

Vpliv postopkov modifikacije in toplotne obdelave na mikrostrukturo in mikrotrdoto aluminijeve zlitine AlSi9Cu3

Influence of modification and heat treatment procedures on microstructure and microhardness of aluminium alloy AlSi9Cu3

Povzetek

V tem delu je raziskan vpliv modifikacije s stroncijem in različnih postopkov toplotne obdelave na mikrostrukturo in mikrotrdoto zlitine AlSi9Cu3. Nemodificirane in modificirane zlitine so bile ulite pri 750 °C v bakreno kokilo s premerom 20 mm. Ulitki v litem in toplotno obdelanem stanju T5 vsebujejo fazo β_{Si} v obliki velikih lamel. Mikrostruktura zlitine, modificirane s stroncijem, po toplotni obdelavi T5 kaže modificiran evtektik brez lamelnega β_{Si} . Nemodificirana in modificirana zlitina po toplotni obdelavi T6 kaže podobno mikrostrukturo s fazo β_{Si} v obliki večjih sferičnih delcev. Mikrotrdota osnove α_{Al} je po toplotni obdelavi T6 višja kot po T5, kar je posledica večje vsebnosti bakra v primeru T6. Višja mikrotrdota, opažena pri zlitinah, modificiranih s stroncijem, je lahko posledica zelo nizke topnosti stroncija v α_{Al} .

Ključne besede: Aluminijeve zlitine, modifikacija, mikrostruktura, mikrotrdota

Abstract

In this work, the influence of modification with strontium and various heat treatment processes on the microstructure and microhardness of the alloy AlSi9Cu3 is investigated. Unmodified and modified alloy melts were cast at 750 °C in a copper mould with a diameter of 20 mm. The cast and heat-treated T5 castings contain β_{Si} phases in the form of large lamellae. The microstructure of the Sr-modified alloy after heat treatment T5 shows a fine modified eutectic without lamellar β_{Si} , while the unmodified and Sr-modified AlSi9Cu3 alloy after T6 shows a similar microstructure with β_{Si} in the form of larger spherical particles. The microhardness of the α_{Al} matrix is higher in T6 compared to T5 heat treatment processes, which is due to the higher copper content in the former case. The higher microhardness observed in Sr-modified alloys could be due to a very low solubility of Sr in α_{Al} .

Keywords: Aluminium alloys, modification, microstructure, microhardness

1 Uvod

Aluminijeve zlitine v zadnjih desetletjih igrajo pomembno vlogo pri lahkih konstrukcijah v transportni industriji in jo imajo še danes – pa naj bo to v ladijskem prometu, vesoljski industriji ali avtomobilski industriji [1].

1 Introduction

Aluminium alloys have played an important role in lightweight construction in the transport industry over the past decades and continue to do so today – be it in shipping, aerospace or the automotive

Uvrstitev aluminija med kritične surovine s strani Evropske komisije leta 2023 poudarja njegov osrednji pomen za številne sektorje evropske industrije [2].

Zmanjšanje teže vozil velja za pomemben način doseganja večje učinkovitosti porabe goriva in nižjih emisij [3]. Ta težnja po doseganju visokega razmerja med trdnostjo in težo zlitin je privedla do modifikacije obstoječih vrst komercialno dostopnih zlitin ter razvoja in uvedbe novih aluminijevih zlitin [4]. Končne lastnosti aluminijeve zlitine so kumulativni rezultat izbrane kemijske sestave, procesnih parametrov, mikrostrukture in kasnejših toplotnih obdelav [5].

Večina litih aluminijevih zlitin je na osnovi Al-Si in vsebuje evtektik ($\alpha_{Al} + \beta_{Si}$). Pri počasnem strjevanju teh zlitin tvori faza β_{Si} velike lamele. Te lamele lahko močno vplivajo na mehanske lastnosti teh zlitin [6], saj ostri robovi teh lamel povzročajo tako imenovani zarezni učinek. Zarezni učinek vodi do lokaliziranih koncentracij napetosti, ki lahko presežejo natezno trdnost materiala, kar povzroči nastanek in širjenje razpok ter na koncu porušitev dela izdelanega iz te zlitine [7].

Zarezni učinek lahko odpravimo z modifikacijo pri kateri se morfologija evtektične faze β_{Si} spremeni iz velikih (igličastih) lamel v obliko podobno drobnim koralam, ki ne povzroča tako imenovanega zareznega učinka. Modifikacijo je mogoče doseči bodisi z višjo hitrostjo strjevanja bodisi z dodatkom nadzorovanih količin stroncija, natrija, kalcija in antimona [ASM, zv. 2, 8].

