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Termodinamična in mikrostrukturna karakterizacija zlitine AlSi8Cu3

Thermodynamic and Microstructural Characterization of AlSi8Cu3 Alloy

Izvleček

Načrtovanje materialov z izbiro kemične sestave, s termodinamičnim modeliranjem, z obdelavo taline s cepljenjem in modificiranjem, z žarjenjem in pravilno razvito tehnologijo litja lahko izboljšajo lastnosti ulitkov. Zaradi zapletene geometrije ulitkov je včasih potrebna toplotna obdelava kot žarjenje po ulivanju. Strogi režim s sorazmerno visoko temperaturo in dolgim časom zadrževanja pri temperaturi kaže na mikrostrukturne spremembe v materialu in tako neposredno vpliva na njegove mehanske lastnosti. Pomemben vidik za nadaljnje izboljšave in uporabo predstavlja boljše razumevanje spreminjanja mikrostrukturnih sestavin s toplotno obdelavo.

Podevtektične aluminij-silicijeve livne zlitine, kot je zlitina AlSi8Cu3 (EN AC 46200), se široko trgovsko uporabljajo v avtomobilski industriji za varnostne sestavne dele. Termodinamično modeliranje omogoča vpogled v potek strjevanja zlitine AlSi8Cu3. Simultana termična analiza odkriva temperature faznih premen z napovedovanjem reakcij na osnovi termodinamičnega modeliranja. Število in vrednosti dobljenih faznih premen kaže na homogenizacijski učinek toplotne obdelave, kot je potrdila mikrostrukturna analiza. S preiskavami mikrostrukturnih značilnosti se ugotavljajo porazdelitev, morfologija in delež delcev intermetalnih spojin, ki ustrezajo stanju toplotne obdelave. Cilj tega dela je bil ugotoviti potek strjevanja s termodinamičnim modeliranjem ter učinek toplotne obdelave na mikrostrukturo in mehanske značilnosti ločeno ulitih preizkušancev zlitine AlSi8Cu3. Metalograska analiza je ugotovila naslednje mikrostrukturne sestavine: primarne dendrite α_{Al}, evtektične (αAl+βSi) in intermetalne faze na osnovi stehiometrije bakra, Al-Al_xCu-Si, $Al_xMg_ySi_zCu_w$. Žarjena mikrostruktura se je spremenila v bolj enakomerno porazdelitev primarnih aluminijevih dendritov, ki so bili obogateni z bakrom, zato je fragmentacija v zadnjih fazah strjevanja slonela na bakru.

Ključne besede: Al-Si zlitine, termodinamično modeliranje, simultana termična analiza, mikrostruktura, toplotna obdelava

Abstract

The design of materials through the selection of the chemical composition, thermodynamic modelling, melt treatment by inoculation and modification, annealing and correctly developed casting technology could improve castings properties. Due to castings complex geometry, it is sometimes necessary to provide heat treatment such as annealing after casting. Rigorous regime with a relatively high temperature and long holding time indicates the microstructural changes in the material, thus indirectly affects the mechanical properties of the material. An important aspect for further improvement and application is to develop a better understanding of the microstructural constituent changes due to provided heat treatment.

Hypoeutectic aluminium - silicon casting alloy such as AlSi8Cu3 (EN AC 46200) has found a wide commercial applications in automotive industry for safety components. Thermodynamical modelling enables an insight in solidification sequence of the AlSi8Cu3 alloy. Simultaneous thermal analysis reveals corresponding temperatures of phase transformations with predicted reaction on the base of thermodynamical modelling. The number and values of obtained phase transformations indicate homogenization impact of heat treatment, as confirmed by microstructural analysis. Investigation of microstructural features defines distribution, morphology and ratio of particular intermetallic compounds corresponded to heat treatment state. The aim of this work was to determine solidification sequence using thermodynamic modelling and establishment of heat treatment effect on the microstructure and mechanical features of separately cast test AlSi8Cu3 alloy samples. Metallographic analysis established following microstructural constituents: α_{Al} primary dendrites, eutectic (αAl+βSi) and intermetallic phases based on copper stoichiometry Al-Al_xCu-Si, $Al_xMg_ySi_zCu_w$. Annealed microstructure has been changed as more uniformly distribution of primary aluminum dendrites, its copper enrichment, and therefore fragmentation of the last solidifying phases based on copper.

Keywords: Al-Si alloys, thermodynamic modeling, simultaneous thermall analysis, microstructure, heat treatment

1. Uvod

Podevtektične aluminij-silicijeve livne zlitine, kot je zlitina AlSi8Cu3 (EN AC 46200), se široko trgovsko uporabljajo v avtomobilski industriji za varnostne sestavne dele. Zato so stalne zahteve po izboljšanju lastnosti zlitin z izbiro kemične sestave, obdelavo taline, toplotno obdelavo in računanjem pravilne tehnologije litja.

Potek strjevanja podevtektične zlitine Al-Si se začne z razporeditvijo primarnih aluminijevih dendritov α_{Al}, ki postanejo negibljivi zaradi vpliva koherence med njimi, ko nastane toga dendritna mreža [1,2]. Zrna evtektika (αAl + βSi) se izločajo na primarnih zrnih α_{Al} ali neodvisno na že prisotnih fazah, bogatih z železom ali na nečistotah [3]. Osnovna reakcija je binarna evtektična aluminij-silicijeva reakcija, ki je bila prva ali so ji sledile količinsko omejene ternarne ali kvaternarne evtektične reakcije. Vrsta parametrov vpliva na rast in

1. Introduction

Hypoeutectic aluminium-silicon casting alloys such AlSi8Cu3 (EN AC 46200) have found wide application in the automotive industry for safety components. Consequently, there is a constant imperative to improve the properties of alloys by selection of the chemical composition, melt treatment, heat treatment and a calculation of correct casting technology.

Solidification sequence of hypoeutectic Al-Si alloy begins by allocation of primary aluminum dendrites α_{Al} which become immobile due to their impact in dendrite coherency point and therefore formation of rigid dendrite network, [1,2]. Precipitation of eutectic grains (αAl + βSi) occurred on primary α_{Al} grains, or independently on already present iron-rich phases or impurities [3]. The basic reaction is a binary eutectic aluminum-silicon reaction which has been preceded and/or followed

Razpredelnica 1. Potek strjevanja zlitine AlSi8Cu3 [1]

Table 1. Solidification sequence of AlSi8Cu3 alloy [1]

štev. reakcije / reaction No.	reakcija / reaction	predpostavljena temperatura / presumed temperature, °C
1	Developing of dendrite network / developing of dendrite network & - natajanje dendritne mreže in& Al15(Fe,Mn)3Si2	568
2	L→Al+Si+Al5FeSi	575
3	L→Al+Si+Mg2Si+Al8Mg3FeSi6	554
4	L+Mg2Si+Si→Al+Al5Mg8Si6Cu2	529
5	L→Al+Al2Cu+Al5FeSi+Si	525
6	L→Al+Si+ Al5Mg8Si6Cu2	507

morfologijo aluminij-silicijevega evtektika [3]. Najpomembnejši so kemična sestava skupaj z vplivnimi elementi, ki pridejo v talino pri njeni obdelavi [4], in hitrost ohlajevanja [5] ter naknadna toplotna obdelava [6]. Temperature, pri katerih potekajo osnovne reakcije, so prikazane v razpredelnici 1.

