izbira pri izdelavi ulitkov zapletenih geometrij z visokimi mehanskimi lastnostmi [7, 8, 9, 10]. Strjevalno zaporedje se pri hipoevtektičnih zlitinah AlSi7Mg začne z razvojem primarnih aluminijevih dendritov α_{Al} in nastankom dendritne mreže, sledi pa evtektična reakcija (α_{Al} + β_{Si}) na primarnih zrnih α_{Al}

1 Introduction

The increasing demand toward lightweight aluminium alloys have expanded its application in automotive industry due to a downsizing effect and therefore reducing the CO_2 emissions [1,2,3]. Safety-critical aluminium alloys castings have been exposed to high demands of the market related to long term stability in aggressive engine environment. The mechanical properties, hot cracking susceptibility and other quality feature of aluminium components are strongly dependent from chemical composition [4,5,6]. Therefore, the innovative approach to the designing of modified chemical composition of aluminium alloys with higher tensile strength, thermal stability and corrosion resistance becomes significant for structural components in automotive industry.

Excellent castability, recyclability, low cost manufacturing, high specific strength and its favourable relationship to weight, especially in the heat-treated state, indicate conventional AlSi7Mg alloy as a frequent choice for complex geometry castings with high mechanical properties [7,8,9,10]. The solidification sequence of hypoeutectic AlSi7Mg alloys begins with development of primary aluminum dendrites α_{Al} and formation of dendritic network, followed by eutectic reaction (α_{Al} + β_{Si}) on the primary grains α_{Al} or independently on ali samostojno na prisotnih nukleantih, bogatih z železom, in/ali drugih nečistočah z drugačno kristalografsko usmerjenostjo [11]. Način nastanka evtektika določa obseg in morfologijo evtektične faze, pa tudi delež poroznosti v mikrostrukturi. Glavni in najpomembnejši legirni element pri klasični zlitini AlSi7Mg je Si, za katerega sta značilni visoka pretočnost in zmanjšanje krčenja, sledi pa mu Mg, ki je odgovoren za večjo trdnost [12, 13, 14].

Dodani magnezij do 0,7 wt.% krepi prek precipitacije evtektične faze aAl+Mg_2Si in/ali intermetalnih spojin, bogatih z Mg z drugimi legirnimi elementi predvsem zaradi transformacije škodljivih ploščic Al_5FeSi v fazo, podobno kitajskim pismenkam, s sestavo $Al_8Mg_3FeSi_6$. [13, 15, 16]. Glede na vsebnost Mg se lahko trdnost teženja, natezna trdnost in elongacija zlitin Al-Si-Mg v litem stanju spreminjajo glede na vsebnost Mg [17]. Trdnost teženja se je povečala ob večji vsebnosti Mg, vendar pa pri večanju razmerja faze Mg_2Si ni prišlo do kakšne pomembne razlike. Obratno pa se je elongacija s povečanjem razmerja Mg in Mg_2Si v teh zlitini zmanjšala [17].

Tudi Cu se pogosto uporablja kot legirni element za večjo trdnost litih zlitih, zlasti pri toplotni obdelavi. Pri zlitinah Al-Si je Cu dodan v razmerju med 1,5–3,5 wt.% in zato ustvarja intermetalno fazo Al_2Cu [18, 19]. Po drugi strani Cu tvori neprekinjeno mrežo po kristalnih mejah, posledično pa bo prišlo do velikega zmanjšanja duktilnosti [19, 20]. Dodatno baker bistveno znižuje tališče in evtektično temperaturo zlitine. Baker zato povečuje obseg strjevanja zlitine in omogoča boljše pogoje za nastanek poroznosti [21, 22, 23]. Literatura navaja številne raziskave vpliva legirnih elementov na lastnosti zlitine AlSi7Mg [24, 25, 26].

Klasična zlitina AlSi7Mg, ki je skladna s številnimi standardi (EN 1706, IDM

present nucleonts rich on iron and/or other impurities with different crystallographic orientation [11]. The way of eutectic occurs determines the amount and morphology of eutectic phase, and also the porosity ratio in the microstructure. The primary and most important alloying element in conventional AlSi7Mg alloy is Si, which is characterized by high fluidity and reduction in shrinkage, followed by Mg responsible for strength increase [12,13,14].

Magnesium addition up to a 0.7 wt. % has a strengthening effect through the precipitation of a_{Al}+Mg_2Si eutectic phase and/or Mg-rich intermetallics with other alloying elements mostly due to transformation of the deleterious Al_5FeSi platelets into a Chinese script phase with a composition $Al_8Mg_3FeSi_6$. [13,15,16]. The yield strength, tensile strength and elongation of the as-cast Al-Si-Mg alloys can vary by the content of Mg [17]. The yield strength increased with increasing of Mg content, but showed no significant difference with increasing of Mg_2Si phase ratio. Conversely, the elongation was decreased with the increase of Mg and Mg_2Si ratios in this alloy [17].