To delo obravnava zlitino AlSi9Cu3 (226D), katere mikrostruktura je sestavljena predvsem iz primarne faze α_{Al} , obdane z evtektikom ($\alpha_{Al} + \beta_{Si}$). Cilj tega dela je oceniti vpliv modifikacije s stroncijem in različnih toplotnih obdelav, kot sta T5 (umetno staranje) in T6 (raztopno žarjenje, ki mu

industry [1]. The classification of aluminium as a critical raw material in 2023 by the European Commission underlines its central importance for many sectors of European industry [2].

Reducing the weight of vehicles is seen as a promising way to achieve higher fuel efficiency and lower emissions [3]. This drive to achieve high strength-to-weight ratio properties of alloys has led to the modification of existing grades of commercially available alloys and the development and introduction of novel aluminium alloys [4]. The final properties of an aluminium alloy are the cumulative result of the chosen chemical composition, process parameters, microstructure and subsequent heat treatments [5].

Most cast aluminium alloys are Al-Si based and contain an eutectic consisting of ($\alpha_{Al} + \beta_{Si}$). When these alloys cool slowly, the β_{Si} phase forms large lamellae. These lamellae can have a major influence on the mechanical properties of these alloys [6], as the sharp edges of these lamellae cause the so-called notch effect. The notch effect leads to localised stress concentrations that can exceed the ultimate tensile strength of the material, resulting in crack formation and propagation and ultimately failure of the alloy part [7].

To eliminate this notch effect, a modification process has been applied in which the morphology of the eutectic β_{Si} phase is changed from large (acicular) lamellae to a fine coral-like shape that does not lead to the so-called notch effect. The modification can be achieved either by a higher solidification rate or by the addition of controlled amounts of strontium, sodium, calcium and antimony [8].

This work deals with the alloy AlSi9Cu3 (226D), whose microstructure consists mainly of the primary α_{Al} matrix surrounded by an eutectic consisting of ($\alpha_{Al} + \beta_{Si}$). The

sledi umetno staranje), na mikrostrukturo in mikrotrdoto osnove α_{Al} .

2 Eksperimentalno delo

V delu je bila uporabljena komercialno dostopna aluminijeva zlitina AISi9Cu3, znana tudi kot 226D. Meje sestave po standardu EN AC 46000 in dejanska sestava, ugotovljena z EDS, so prikazane v tabeli 1. Zlitina z in brez modifikatorja je bila izdelana v komorni peči pri 750 °C in ulita v bakreno kokilo, prikazano na sliki 1. Vzorci so bili odvzeti iz ulitka za nadaljnjo karakterizacijo v spodnjem delu ulitka s premerom 20 mm. Hitrost ohlajanja v središču tega območja ulitka je bila izračunana s programsko opremo Magmasoft med temperaturama likvidus in solidus in znaša približno 7 °C/s. Evtetični silicij je bil modificiran z dodatkom 0,012 mas.% Sr v obliki komercialne predzlitine Al-Sr10 mas.%. Nemodificirane in modificirane vzorce zlitine smo nato toplotno obdelali. Toplotna obdelava po postopku z oznako T5 pomeni, da je bila zlitina v ulitem stanju starana 4 ure pri 180 °C. Postopek z oznako T6 pomeni, da je bila zlitina v ulitem stanju najprej 4 ure žarjena pri 520 °C, nato kaljena v vodi in nato 4 ure starana pri 180 °C.

Vzorci za mikroskopske analize so bili brušeni in na koncu polirani s koloidno suspenzijo SiO₂. Mikrostrukturo vzorcev zlitin smo pregledali s svetlobnim

aim of this work is to evaluate the effects of strontium modification and different heat treatments such as T5 (artificial ageing) and T6 (solution annealing followed by artificial ageing) on the microstructure and microhardness of the α_{Al} matrix.

2 Experimental Work

The commercially available aluminium alloy AISi9Cu3, also known as 226D, was used for this work. The composition limits according to the EN AC 46000 standard and the actual composition determined by EDS are shown in Table 1. The alloy with and without modifier was produced in a chamber furnace at 750 °C and cast into a copper mould, which is shown in Figure 1. Samples were taken from the casting for further characterisation in the lower part of the casting with a diameter of 20 mm. The cooling rate in the centre of this area of the casting was calculated between the liquid and solidus temperatures and estimated to be approximately 7 °C/s using Magmasoft software. The eutectic silicon was modified by adding 0.012 wt% Sr in the form of the commercial master alloy Al-Sr10 wt%. The unmodified and modified alloy samples were then heat treated. Heat treatment according to the process labelled T5 means that an alloy in the as-cast condition was aged for 4 hours at 180 °C. The process labelled T6 means that the as-cast alloy was first solution annealed at 520 °C for

Tabela 1. Sestava zlitine AISi9Cu3, ugotovljena z EDS in meje sestave v skladu s standardom EN AC 46000.

Table 1. Actual composition of alloy AISi9Cu3 determined by EDS and composition limits according to EN AC 46000.