Aluminijeve livne zlitine se legirajo s številnimi elementi na osnovi silicija, magnezija in bakra ter železa kot pogoste nečistoče. Učinek raztopljenih elementov na razvoj aluminij-silicijevega evtektika ni v celoti pojasnjen. Naraščajoči delež silicija poveča trdoto, natezno trdnost in napetost tečenja, sočasno pa se zmanjša duktilnost [4,7]. Magnezij in baker se dodajata aluminij-silicijevi zlitini za utrjevanje aluminijeve faze. Dodatki majhnih deležev magnezija, 0,3 do 0,7 %, občutno izboljšajo mehanske lastnosti, kot sta napetost tečenja in natezna trdnost. To povečanje trdnosti se pripisuje intermetalni spojini Mg_2Si, ki se v glavnem izloča v osnovi med staranjem [4,5]. Mehanske lastnosti, natezna trdnost in duktilnost so odvisne od tega, ali je baker prisoten v trdni raztopini kot enakomerno porazdeljeni okrogli delci ali kot groba mreža na kristalnih mejah. Če je baker raztopljen v osnovi, se bo trdnost povečala. Na drugi strani, če se baker izloča v obliki zveznih mrež na kristalnih mejah, se lahko pričakuje

by a relatively small amount of ternary and quaternary eutectic reactions. There is a number of parameters that affect the growth and morphology of aluminium-silicon eutectic [3]. The most important are chemical composition along with influenced elements due to melt treatment [4] and the cooling rate [5], and subsequently heat treatment [6]. Temperatures at which the basic reactions take place are as shown in Table 1.

Aluminum cast alloys are alloyed with the wide range of elements on the base of silicon, magnesium and copper, and with iron as a common impurity. The effect of dissolved elements on development of aluminum - silicon eutectic is not completely explained. Increasing the silicon content, implies the increase of hardness, tensile strength and yield strength, but its higher concentration indicate a reduction in ductility [4,7]. Magnesium and copper are added to aluminum - silicon alloy for hardening of aluminum phase. Addition of small amounts of magnesium, 0,3 to 0,7%, implies significant increase of mechanical properties such as yield strength and tensile strength. This improvement in strength will be attributed to the intermetallic compound Mg_2Si which generally precipitates in the matrix due to aging [4-5]. Mechanical zmanjšanje duktilnosti [8] in povečanje mikroporoznosti [6].

Pogosto se kot del splošne obdelave ulitka (tj. obdelava za odstranitev neustrezne mikrostrukture v sredini) in/ali zaradi izboljšanja lastnosti uporabi toplotna obdelava. Toplotna obdelava lahko vpliva na spremembo mikrostrukturnih značilnosti in tako neposredno na spremembo livnih lastnosti. Cilj tega dela je bil ugotoviti potek strjevanja s termodinamičnim modeliranjem ter učinek toplotne obdelave na mikrostrukturo in mehanske značilnosti ločeno ulitih preizkušancev zlitine AlSi8Cu3.

2. Eksperimentalna metodologija

Metodologija preiskav obsega termodinamično modeliranje, preiskavo mikrostrukturnih in mehanskih značilnosti ločeno ulitih vzorcev livne zlitine AlSi8Cu3 v ulitem stanju in po toplotni obdelavi.

Predhodno je bila ugotovljena kemična sestava vzorcev zlitine AlSi8Cu3 z optičnim spektrometrom ARL-3460. Kemična sestava taline predstavlja začetni pogoj za računanje ravnotežnega faznega diagrama s programsko opremo ThermoCalc (TCW 4). Modeliranje ravnotežnega faznega diagrama na osnovi ugotovljene kemične sestave je omogočilo ugotoviti možne interakcije in potek strjevanja zlitine. Toplotna obdelava je potekala na naslednji način: dvourno segrevanje s sobne temperature do temperature žarjenja 480 °C, zadrževanje pri temperaturi žarjenja 8 ur, nato ohlajanje na zraku, kot je prikazano na sliki 1.

Napravili smo simultano termično analizo obeh vzorcev zlitine AlSi8Cu3, tj. v ulitem stanju in po toplotni obdelavi. Z diferenčno termično analizo (DTA) na aparaturi Netzsch STA 449C smo dobili

properties, tensile strength and ductility depend on whether the copper is present in solid solution as evenly distributed spherical particles or as a coarse network at the grain boundaries. If copper is dissolved in matrix, strength will increase. On the other hand, if the copper precipitates in the form of a continuous network at the grain boundaries, the decrease of ductility [8] and increase of microporosity could be expected [6].

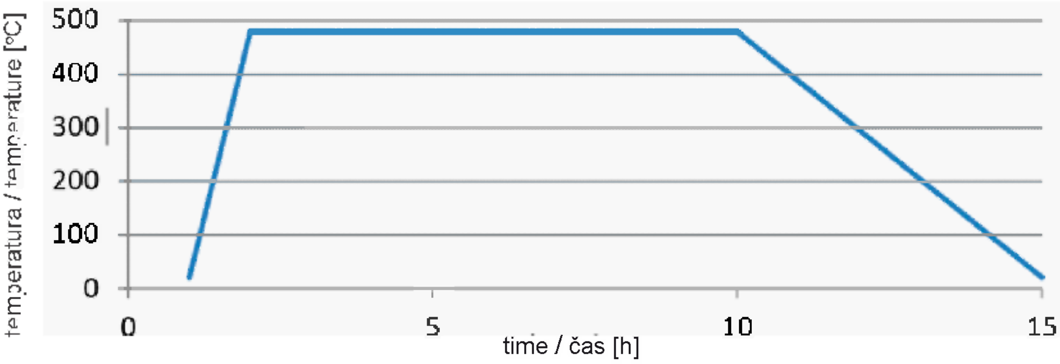
Often, as a part of the common procedure of final casting treatment (i.e. decorement treatment) and/or with the aim of properties improving, heat treatment has been applied. Heat treatment could affect the microstructural features change and thus indirectly the change in casting properties.

The aim of this work was to determine solidification sequence using thermodynamic modelling and establishment of heat treatment effect on the microstructure and mechanical features separately cast test samples AlSi8Cu3 alloys.

2. Experimental Methodology

Investigation methodology included thermodynamic modelling, examination of microstructural and mechanical features of separately cast samples of AlSi8Cu3 cast alloy in as-cast and heat-treated condition.