Also, Cu is commonly used as an alloying element to increase the strength of cast alloys, especially when heat treatment is applied. In Al-Si alloys, Cu is usually added in levels between 1.5 – 3.5 % and forms the intermetallic phase Al_2Cu [18,19]. On the other hand, when Cu forms a continuous network at the grain boundaries the consequence will be a serious reduction in ductility [19,20]. Additionally, copper significantly decreases the melting point and eutectic temperature of the alloy. Therefore, the copper increases the solidification range of the alloy, and facilitates the condition of porosity formation [21,22,23]. The literature survey reveals a number of investigations

4234) [27, 28], je bila predhodno predmet raziskave [29].

Snovanje novih kemijskih sestav zlitine AlSi7MgCu z dodatkom Cu (do 1.435 wt.%) predstavlja izziv na poti k doseganju naprednih lastnosti. Širok razpon zapletenih reakcij in intermetalnih faz izhajata iz številnih interakcij legirnih elementov (Si, Mg, Cu) in elementov v sledovih (Fe, Mn). Pridobljene napredne mehanske lastnosti so močno odvisne od razvoja kompleksne mikrostrukture na podlagi posebne interakcije elementov. Čeprav izračun stabilnosti faze kaže določitev zaporedja strjevanja, je interakcija z ostalimi elementi pokazala številne kombinacije. Te kombinacije prikrivajo infiltracijo dodatnih elementov pri rednih in pogosto prisotnih fazah. Cilj te raziskave je določiti vpliv bakra na razvoj mikrostrukture.

2 Poskusni postopek

Lastnosti novo zasnovane zlitine AlSi7MgCu so bile opredeljene v litem stanju in po toplotni obdelavi [9,10,10].

Talino novo zasnovane zlitine AlSi7MgCu smo pripravili v indukcijski peči ABB IMTK 2000 z ingoti in povratnim razmerjem dovajanega materiala 1: 1. Po topljenju pri temperaturi 770± 5 °C smo talino razplinili z dušikom (N_2) s pomočjo opreme MTS 1500 – Foseco. Talino smo obdelali s cepljenjem s predzlitino AlTi5B in modifikacijo s predzlitino AlSr10. Analizo kemijske sestave smo opravili z optičnim spektrometrom ARL-3460.

Toplotna obdelava je potekala po naslednjem postopku: segrevanje od sobne temperature do temperature žarjenja 480 °C – 2 uri, ohranjanje končne temperature žarjenja – 8 ur, sledilo je zračno hlajenje.

Predhodna raziskava zajema razvoj faznega diagrama ravnovesja, related to the influence of alloying elements on the AlSi7Mg alloy properties [24,25,26].

The conventional AlSi7Mg alloy, corresponded to the numerous standards (EN 1706, IDM 4234) [27,28], has been investigated previously [29]. The designing of new chemical composition of AlSi7MgCu alloy with extra addition of Cu (up to 1,435 wt.%) represents a challenge in order to achieve advanced properties. A wide range of complex reactions and intermetallic phases occurs due to numerous alloying (Si, Mg, Cu) and trace elements (Fe, Mn) interaction. Obtained advanced mechanical properties are strongly depended from the complex microstructure development based on particular elements interaction. Although the calculation of phase stability indicates solidification sequence determination, the interaction with other elements brought out numerous combinations. Those combinations cover up infiltration of additional elements in regular, commonly present phases. The aim of this investigation is to determine the influence of copper on microstructure development.

2 Experimental

Characterization of newly designed AlSi7MgCu alloy has been performed in as-cast and heat- treated state [9,10,10].

An AlSi7MgCu alloy melt was prepared in an induction furnace ABB IMTK 2000 with the ingot and return ratio in charge material 1: 1. After melting at a temperature of 770 ± 5 ° C, degassing of the melt was performed with the nitrogen (N_2) using MTS 1500 - Foseco equipment. Melt treatment was performed through inoculation with AlTi5B master alloys and modification with AlSr10 master alloy. Chemical composition analysis was performed on an optical emission spectrometer ARL-3460.

sočasno toplotno analizo ter analizo mehanskih lastnosti [8,9,10]. Podrobne metalografske raziskave so bile opravljene s svetlobno mikroskopijo (Olympus GX 51), mikrostrukturne raziskave (SEM/EDS) pa z vrstičnim elektronskim mikroskopom Tescan Vega TS 5136 MM, opremljenim z energijsko disperzivnim spektrometrom Bruker.

Vzorce za metalografsko raziskavo smo pripravili s standardnim metalografskim postopkom za pripravo z mletjem in poliranjem, sledilo pa je jedkanje v 0,5-odstotni fluorovodikovi kislini.

3 Rezultati in razprava

Kemijsko spojino zlitine AlSi7MgCu z dodatkom bakra smo zasnovali in primerjali s predhodno raziskano klasično zlitino AlSi7Mg [29], kot je prikazano v Preglednici 1.

Zlitina AlSi7MgCu je skladna s standardom EN 42000 AC za zlitino AlSi7Mg v povezavi z vsebnostjo osnovnih legirnih elementov Si in Mg ter elementov v sledeh, kot sta Fe in Mn [27]. Odklon je bil uveden z bistvenim zvečanjem vsebnosti Cu.