Preliminary, chemical composition of AlSi8Cu3 alloy samples was established by optical spectrometer ARL-3460. Chemical composition of melt represents an initial precondition for calculation of equilibrium phase diagram by ThermoCalc (TCW 4) programme. Modelling of equilibrium phase diagram" for examined chemical composition has been performed, which enables possible interaction and alloy solidification sequence establishment.



Slika 1. Uporabljen režim toplotne obdelave

Figure 1. Applied heat treatment regime

segrevalne in ohlajevalne krivulje pri hitrosti 0,17 K/s.

Natezno trdnost, napetost tečenja in raztezek [9] ter mikrotrdoto smo ugotavljali za vzorca v ulitem stanju in po toplotni obdelavi.

Vzorce za mikrostrukturno preiskavo smo pripravili po standardni metodi brušenja, poliranja in jedkanja 5 s v 0,5 %ni raztopini HF. Za mikrostrukturno analizo smo uporabili svetlobni mikroskop Olympus GX 51 in vrstični elektronski mikroskop TescanVega (SEM), opremljen z energijskodisperzijskim spektrometrom Bruker (EDS).

Z optično metalografsko analizo smo primerjali našo morfologijo intermetalnih spojin z morfologijo v literaturnih virih, kar je omogočilo vizualno razpoznavanje, medtem ko je elektronska mikroskopijam omogočila podroben vpogled v kemično sestavo faz kot tudi porazdelitev posameznih elementov po preiskanih površinah. Z optično mikroskopijo in računalniško opremo za analizo slik AnalysisResearchLab ® smo ugotavljali mikrostrukturne značilnosti.

Applied heat treatment followed the next regime: heating, starting 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, as shown in Figure 1.

Simultaneous thermal analysis was performed on both AlSi8Cu3 alloy samples, i.e. in as-cast and heat-treated state. Applied method of differential thermal analysis (DTA) performed on Netzsch STA 449C Jupiter, resulted in heating and cooling curves, obtained by 0,17 K/s.

The tensile strength, yield strength and elongation [9] and microhardness examination was performed on as-cast and heat-treated samples.

Samples for microstructural studies were prepared by the standard method of grinding, polishing and etching in dilute HF 0.5% over 5s. Microstructural investigations were performed on an optical microscope Olympus GX 51 and the scanning electron microscope TescanVega (SEM) equipped with an energy dispersive spectrometer Bruker (EDS).

3. Rezultati in razprava

Kemično sestavo preiskovane zlitine AlSi8Cu3 in primerjalen pregled zahtevanih vrednosti po evropskem standardu prikazuje razpredelnica 2.

Kemična sestava preiskovanih vzorcev je bila v skladu z zahtevami. Termodinamični račun stabilnosti posameznih faz, povezan z začetno temperaturo litja 726,85 °C pri tlaku 101,325 kPa in za dobljeno kemično sestavo, je dal ravnotežni fazni diagram, ki je prikazan na sliki 2.

Črtkana črta označuje delež silicija 9,34 mas. % v preiskani zlitini. Ravnotežni fazni diagram prikazuje naslednji potek strjevanja zlitine: nastanek dendritov, visokotemperaturne železove faze, osnovnega evtektika in končno izločanje sekundarnih evtektičnih faz. Nadaljnje modeliranje je razkrilo natančne temperature faznih premen in ustrezne Gibbsove proste energije ter entalpije, ki so prikazane v razpredelnici 3.

Temperatura konca strjevanja (TS) je višja kot temperatura izločanja sekundarnih evtektikov, kar kaže, da so ti nastali v trdnem stanju kot tri binarne evtektične faze, ki so sestavljene iz trdne raztopine α_{Al}, prenasičene z bakrom in magnezijem.

S simultano termično analizo (DTA) smo dobili segrevalne in ohlajevalne krivulje

Optical metallographic analyzes compared the morphology of intermetallic compounds with those in the literature which enable visual recognition, while electron microscopy allowed detailed insight into the chemical composition of the phases, as well as the distribution of the individual elements of the study area. An analysis of microstructural features was perfomed on an optical microscope using software for image analysis AnalysisResearchLab ®.

3. Results and Discussion

Chemical composition of investigated AlSi8Cu3 alloy, as well as comparative review of required values demanded by European norm is shown in Table 2.

The chemical composition of the investigated samples is in accordance with the requirements.

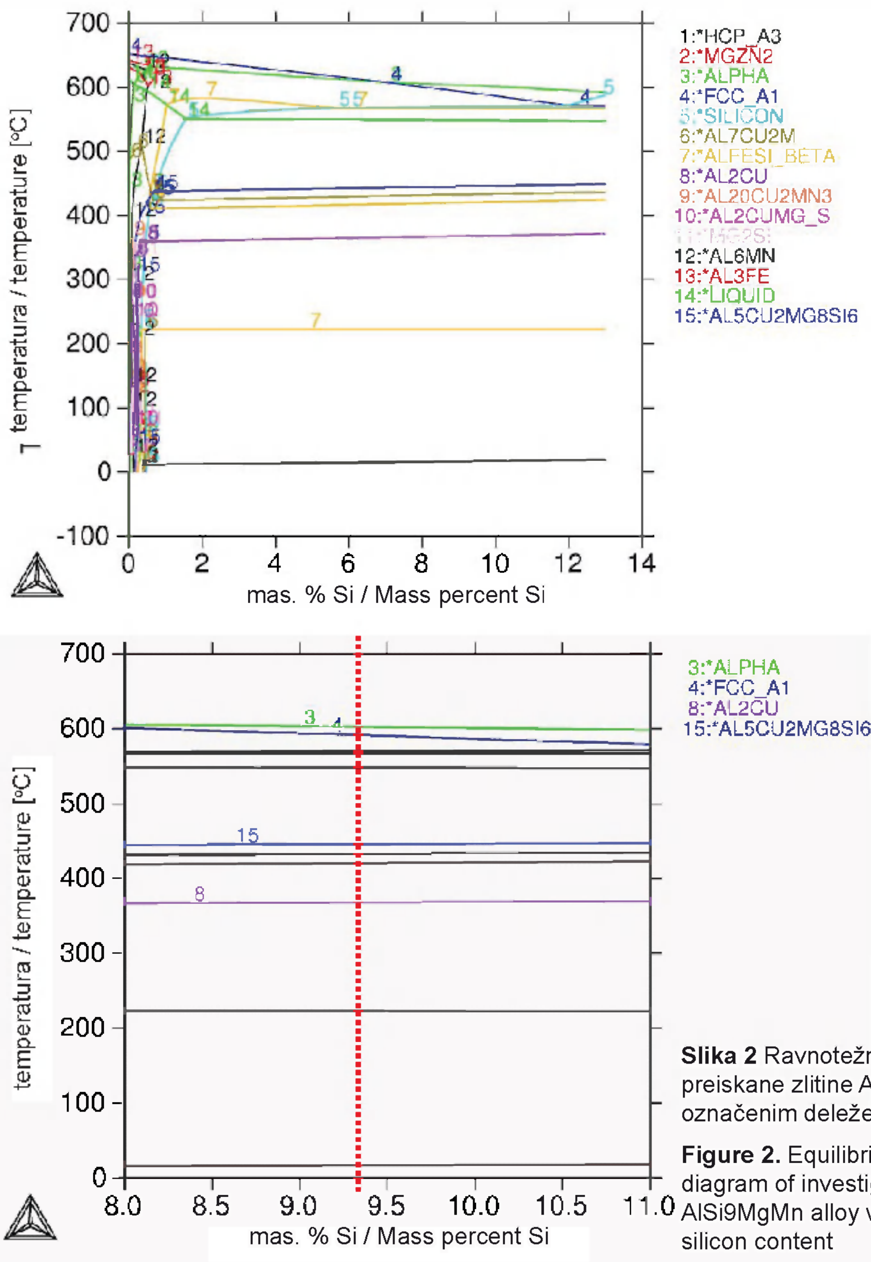
Thermodynamic calculation of stability of particular phases accompanied by initial condition of pouring temperature of 726,85°C, pressure 101,325 kPa and obtained chemical composition resulted in equilibrium phase diagram shown in Figure 2.

Dashed line indicates silicon content of 9,34 % in investigated alloy. Equilibrium phase diagram indicates solidification

Razpredelnica 2. Kemična sestava preiskovanih zlitin in primerjava s kemično sestavo, zahtevano po EN 1706:1998 [10]

Table 2. Chemical composition of the investigated alloy and comparative chemical composition required by EN 1706:1998 [10]

kemični element / chemical element vzorec/ sample	mas. %/ Wt. %	Si	Fe	Cu	Mn	Mg	Zn	Ti	Ni	Pb	razlika / balance
Sample	povprečje / average	9,34	0,61	2,30	0,30	0,39	0,76	0,14	0,04	0,003	0,06
EN 1706:1998 (AC 46200)	min.	7,5		2,00	0,15	0,05					
	max.	9,5	0,80	3,50	0,65	0,55	1,20	0,25	0,35	0,25	0,05



Slika 2 Ravnotežni fazni diagram preiskane zlitine AlSi9MgMn z označenim deležem silicija

Figure 2. Equilibrium phase diagram of investigated AlSi9MgMn alloy with marked silicon content

za obe stanji pri 0,17 K/s, kar je primerjalno prikazano na sliki 3.

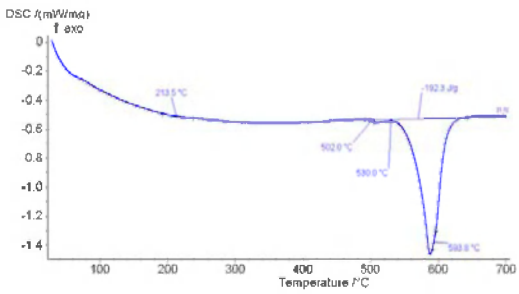
Diagrami na sliki 3 prikazujejo natančne vrednosti pomembnih temperatur faznih

sequence of an alloy as follows: dendrite development, high-temperature iron phase, main eutectic development and finally secondary eutectic phases precipitation.

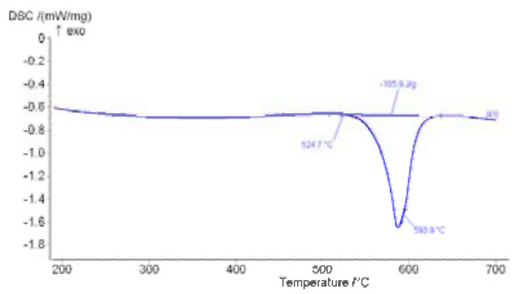
Razpredelnica 3. Potek strjevanja zlitine AlSi8Cu3 ter ustrezni termodinamični podatki

Table 3. Solidification sequence of AlSi8Cu3 alloy and corresponding thermodynamic data

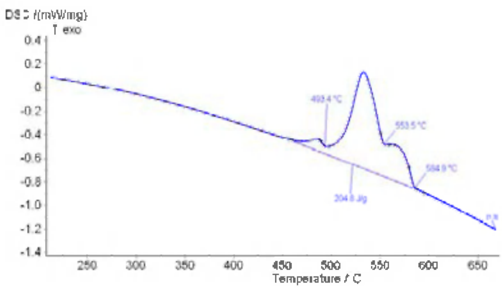
Štev. reakcije / reaction no.	predpostavljena reakcija / presumed reaction	temperatura / temperature (°C)	ΔG (J/mol) x 10^4	ΔH (J/mol) x 10^4
1	Nastajanje dendritne mreže / dendrite network development	596,85	-3,47381	2,90462
2	L→L1+ αAl	576,85	-3,32805	2,82990
3	L2→L3+ Al5FeSi (AlFeSi_BETA)	570,85	-3,28496	2,59755
4	L1→ L2 + (αAl + βSi)	566,85	-3,25885	1,96360
	Ts (konec strjevanja) / Ts (solidification end)	548,85	-3,15485	1,42767
5	αAl → α'Al +Al5Cu2Mg8Si6	446,85	-2,60926	1,08381
6	α'Al → α''Al +Al7Cu2	434,85	-2,54803	1,04486
7	α''Al → α'''Al +Al2Cu	368,85	-2,22343	0,83409



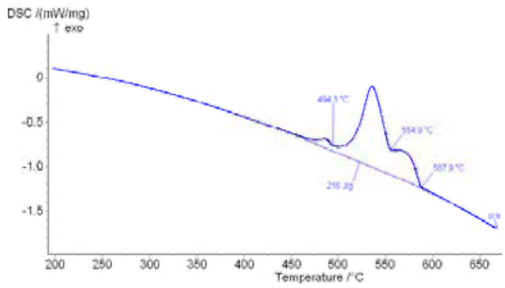
a) Segrevalna krivulja, lito stanje (F)
Heating curve, as cast (F) state



b) Segrevalna krivulja, toplotno obdelano stanje (T)
Heating curve, heat-treated (T) state



c) Ohlajevalna krivulja, lito stanje (F)
Cooling curve, as cast (F) state



d) Ohlajevalna krivulja, toplotno obdelano stanje (T)
Cooling curve, heat-treated (T) state

Slika 3. Simultana termična analiza vzorcev zlitine AlSi8Cu3 po metodi DTA

Figure 3. Simultaneous thermal analysis of the AlSi8Cu3 alloy samples by DTA method

premen. Začetek strjevanja (temperatura likvidus) pri 584,9 °C za stanje F in 587,9 °C za stanje T, izračunana evtektična temperatura 553,5 °C za stanje F in 554,9

Further modelling reveals exact temperatures of phase transformations and corresponding Gibbs free energy and enthaply as given in Table 3.

°C za stanje T, nastanek sekundarnih evtektičnih faz pri 493,4 °C za stanje F in 494,3 °C za stanje T na ohlajevalni krivulji.