Modeliranje novo zasnovane zlitine AlSi7MgCu s programom ThermoCalc (TCW 5.0) je potekalo skladno s predhodno izračunanim faznim diagramom ravnovesja [10]. Interakcija legirnih elementov in elementov v sledovih odkriva širok nabor intermetalnih faz, ki jim sledi izračun strjevalnega zaporedja zlitine AlSi7MgCu. Izračunano strjevalno zaporedje ravnovesja

Heat treatment was performed following the regime: heating from room temperature to the annealing temperature of 480° C for 2 hours, and the retention of the final annealing temperature during 8h, followed by air cooling.

Previous investigation comprehends development of equilibrium phase diagram, simultaneous thermal analysis and mechanical properties analysis [8,9,10]. Detail metallographic investigations were performed using light microscopy (Olympus GX 51) and microstructural investigations (SEM/EDS), using scanning electron microscopes Tescan Vega TS 5136 MM equipped with energy dispersive spectrometer Bruker.

Samples for metallographic investigation were prepared by standard metallographic preparation procedure by grinding and polishing, followed by etching in 0.5% HF.

3 Results and Discussion

Chemical composition of AlSi7MgCu alloy with extra addition of copper has been designed and compared with previously investigated conventional AlSi7Mg alloy [29], as shown in Table 1.

An AlSi7MgCu alloy is in line with the EN 42000 AC standard for AlSi7Mg alloy in relation to the content of the base alloying elements Si and Mg, and trace elements such as Fe and Mn [27]. Deviation has been implemented with significant increase in Cu content.

Preglednica 1. Kemijska sestava zlitin AlSi7Mg/AlSi7Mg(Cu)

Table 1. The chemical compositions of AlSi7Mg / AlSi7Mg(Cu) alloys

Element, wt.%	Si	Fe	Cu	Mn	Mg	Ti	Sr
AlSi7Mg	7,008	0,101	0,130	0,010	0,320	0,139	0,0121
AlSi7MgCu	7,527	0,235	1,435	0,076	0,348	0,147	0,0223

Preglednica 2. Izračunano strjevalno zaporedje ravnovesja zlitine AlSi7MgCu [10]

Table 2. Calculated equilibrium solidification sequence of AlSi7MgCu alloy [10]

Opis reakcije / Reaction description	Reakcija / Reaction
Temperatura likvidusa, T_l / Liquidus temperature, T_l	$L \rightarrow L_1 + \alpha_{Al}$
Evtektična temperatura, T_e / Eutectic temperature, Te	$L_1 + \alpha_{Al} \rightarrow L_2 + \alpha_{Al} + (\alpha_{Al} + \beta_{Si})$
Temperatura pri precipitaciji sekundarnih intermetalnih faz, T_1 / Precipitation of secondary intermetallic phases temperature, T_1	$L_2 + (\alpha_{Al} + \beta_{Si}) \rightarrow L_3 + (\alpha_{Al} + \beta_{Si}) + Al_{15}(FeMn)_3Si_2$
Temperatura pri precipitaciji sekundarnih intermetalnih faz, T_2 / Precipitation of secondary intermetallic phases temperature, T_2	$L_3 \rightarrow L_4 + Al_5Cu_2Mg_8Si_6$
Temperatura pri precipitaciji sekundarnih intermetalnih faz, T_3 / Precipitation of secondary intermetallic phases temperature, T_3	$L_4 + Al_5Cu_2Mg_8Si_6 \rightarrow L_5 + Al_8FeMg_3Si_6$
Temperatura pri precipitaciji sekundarnih intermetalnih faz, T_4 / Precipitation of secondary intermetallic phases temperature, T_4	$L_5 \rightarrow L_6 + Al_7Cu_2M$
Temperatura pri precipitaciji sekundarnih intermetalnih faz, temperatura solidusa, T_s / Precipitation of secondary intermetallic phases temperature, Solidus temperature, T_s	$L_6 \rightarrow Al_2Cu$

zlitine AlSi7MgCu je prikazano v Preglednici 2 [10].