Te konice nakazujejo izračunan evtektični interval nastanka kompleksnih večkomponentnih faz.

Na segrevalni krivulji je prikazan začetek taljenja večkomponentnih faz pri 502,0 °C, in poleg tega še pri 530,0 °C za stanje F ter majhen delež faznih premen pri 213,5 °C, kar vse kaže na večje število različnih nizkotemperaturnih sekundarnih evtektičnih faz v litem stanju. Vendar je pri stanju T enotna temperatura 524,7 °C, kar kaže na homogeniziranje mikrostrukture zaradi toplotne obdelave s poudarkom na sekundarnih evtektičnih fazah.

Tudi DTA kaže nastanek dendritov pri 593,8 °C za stanje F in 593,9 °C za stanje T, kar je zelo blizu teoretičnim vrednostim.

Če primerjamo s teoretičnimi vrednostmi, dobljenimi z TCW, pride pri dejanskih vzorcih do nekaterih razlik, kot kaže razpredelnica 4.

Temperature pri dejanskih vzorcih ustrezajo teoretičnim za nastanek dendritov, a so rahlo višje za α_{Al} ter nižje za nastanek glavnega evtektika (αAl + βSi). Na diagramih DTA ni bilo nakazano nastajanje železove faze. Glavna razlika je v številu premen nizkotemperaturnih faz v litem stanju, če se

Temperature of solidification end (TS) is higher then temperature of secondary eutectics precipitation which indicate its development in solid state as a three binary eutectic phases consists from αAl solid solution supersaturated with copper and magnesium.

Simultaneous thermal analysis (DTA) resulted in heating and cooling curves for both states, obtained by 0,17 K/s, comparatively shown in Figure 3.

Diagrams in the figure 3 resulted in exact values of significant temperatures of the phase transformations. Solidification beginning (liquidus temperature) at 584,9 °C for F state and 587,9 °C for T state, eutectic evaluation temperature at 553,5 °C for F state and 554,9 °C for T state, and secondary eutectic phases development at 493,4 °C for F state and 494,3 °C for T state were indicated on the cooling curve. Those peaks indicate eutectic interval evaluation of complex multicomponent phases development.

The heating curve indicates beginning of multicomponent phases melting at 502,0 °C and furthermore at 530,0 °C for F state, and a small amount of phase transformation at 213,5 °C, all of which indicate a number of various low-temperature secondary eutectic phases in as cast state. Nevertheless,

Razpredelnica 4. Primerjava poteka strjevanja zlitine AlSi8Cu3 po TCW in DTA

Table 4. Compared solidification sequence of AlSi8Cu3 alloy obtained by TCW and DTA

Štev. reakcije / reaction no.	predpostavljena reakcija / presumed reaction	temperatura / temperature °C TCW	Temperatura, °C stanje F	Temperatura, °C stanje T
1	Nastajanje dendritne mreže / dendrite network development	596,85	593,8	593,9
2	L→L1+ αAl	576,85	584,9	587,9
3	L2→L3+ Al5FeSi (AlFeSi_BETA)	570,85		
4	L1 → L2 + (αAl + βSi)	566,85	553,5	554,9
	Ts (konec strjevanja) / Ts (solidification end)	548,85		
5	αAl → α’Al +Al5Cu2Mg8Si6	446,85	530,0	524,7
6	α’Al → α”Al +Al7Cu2	434,85	502,0	
7	α”Al → α’”Al +Al2Cu	368,85	213,5	

Razpredelnica 5. Primerjava vrednosti mehanskih lastnosti zlitine AlSi8Cu3 v ulitem in toplotno obdelanem stanju in vrednosti, ki jih predpisujejo standardi [10]

Table 5. Comparative values of mechanical properties AlSi8Cu3 alloy cast and annealed state, and the values prescribed norms [10]

	RP02 / MPa	Rm / MPa	A5 / %	HV
preiskovana zlitina / ulito stanje (F) / investigated alloy / as cast state (F)	171	229	1,9	97,3
preiskovana zlitina / toplotno obdelano stanje (T) / Investigated alloy / heat treated state (T)	169	253	2,5	110,5
zahtevane vrednosti EN 1706 / required values EN 1706	90	150	1,0	60

primerja z enotno temperaturo pri toplotno obdelanem stanju. Te temperature so precej višje od teoretično napovedanih.

Po EN 1706:1998 [10] pričakovane mehanske lastnosti so bile primerjane s standardnimi vrednostmi posebej ulitih preizkušancev za mehansko preskušanje [12], ki so bili in niso bili toplotno obdelani, kot kaže razpredelnica 5.

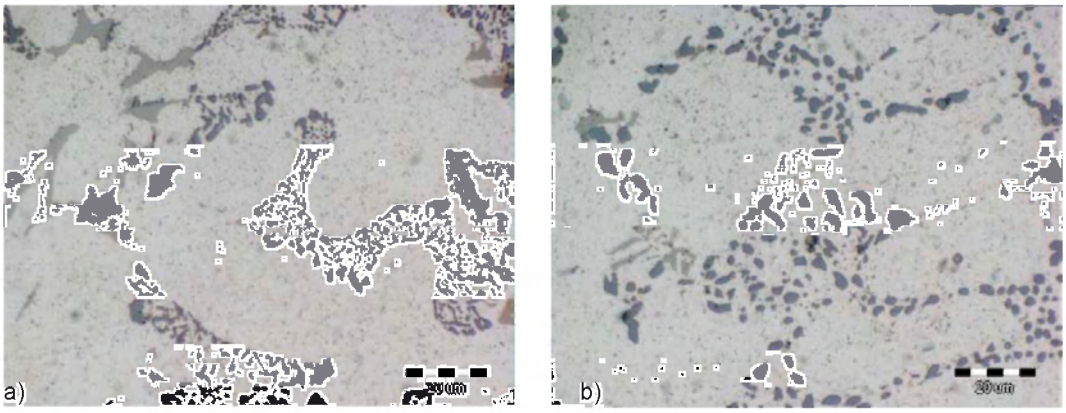
Primerjava mehanskih lastnosti vzorcev v litem in toplotno obdelanem stanju kaže na povečanje natezne trdnosti in raztezka, posebno pa mikrotrdote vzorcev, ki so bili toplotno obdelani, njihove vrednosti pa so občutno večje od zahtevanih.

T state reveals unique temperature at 524,7 °C, which indicated microstructure homogenization due to heat treatment with impact on secondary eutectic phases.

Also, DTA indicates dendrite development at 593,8 °C for F state and 593,9 °C for T state, which closely correspond to theoretical values.

When compared to theoretical values obtained by TCW, some differences in real samples occur as shown in Table **4**.

Real samples values corresponds to theoretical ones for dendrite development temperature, but these are slightly higher for αAl, and lower for main eutectic evolution



Slika 4. Primerjava mikrostrukture zlitine AlSi8Cu3 v a) ulitem stanju (F) in b) toplotno obdelanem stanju, 1000 x

Figure 4. Comparative overview of the AlSi8Cu3 alloy microstructure samples in a) as cast state (F), and b) heat-treated state, 1000x

Nastanek določenih intermetalnih spojin s svojo velikostjo, morfologijo in porazdelitvijo delcev neposredno vpliva na mehanske lastnosti ulitkov iz zlitine AlSi8Cu3. Preiskava s svetlobnim mikroskopom je omogočila primerjalne serije mikroposnetkov ulitih in toplotno obdelanih vzorcev, kot kaže slika 4.

Mikrostruktura vzorca v litem stanju odkriva dendritno mrežo primarnega aluminija α_{Al}, ki jo prekinjajo intermetalne faze na osnovi železa (Al_5FeSi), podmodificiran evtektik z mešano igličasto-vlaknato morfologijo (αAl + βSi) v meddendritnih prostorih in sekundarnimi evtektičnimi fazami na osnovi bakra, ki imajo različno, grobo, nepravilno morfologijo in so se strdile zadnje, vse potisnjene na mejo zrn. Vzorci v toplotno obdelanem stanju kažejo enakomerno porazdelitev dendritnih mrež kot tudi fino porazdelitev popolnoma modificiranega vlaknatega silicija na interdendritnih ploskvah. Sekundarne evtektične faze na osnovi bakra so manj vidne kot pri litem stanju, vendar še vedno v območju morfologij, odvisnih od kemične sestave.

Vrstična elektronska mikroskopija je omogočila identifikacijo določenih mikrostrukturnih sestavin. Glavne sestavine so primarna mreža dendritov (α_{Al}), evtektik (αAl + βSi), visokotemperaturne faze na osnovi železa (Al_5FeSi) in številne intermetalne spojine na osnovi bakra. Opazili smo prisotnost treh različnih intermetalnih faz na osnovi bakra:

a) kompleksne intermetalne faze z bakrom in magnezijem, ki so obogatene z železom in manganom, Alx(Fe, Mn) yMgzSiuCuw, in ustrezajo fazi α‘Al + Al5Cu2Mg8Si6, ugotovljeni s TCW,
b) kompleksne intermetalne faze z bakrom, ki so obogatene z železom in manganom, Alx(Fe, Mn)yMgzSiuCuw, in ustrezajo fazi α“Al +Al7Cu2 ,

(αAl + βSi). There was no indication for iron phase evolution in DTA diagrams. The main difference has been revealed in a number of low-temperature phase transformations in as cast state when compared to unique one in heat treated state. Those temperature are much higher then theoretically predicted ones.

Expected mechanical properties of alloys AlSi8Cu3 to EN 1706:1998 [10] compared with standard values separately cast test specimens for mechanical testing carried out with and without heat treatment, are shown in Table 5.

Comparison of mechanical properties of the samples in as-cast and heat-treated state indicates an increase in tensile strength and elongation, and significantly microhardness (HV) in samples subjected to heat treatment, the values of which significantly exceed the required ones.

The development of particular intermetallic compounds directly affects the mechanical properties of AlSi8Cu3 alloy castings by size, morphology and distribution. Optical microscope examination gave the comparative series micrographs of as-cast and heat-treated samples, as shown in Figure 4.

Microstructure of the sample in as-cast state reveals dendrite network of primary aluminum αAl intersected by intermetallic phases on iron base (Al5FeSi), hypomodified eutectic with mixed needle-fiber morphology (αAl + βSi) in the interdendritic regions, and last solidified secondary eutectic phases on the copper base with various coarse irregular morphology, all pushed to the grain boundaries. Samples in heat-treated state indicate a uniform distribution of dendrite networks, as well as fine distribution of completely modified fibrous eutectic silicon in the interdendritic areas. Secondary eutectic phases on the copper base are less visible when compared to as-cast state, but ugotovljeni s TCW,

c) ternerni evtektik Al-Al2Cu-Si, ki ustreza fazi α'“Al +Al2Cu, ugotovljeni s TCW.

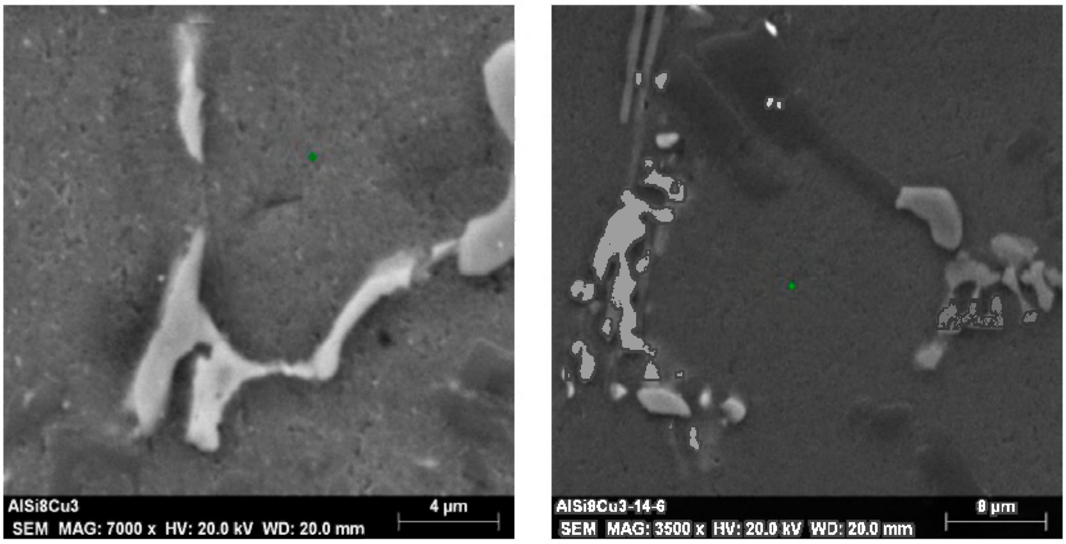
Kemična sestava osnove in sekundarnega evtektika se razlikuje v litem (F) in toplotno obdelanem (T) stanju zaradi fizikalne spremembe v materialu med žarjenjem. Razliko deleža bakra v osnovi kaže slika 5.

Značilno povečanje deleža bakra za 1,46 mas. % (0,63 at. %) smo opazili pri toplotno obdelanem vzorcu, kar potrjuje hipotezo, da se zadnje strjene faze raztapljajo, ker postanejo nestabilne pri temperaturi žarjenja in zato pride do izločanja raztopljenega bakra v kristalni mreži primarnega aluminija. Ta mehanizem pojasnjuje povečanje trdnosti in duktilnosti toplotno obdelanih vzorcev. Rezultati preiskave kemične sestave faz still with a range of morphologies depended from the chemical composition.