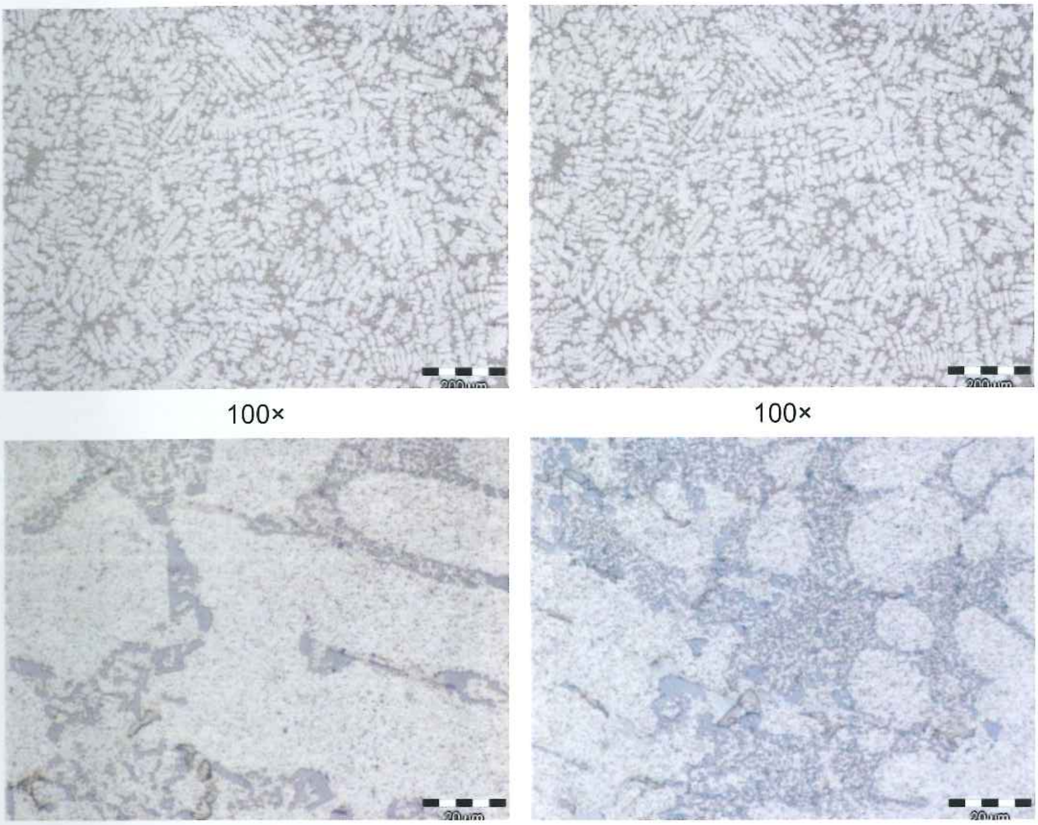
Mikrostrukturo zlitine AlSi7MgCu v litem stanju (F) in po toplotni obdelavi (T) smo raziskali s pomočjo svetlobne mikroskopije, kot je prikazano na Sliki 1 [9].

Manjša povečava (100-kratna) kaže enakomerno porazdeljenost primarne dendritne mreže z enakomerno porazdeljenimi interdendritnimi območji v obeh stanjih, litem (F) in po toplotni obdelavi (F). Večja povečava kaže bolj grobe in prekinjene veje dendrita, posejane z intermetalnimi fazami nosilcev železa iglaste oblike (Al_5SiFe) in hrapave sekundarne intermetalne faze na mejah zrn v litem stanju (F). Največja povečava (1.000-kratna) nakazuje prisotnost nespremenjenih evtektov (mešana vlakna in lamelarna oblika). Po toplotni obdelavi (T) se kaže enakomerna razporejenost vlaknastih oblik glavnega evtekta ($\alpha_{Al} + \beta_{Si}$).

The modelling of newly designed AlSi7MgCu alloy by ThermoCalc (TCW 5.0) program resulted with previously calculated equilibrium phase diagram [10]. Interaction of alloying and trace elements reveals a wide range of intermetallic phases, followed with the calculation of solidification sequence of AlSi7MgCu. Calculated equilibrium solidification sequence of AlSi7MgCu alloy is shown in Table 2 [10].

Microstructure of AlSi7MgCu alloy in as-cast (F) and heat-treated (T) state was investigated using light microscopy, as shown in Figure 1 [9].

A smaller magnification (100x) reveals uniform distribution of primary dendritic network with evenly distributed interdendritic areas in both states, as-cast (F) and heat-treated (F), respectively. A higher magnification indicates rougher and broken dendritic branches dotted with iron-bearing intermetallic phases with