Scanning electron microscopy allowed the identification of particular microstructural constituents. The major constituents are primary dendrite network (αAl), eutectic (αAl + βSi), high temperature iron base phases (Al5FeSi) and a number of intermetallic compounds on the basis of copper. The presence of three different intermetallic phases on the copper base has been noticed:

a) complex intermetallic phases with copper and magnesium enriched by iron and manganese Alx(Fe, Mn) yMgzSiuCuw, which corresponds to α'Al + Al5Cu2Mg8Si6 phase obtained by TCW.

b) complex intermetallic phases with copper enriched by iron and manganese



Element	mas. % / wt.%	at.%	Element	wt.%	at.%
Al	73,37	75,30	Al	95,70	98,13
Si	23,79	23,46	Si	-	-
Cu	2,84	1,24	Cu	4,30	1,87

Slika 5. Kemična sestava osnove, ugotovljena z EDS

Figure 5. Chemical composition of matrix obtained by EDS investigation

Razpredelnica 6. Kemične sestave določenih intermetalnih spojin na osnovi bakra v litem in toplotno obdelanem stanju zlitin AlSi8Cu3

Table 6. Chemical compositions of particular intermetallic compounds on the copper base in as-cast and heat-treated samples of AlSi8Cu3 alloy

kemični element / element mas.% / wt %	faza / phase					
	Al-Al2Cu-Si		Alx(Fe,Mn)ySizCuw		Alx(Fe,Mn)yMgzSiuCuw	
	F	T	F	T	F	T
Al	73,37	95,70	59,63	64,55	55,54	54,91
Si	23,79	-	6,95	6,08	6,35	7,67
Cu	2,84	4,30	5,17	5,96	16,42	18,31
Fe	-	-	19,65	16,22	13,06	7,44
Mn	-	-	8,61	7,19	6,86	8,47
Mg	-	-	-	-	1,78	3,19

na osnovi bakra pri obeh stanjih prikazuje razpredelnica 6.

Intermetalne spojine na osnovi bakra so v toplotno obdelanem stanju (T) postale drobnejše, za njih pa je značilna bolj kompaktna morfologija, vsebujejo pa tudi več Mg in Cu, kar se smatra, da povečuje trdnost teh vzorcev. Ker je toplotna obdelava z žarjenjem potekala pri 480 °C, kar je blizu temperature območja stabilnosti sekundarnih bakrovih faz (507-529 °C), se pričakuje, da ima to neposreden vpliv zaradi ponovnega delnega taljenja.

Mikrostrukturne analize so obsegale razporeditev in velikost določenih intermetalnih faz, tako v litem kot v toplotno obdelanem stanju. Fazna analiza mikrostrukturnih sestavin na osnovi železa (Fe), silicija (Si) in bakra (Cu) je pokazala, da so v litem (F) oz. toplotno obdelanem (T) stanju v določenih fazah različni deleži teh elementov, kar je prikazano na diagramu na sliki 6.

Opazili smo približno podobno razmerje faz na osnovi Fe in Si; v toplotno obdelanem stanju smo ugotovili občutno zmanjšanje deleža bakrovih faz (7,99% → 2,02%). Ugotovljene vrednosti kažejo, da visokotemperaturna faza na osnovi Fe in Si ni občutljiva na toplotno obdelavo. Toplotna obdelava z žarjenjem vodi do ponovnega

Alx(Fe,Mn)ySizCuw, which corresponds to α''Al +Al7Cu2 phase obtained by TCW

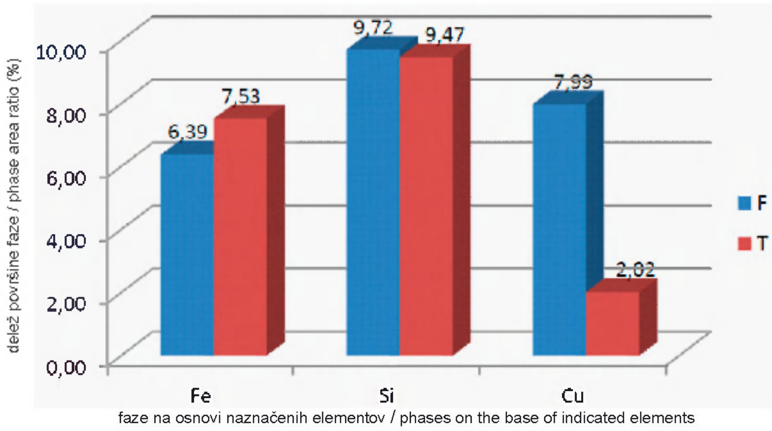
c) ternary eutectic Al-Al2Cu-Si, which corresponds to α'''Al +Al2Cu phase obtained by TCW

Chemical composition of matrix and secondary eutectic differs in as-cast (F) and heat-treated (T) state due to physical changes in materials during annealing. Difference in copper content in matrix is shown in Figure 5.

A significant increase in the copper content of 1,46 % (0,63 at.%) was noticed in heat-treated state, which confirms the hypothesis of dissolving the last solidifying phases, which become unstable at annealing temperature and thereby leads to precipitation of dissolved copper in the crystal lattice of primary aluminum. This mechanism explains an increase in strength and ductility of heat-treated samples.

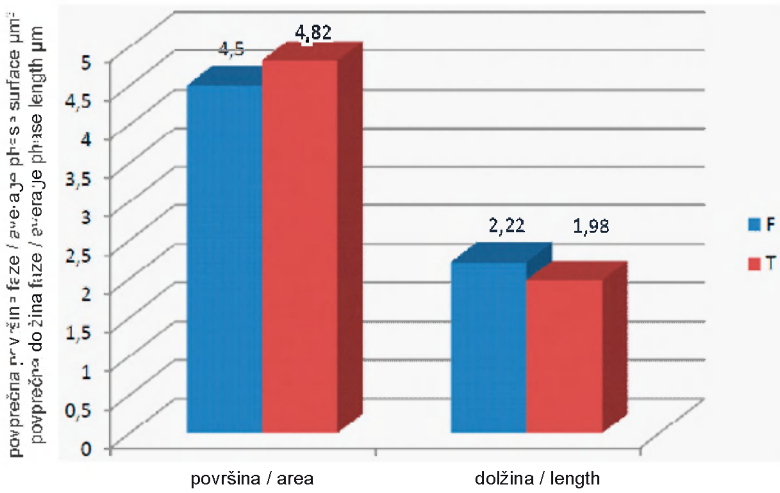
Results of chemical composition investigations of copper base phases in both states are shown in Table 6.

Intermetallic compounds on the copper base in heat-treated (T) state become finer and characterized with more compact morphology, but also richer in Mg and Cu content, which is considered responsible for increasing the strength of these samples.



Slika 6. Fazna analiza mikrostrukture vzorcev zlitine AlSi8Cu3 v litem (F) in toplotno obdelanem (T) stanju

Figure 6. Phase analysis of the microstructure of as-cast (F) and heat-treated (T) samples of the AlSi8Cu3 alloys



Slika 7. Povprečna velikost delcev in njihove dolžine v mikrostrukturi ulitih (F) in toplotno obdelanih vzorcev (T) zlitine AlSi8Cu3

Figure 7. PThe average particle size and the length of the microstructure of as cast (F) and heat-treated (T) samples of the AlSi8Cu3 alloys

taljenja nizkotaljive bakrove faze, zato se njen delež v osnovi zmanjšuje.

Ugotovili smo odvisnost med povprečno površino in dolžino delcev mikrostrukturnih sestavin po toplotni obdelavi, kar je prikazano na sliki 7.

Vidi se, da se je povprečna velikost delcev v toplotno obdelanih zlitinah rahlo povečala, medtem ko se je dolžina vseh delcev zmanjšala, kar se lahko pripiše vplivu toplotne obdelave zaradi raztapljanja posameznih faz, enakomerne porazdelitve mikrostrukturnih sestavin in učinka modificiranja.

Since the heat treatment by annealing is carried out at a temperature of 480 °C, which is nearby the temperature stability range of secondary copper phase (507-529 °C), it is expected to have direct influence through partial remelting.

Microstructural studies included classification and size of the particular intermetallic phases in the as-cast and heat-treated state. Phase analysis of the microstructure constituents on the basis of iron (Fe), silicon (Si) and copper (Cu) resulted in different amounts of particular phases in the as-cast (F) and heat-treated

4. Sklep

Cilj raziskave je bil ugotoviti vpliv toplotne obdelave z žarjenjem na mikrostrukturne značilnosti ločeno ulitih preizkušancev zlitine AlSi8Cu3. Termodinamično modeliranje se je uporabilo kot orodje za razkrivanje, kako se je oblikovala mikrostruktura.

S simultano termično analizo so se ugotovile temperature faznih premen z napovedovanjem reakcij na osnovi termodinamičnega modeliranja. DTA je dala primerjavo med napovedano in dejansko temperaturo nastanka dendritov in pokazala dobro ujemanje za kristalizacijo primarnega aluminija in razvoja glavnega evtektika pri obeh stanjih zlitine AlSi8Cu3. Glavna razlika se je pojavila pri številu nizkotemperaturnih sekundarnih evtektičnih faz, za katere je bila izračunana višja temperatura. Njihovo število in vrednosti kažejo na homogenizacijski učinek toplotne obdelave, kar je potrdila mikrostrukturna analiza. Metalografska analiza je pokazala na obstoj naslednjih mikrostrukturnih sestavin: primarni dendriti α_{Al}, evtektik (α_{Al} + β_{Si}) z mešano, ne dokončno modificirano morfologijo v litem in v celoti modificirano nitasto morfologijo v toplotno obdelanem stanju, ter intermetalne faze na osnovi bakra: Al-Al_2Cu-Si, kompleksne intermetalne faze na osnovi bakra, obogatene z železom in manganom, $Al_x(Fe,Mn)_ySi_zCu_w$, in dodatne intermetalne faze z bakrom ter magnezijem, obogatene z železom in manganom, $Al_x(Fe,Mn)_ySi_zCu_w$.

Mikrostruktura po toplotni obdelavi je doživela spremembe z enakomerno porazdelitvijo dendritov aluminija, za katere je bilo značilno povečanje koncentracije bakra za 1,46 mas. % (0,63 at. %). Obogatitev osnove z bakrom pojasnjuje, zakaj se je povečala trdnost za 24 MPa in raztezek za 0,6 % ter občutno povečala mikrotrdota (97,3 → 110,5 HV). Intermetalne (T) state, as shown in the diagram in Figure 6.

Approximately similar ratios of phase on the basis of Fe and Si were observed; while significant decrease of copper phases ratio in the heat-treated state (7,99% → 2,02%) was determined. Determined values indicate that the high-temperature phase on the basis of Fe and Si are insensitive to heat treatment. Heat treatment by annealing leads to remelting of the low-temperature copper phase, thus their share in matrix falls.

Consequently, the dependence of average surface and the length of particle microstructure constituents of provided heat treatment were established, as shown in Figure 7.

It has been shown that the total average size of particles in the heat-treated alloys slightly increases, while the average length of all particles falls which is attributed to the impact of heat treatment in terms of dissolution of individual phases, uniform distribution of microstructural constituents and performance modifications.

4 Conclusion

The aim of this study was to determine the influence of heat treatment by annealing on microstructural features of separately cast test samples of AlSi8Cu3 alloy. Thermodynamic modelling was used as a tool for revealing the microstructure development.

Simultaneous thermal analysis reveals corresponding temperatures of phase transformations with predicted reaction on the base of thermodynamical modelling. The DTA values reveal corresponding temperatures with modelled one for dendrite development, and close coincidence for primary aluminum and main eutectic bakrove faze so po toplotni obdelavi postale drobnejše in bogatejše z Mg ter Cu, kar je tudi prispevalo k trdnosti zlitine. Zmanjšanje povprečne dolžine delcev v vzorcih po toplotni obdelavi kaže na delno stalitev nizkotemperaturnih sekundarnih evtektičnih faz in enakomernejšo porazdelitev mikrostrukturnih sestavin. V splošnem je bilo ugotovljeno, da je imela toplotna obdelava z žarjenjem pozitiven učinek na razvoj mikrostrukture in izboljšanje mehanskih lastnosti vzorcev zlitine AlSi8Cu3.

evolution for both states of AlSi8Cu3 alloy. The main difference appears in the number of low-temperature secondary eutectic phases which evaluate at higher temperature. Also, their number and values indicate homogenization impact of heat treatment, as confirmed by microstructural analysis.

Methods of metallographic investigation indicated following microstructural constituents: primary dendrites αAl, eutectic (αAl + βSi) with mixed hypomodified morphology in as-cast and completely modified fiber morphology in heat-treated state and intermetallic phases on the basis of copper: Al-Al2Cu-Si, complex intermetallic phases on the copper base enriched with iron and manganese Alx(Fe,Mn)ySizCuw, and additionally intermetallic phases on the copper and magnesium phase enriched with iron and manganese Alx(Fe,Mn) yMgzSiuCuw.

Microstructure after heat treatment experiences changes in terms of uniform distribution of primary aluminium dendrites characterized by the copper enrichment for 1,46 % (0,63 at.%). Copper enrichment of matrix explains an increase in strength for 24 MPa and elongation for 0,6% and a

significant increasing in microhardness (97,3 → 110,5 HV). Intermetallic copper phases become finer and enriched on Mg and Cu content, due to heat treatment which also comprehend the increasing the alloy strength. The decrease in the average length of particles in samples, undergone the heat treatment, indicates a partial remelting of low temperature secondary eutectic phases and more uniform distribution of microstructural constituents.

Generally, a positive effect of heat treatment by annealing on the development of microstructure and mechanical properties of samples AlSi8Cu3 alloys has been established.

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