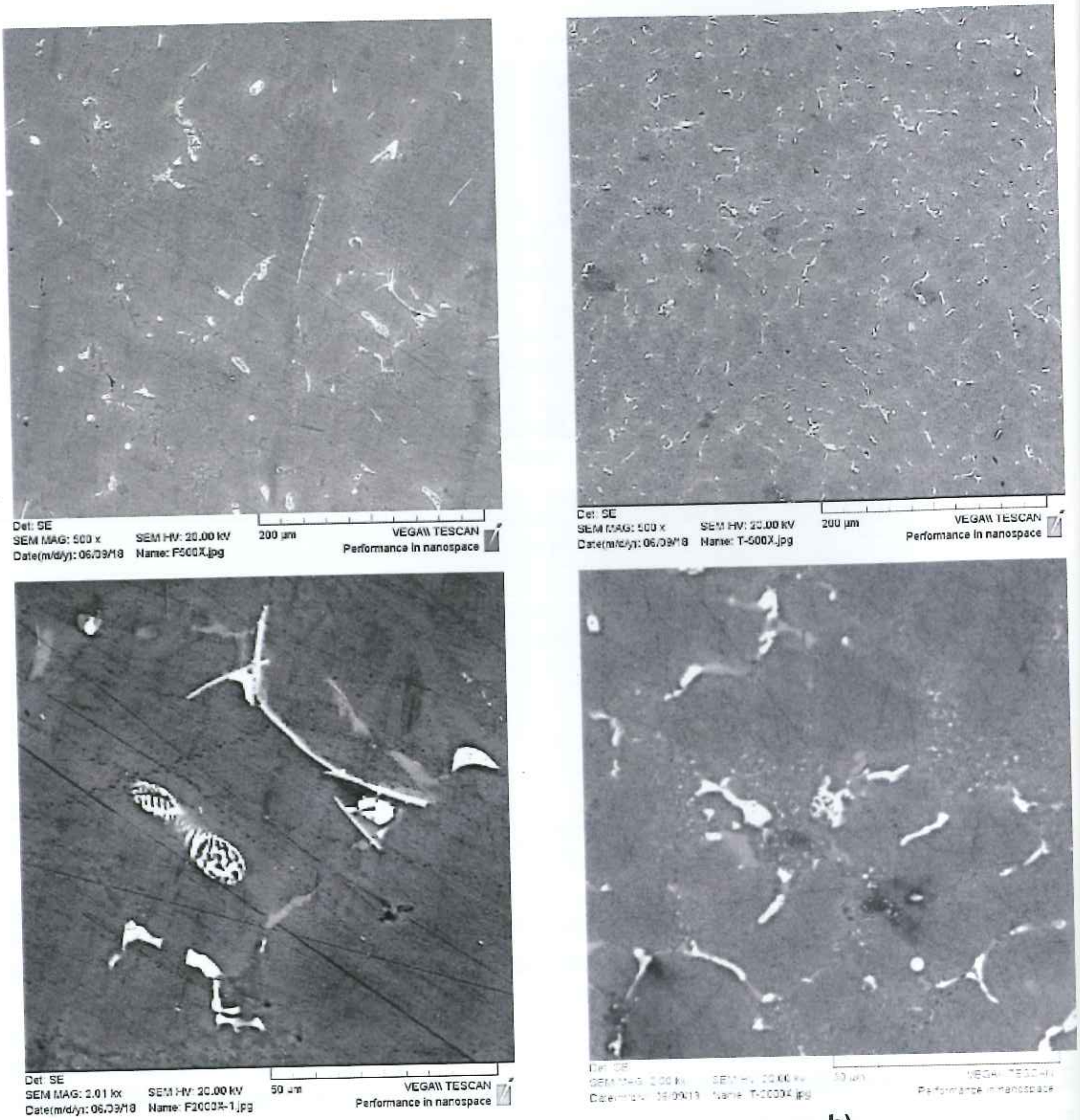
Slika 1. Mikrografi zlitine AlSi7Mg(Cu), pridobljeni s svetlobno mikroskopijo [9]

Figure 1. Micrographs of AlSi7Mg(Cu) alloy obtained by light microscopy [9]

Zadnje faze strjevanja so bile opažene na mejah zrn. Njihova oblika in barva kaže sekundarne evtektične faze aAl+Al_2Cu (delci in klastri ploščic) ter aAl+Mg_2Si (tanki razvejani črni delci) v litem stanju (F). Stanje po toplotni obdelavi kaže dobro razdelane sekundarne intermetalne faze na mejah zrn.

Primerjava porazdelitve mikrostrukturnih sestavnih delov in velikosti, zaznane z vrstičnimi elektronskimi

needle-like morphology, (Al5SiFe), and coarse secondary intermetallic phases at grain boundaries in as-cast state (F). The highest magnification (1000x) indicates the presence of under-modified eutectic (mixed fiber and lamella morphology). The heat-treated state (T) indicated uniformly distributed fiber morphology of main eutectic (αAl+βSi). Last solidifying phases have been noticed at grain boundaries. Theirmorphology and colour reveals secondary eutectic phases aAl+Al2Cu



a) b)

Slika 2. Vrstični elektronski posnetki zlitine AlSi7MgCu v a) litem stanju (F) in b) po toplotni obdelavi (T)

Figure 2. Scanning electron images of AlSi7MgCu alloy in a) as-cast (F) and b) heat-treated state (T)

mikroskopi pri največji povečavi, je prikazana na Sliki 2.

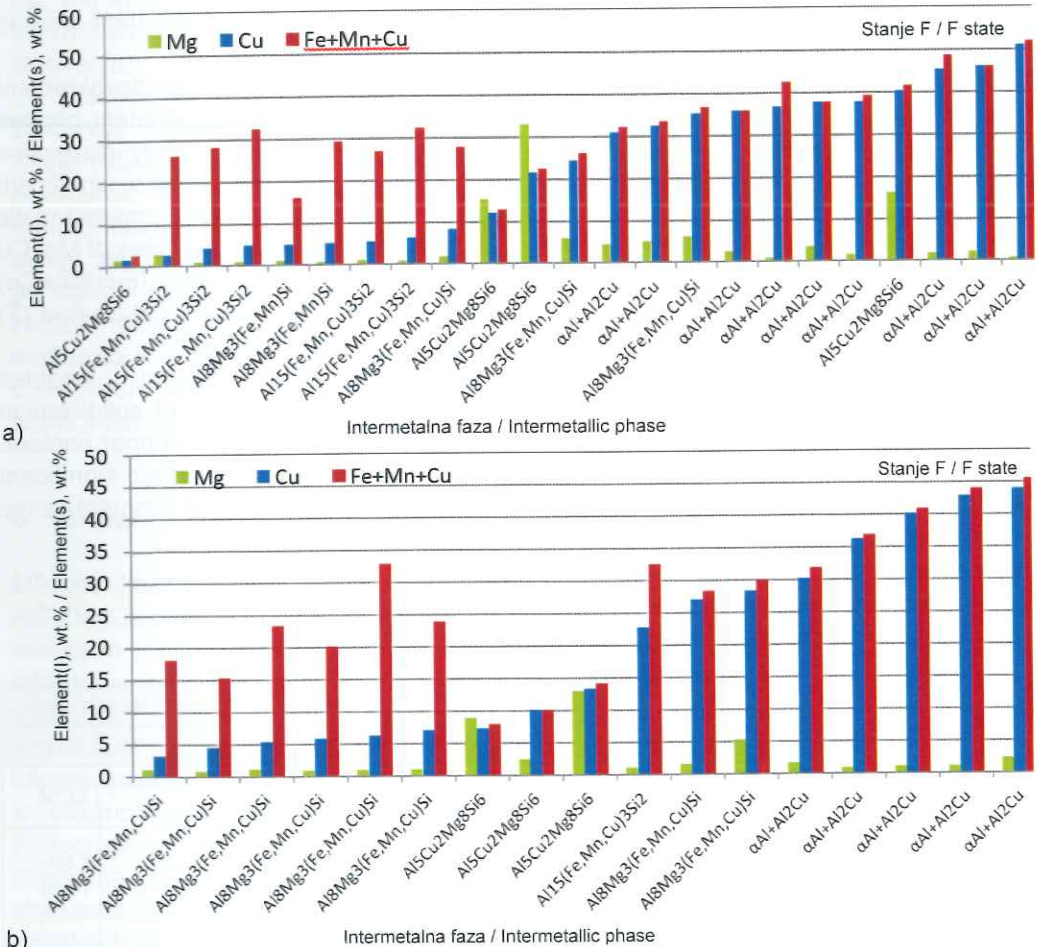
Poleg dendritske mreže je treba najprej oceniti železove iglaste formacije Al_5SiFe in/ali kompleksno formacijo, podobno

(platelets particles and clusters) and $aAl+Mg_2Si$ (thin ramified black particles) in as-cast (F) state. Heat-treated state reveals fine fragmented secondary intermetallic phases at the grain boundaries.

kitajskim pismenkam, $Al_{15}(Fe,Mn,Cu)_3Si_2$. Ustrezno razmerje precipitata Cu in Mg je v kovinski matriki, medtem ko masa kohezijsko tvori kompleksne evtektične klastre $Al_8Mg_3(Fe,Mn,Cu)Si_6$ in fazo $Al_5(Mn,Fe,Cu)_2Mg_8Si_6$. Strjevanje se zaključi s precipitacijo sekundarne evtektične faze α_{Al}+Mg_2Si in α_{Al}+$Al_2(Fe,Mn,Cu)$. Toplotna obdelava pozitivno vpliva na enakomerno

Comparison of microstructural constituents' distribution and size revealed with scanning electron images at higher magnification is given in Figure 2.

Beside dendrite network, first to evaluate is iron-based needle-like Al_5SiFe and / or complex Chinese script formation $Al_{15}(Fe,Mn,Cu)_3Si_2$. Appropriate ratio of Cu and Mg precipitate in a metal matrix,



Slika 3. Analiza vrstičnih elektronskih posnetkov zlitine AlSi7MgCu z energijsko disperzivno spektrometrijo v a) litem stanju (F) in b) po toplotni obdelavi (T)

Figure 3. Analysis of scanning electron images of AlSi7MgCu alloy by energy dispersive spectrometry in a) as-cast (F) and b) heat-treated state (T)

porazdelitev in izboljšavo intermetalnih faz. Morfološko škodljive intermetalne faze, obogatene v železu in znane kot faza β (Al_5SiFe), pri tovrstni obliki niso več prisotne. Po toplotni obdelavi so odpravljeni tudi klasični klastri Al_2Cu.

Analiza razvoja mikrostrukture je bila zaradi faz s CU opravljena pri obeh tipih vzorcev. Analiza z energijsko disperzivno stehiometrijo nakazuje bistveno obogatitev značilnih intermetalnih faz z bakrom. Pregled vsebnosti Mg, Cu in celotna vsebnost prehodnih elementov (Fe+Mn+Cu) v litem stanju (F) in toplotno obdelanem stanju (T) sta predstavljena na Sliki 3.

Raziskava SEM/EDS omogoča določitev spremembe poti strjevanja zaradi večje vsebnosti bakra. Vsebnost magnezija, bakra in drugih pomembnih prehodnih elementov (Fe, Mn) v obeh stanjih je bila določena, kot je prikazano v Preglednici 3. Obe stanji sta nakazali veliko vsebnost pogostih prehodnih (Fe, Mn) in sekundarnih elementov (Mg, Cu). Stanje po toplotni obdelavi je v primerjavi z litim stanjem pokazalo upad vsebnosti magnezija, bakra in (Fe+Mn+Cu) na splošno tako zaradi procesa homogenizacije kot tudi zaradi

while the bulk cohesively forms complex eutectic clusters of $Al_8Mg_3(Fe,Mn,Cu)Si_6$ and $Al_5(Mn,Fe,Cu)_2Mg_8Si_6$ phase. Solidification ends with secondary eutectic phase precipitations $\alpha_{Al}+Mg_2Si$ and $\alpha_{Al}+Al_2(Fe,Mn,Cu)$. Heat treatment has a positive influence on uniform distribution and refining of intermetallic phases. Morphological detrimental intermetallic phases enriched in iron known as β phase (Al_5SiFe) are no longer present in that particular morphology. Also, classical Al_2Cu clusters have been resolved in heat- treated state.

Analysis of microstructure development was performed due to Cu content phases in both samples type. Energy dispersive stoichiometry analysis reveals significant copper enrichment of characteristic intermetallic phases. An overview of Mg, Cu and total transition elements (Fe+Mn+Cu) content in as-cast (F) and heat-treated (T) state is presented in Figure 3.

SEM/EDS investigation enables determination modification of solidification path induced by increased copper content. Magnesium, copper and other significant transition elements (Fe, Mn) content range

Preglednica 3. Mikrostrukturna analiza faz, ki prenašajo baker

Table 3. Microstructural analysis of copper bearing phases

Opis reakcije / Reaction description	Intermetalna faza / Intermetallic phase	Mg, wt.%		Cu, wt.%		Fe+Mn+Cu, wt.%	
		F	T	F	T	F	T
$L \rightarrow L_1+\alpha_{Al} + Al_5SiFe + Al_{15}(Fe,Mn,Cu)_3Si_2$	$Al_{15}(Fe,Mn,Cu)_3Si_2$	0,88–2,80	1,12	2,65–6,34	22,77	26,04–32,32	32,54
$L_2 \rightarrow L_3+ Al_5(Fe,Mn,Cu)_2Mg_8Si_6 + Al_8Mg_3(Fe,Mn,Cu)Si_6$	$Al_5(Fe,Mn,Cu)_2Mg_8Si_6$	1,53–33,03	2,58–13,09	1,61–40,22	7,3–13,41	2,65–41,42	7,96–14,16
$L_2 \rightarrow L_3+ Al_5(Fe,Mn,Cu)_2Mg_8Si_6+ Al_8Mg_3(Fe,Mn,Cu)Si_6$	$Al_8Mg_3(Fe,Mn,Cu)Si_6$	0,82–6,07	0,85–5,29	4,87–35,3	3,26–28,35	15,83–36,68	15,37–32,93
$L_4 \rightarrow \alpha_{Al}+ Al_2(Fe,Mn,Cu)$	$\alpha_{Al}+Al_2(Fe,Mn,Cu)$	0,71–5,02	0,89–2,33	30,86–45,96	30,23–43,98	32,07–51,89	31,88–45,55

ločevanja Mg in Cu v matrici [9]. Velika vsebnost Mg in Cu v določenih fazah je odvisna od položaja faz v hierarhiji procesa strjevanja in končne velikosti. Infiltracija pogostih prehodnih elementov, npr. Fe in Mn v fazah, ki prenašajo Cu, je privedla do visoke vsebnosti >30 wt.%, razen pri $Al_5(Fe,Mn,Cu)_2Mg_8Si_6$ z visoko vsebnostjo Mg. Čeprav veljajo faze, ki prenašajo Fe in Mn, za visokotemperaturne faze, kažejo rezultati raziskave tudi trajno interakcijo Fe, Mn in Cu pri tvorbi širokega razpona intermetalnih faz skozi celoten proces strjevanja.

Predhodne raziskave kažejo določitev zaporedja strjevanja in določitev lastnosti zlitine AlSi7MgCu [8,9,10] ter pomembno povečanje trdnosti teženja in natezne trdnosti inovativne zlitine AlSi7MgCu v litem stanju ter bistveno povečanje elongacije po toplotni obdelavi. Podobna raziskava v zvezi s fazami, ki prenašajo Cu, kaže na močnejšo interakcijo prehodnih elementov v zaporedju strjevanja prek sodelovanja pri tvorbi intermetalnih faz.

4 Sklepi

Mikrostrukturna raziskava zlitine AlSi7MgCu odkriva širok razpon zapletenih reakcij in možnih intermetalnih faz zaradi interakcije legirnih elementov in elementov v sledovih. Dodatek Cu (do 1,435 wt.%) kot sekundarni legirni element sproža dodatno interakcijo s prehodnimi elementi Fe, Mn in sekundarnim legirnim elementom Mg. Razvoj mikrostrukture in določitev zaporedja strjevanja zagotavljajta karakterizacijo poti strjevanja tako neobdelanih kot toplotno obdelanih ulitkov.

Mikrostrukturna raziskava odkriva naslednje sestavine: dendritna mreža; železna iglasta formacija Al_5SiFe in/ali kompleksna formacija, podobna kitajskim

in both states has been determined as shown in Table 3.

Both states indicated a wide range of common transition (Fe, Mn) and secondary elements (Mg, Cu) content. Theheat-treated state revealed decreasing of magnesium, copper and (Fe+Mn+Cu) content in general when compared to as-cast state, due to homogenisation process as well as resolving of Mg and Cu in matrix [9]. A wide range of Mg and Cu content in particular phases is dependent to the phases´ position in solidification process hierarchy and final size. Infiltration of common transition elements such as Fe and Mn in Cu bearing phases resulted in high total content >30 wt.%, except for $Al_5(Fe,Mn,Cu)_2Mg_8Si_6$ with high Mg content. Although Fe and Mn bearing phase are considered to be a high-temperature phases, the investigation results indicate continuous interaction of Fe, Mn and Cu in formation of wide range of intermetallic phases through the whole solidification process.

Previous investigation indicates a determination of solidification sequence and characterization of AlSi7MgCu alloy [8,9,10], indicating the significant increase in yield strength and tensile strength of innovative AlSi7MgCu alloy in as-cast state and significant increase of elongation in heat-treated state. The detailed microstructure investigation relating to the Cu bearing phases reveals a stronger interaction of transition elements in solidification sequence through participation in forming the intermetallic phases.

4 Conclusion

The microstructural investigation of AlSi7MgCu alloy reveals a wide range of complex reactions and possible intermetallic phases due to the interaction of alloying and pismenkam $Al_{15}(Fe,Mn,Cu)_3Si_2$; glavna evtektska ($\alpha_{Al}+\beta_{Si}$); kompleksen evtektski grozd faze $Al_8Mg_3(Fe,Mn,Cu)Si_6$ in faze $Al_5(Fe,Mn,Cu)_2Mg_8Si_6$. Strjevanje se zaključi s precipitacijo sekundarne evtektične faze $\alpha_{Al}+Mg_2Si$ in $\alpha_{Al}+Al_2(Fe,Mn,Cu)$.

Ustrezno razmerje precipitata Cu in Mg v kovinski matrici, zlasti po toplotni obdelavi. Razmerje Mg in Cu v določenih intermetalnih fazah odkriva velik obseg njihove vsebnosti, kar je povezano s položaji faz v hierarhiji procesa strjevanja in končne velikosti. Infiltracija pogostih prehodnih elementov, npr. Fe in Mn v fazah, ki prenašajo Cu, je privedla do visoke vsebnosti prehodnih elementov (Fe+Mn+Cu)>30 wt.%, razen pri $Al_5(Fe,Mn,Cu)_2Mg_8Si_6$ z visoko vsebnostjo Mg. Čeprav veljajo faze, ki prenašajo Fe in Mn, za visokotemperaturne faze, kažejo rezultati raziskave tudi trajno interakcijo Fe, Mn in Cu pri tvorbi širokega razpona intermetalnih faz skozi celoten proces strjevanja.

Narava (morfologija in interakcije legirnih elementov) tvorjenih intermetalnih faz ustreza razvoju nateznih in mehanskih lastnosti zaradi močnih vezi in interakcije med celotnim procesom strjevanja.

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trace elements. An extra addition of Cu (up to 1,435 wt.%) as a secondary alloying element initiates additional interaction with transition elements Fe, Mn and secondary alloying element Mg. Evolution of microstructure and determination of solidification sequence enables characterization of solidification path in both states, as-cast and heat-treated.

The microstructural investigation reveals following constituents: dendrite network; iron-based needle-like Al_5SiFe and/or complex Chinese script formation $Al_{15}(Fe,Mn,Cu)_3Si_2$; main eutectic ($\alpha_{Al}+\beta_{Si}$); complex eutectic clusters of $Al_8Mg_3(Fe,Mn,Cu)Si_6$ and $Al_5(Fe,Mn,Cu)_2Mg_8Si_6$ phase. Solidification ends with secondary eutectic phase precipitations $\alpha_{Al}+Mg_2Si$ and $\alpha_{Al}+Al_2(Fe,Mn,Cu)$.

The appropriate ratio of Cu and Mg also precipitate in a metal matrix, especially in heat-treated state. Ratio of Cu and Mg developed in particular intermetallic phases reveals a wide range of theirs content, which is connected to the phases´ position in solidification process hierarchy and final size. Infiltration of common transition elements such as Fe and Mn in Cu bearing phases' resulted in high total content of transition elements (Fe+Mn+Cu)>30 wt.%, except for $Al_5(Fe,Mn,Cu)_2Mg_8Si_6$ with high Mg content. Although Fe and Mn bearing phase are considered to be a high-temperature phases´, the investigation results indicate a continuous interaction of Fe, Mn and Cu in formation of wide range of intermetallic phases through the whole solidification process.

The nature (morphology and alloying elements interaction) of formed intermetallic phases comprehends to the tensile mechanical properties' development due to strong connections and interactions during solidification process as a whole.

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