	Al	Si	Cu	Zn	Fe	Mn	Mg
EN AC 46000	ost.	8,0 - 11,0	2,0 - 4,0	max 1,2	max 1,3	max 0,55	0,05 - 0,55
EDS	ost.	11,3	2,4	1,0	0,7	0,3	0,2

mikroskopom ZISS Axio Imager.A1m z Axiocam 208 Colour, medtem ko smo preiskave z vrstično elektronsko mikroskopijo in mikroanalizo izvedli s Thermo Fisher Scientific Quanta 650 ESEM, opremljenim z Oxford Instruments Ultim Max SDD 40 mm² EDS pri 20 kV. Mikrotrdoto vzorcev po Vickersu smo izmerili pri 10 g in 15 s z uporabo Kason HTMV-1000AD. Meritve so bile izvedene v največjih opazovanih območjih primarnega α_{Al} .



Slika 1. Bakrena kokila, uporabljena v procesu ulivanja.

Figure 1. Copper mould used in a casting process.

3 Rezultati in diskusija

Slika 2 prikazuje posnetke LM (svetlobna mikroskopija) mikrostrukture zlitine v litem stanju brez dodanega modifikatorja, posnete v osrednjem območju prereza ulitkov. Mikrostruktura razkriva velike dendrite primarnega α_{Al} , obdane večinoma

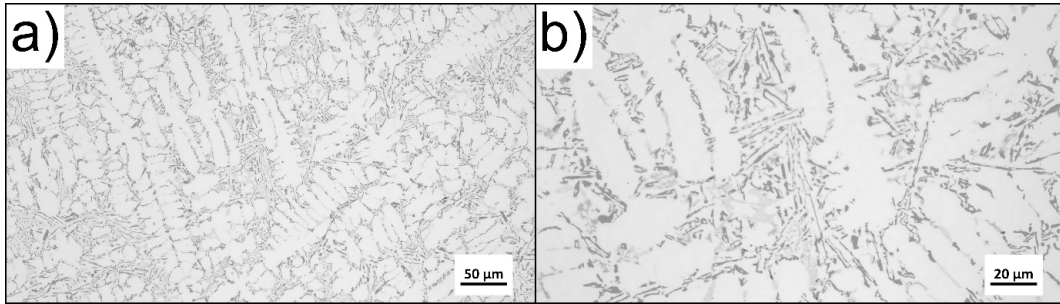
4 hours, then quenched in water and then aged at 180 °C for 4 hours.

The samples for the microscopic analyses were ground and polished with colloidal SiO₂ suspension. The microstructure of the alloy samples was examined by light microscopy using the ZISS Axio Imager.A1m with Axiocam 208 Colour, while scanning electron microscopy and microanalysis was performed using the Thermo Fisher Scientific Quanta 650 ESEM equipped with an Oxford Instruments Ultim Max SDD 40 mm² EDS at 20 kV. The Vickers microhardness of the samples was measured at 10 gf for 15 s using the Kason HTMV-1000AD. Measurements were performed in the largest observable areas of primary α_{Al} .

3 Results and Discussion

Figure 2 represents LM (light microscopy) images of the as-cast microstructure of the alloy without any added modifier captured in the central region of the castings cross section. Microstructure reveals large dendrites of primary α_{Al} surrounded mostly by binary eutectic ($\alpha_{Al} + \beta_{Si}$). The β_{Si} phase has a form of large lamella which indicates that the eutectic in the as cast alloy is not modified.

LM images of the microstructure of the alloy AlSi9Cu3 after the heat treatment T5 (only artificial aging) is presented in Figure 3 a) and b). LM images reveal similar microstructure as the one in the as-cast state presented in Figure 2. In contrast to this, the microstructure of the alloy AlSi9Cu3 with the addition of 0.012 wt. % of Sr after the heat treatment T5, which is presented in Figure 3 c) and d), shows fine modified heterogeneous structure of eutectic ($\alpha_{Al} + \beta_{Si}$) with absence of lamellar β_{Si} .



Slika 2. LM posnetka a), b) aluminijeve zlitine AISi9Cu3 v litem stanju.

Figure 2. LM images a), b) of as cast aluminium alloy AISi9Cu3.

z binarnim evtektikom ($\alpha_{Al} + \beta_{Si}$). Faza β_{Si} ima obliko velikih lamel, kar kaže na to, da evtektik v zlitini v litem stanju ni modificiran.

LM posnetek mikrostrukture zlitine AISi9Cu3 po toplotni obdelavi T5 (samo umetno staranje) je predstavljen na sliki 3 c) in d). Posnetki prikazujejo podobno mikrostrukturo kot je tista v litem stanju, predstavljena na sliki 2. V nasprotju s tem je mikrostruktura zlitine AISi9Cu3 z dodatkom 0,012 mas. % Sr po toplotni obdelavi T5, ki je predstavljen na sliki 2 c) in d), kaže droben modificiran heterogeni zlog evtektika ($\alpha_{Al} + \beta_{Si}$) brez velikih lamel β_{Si} .

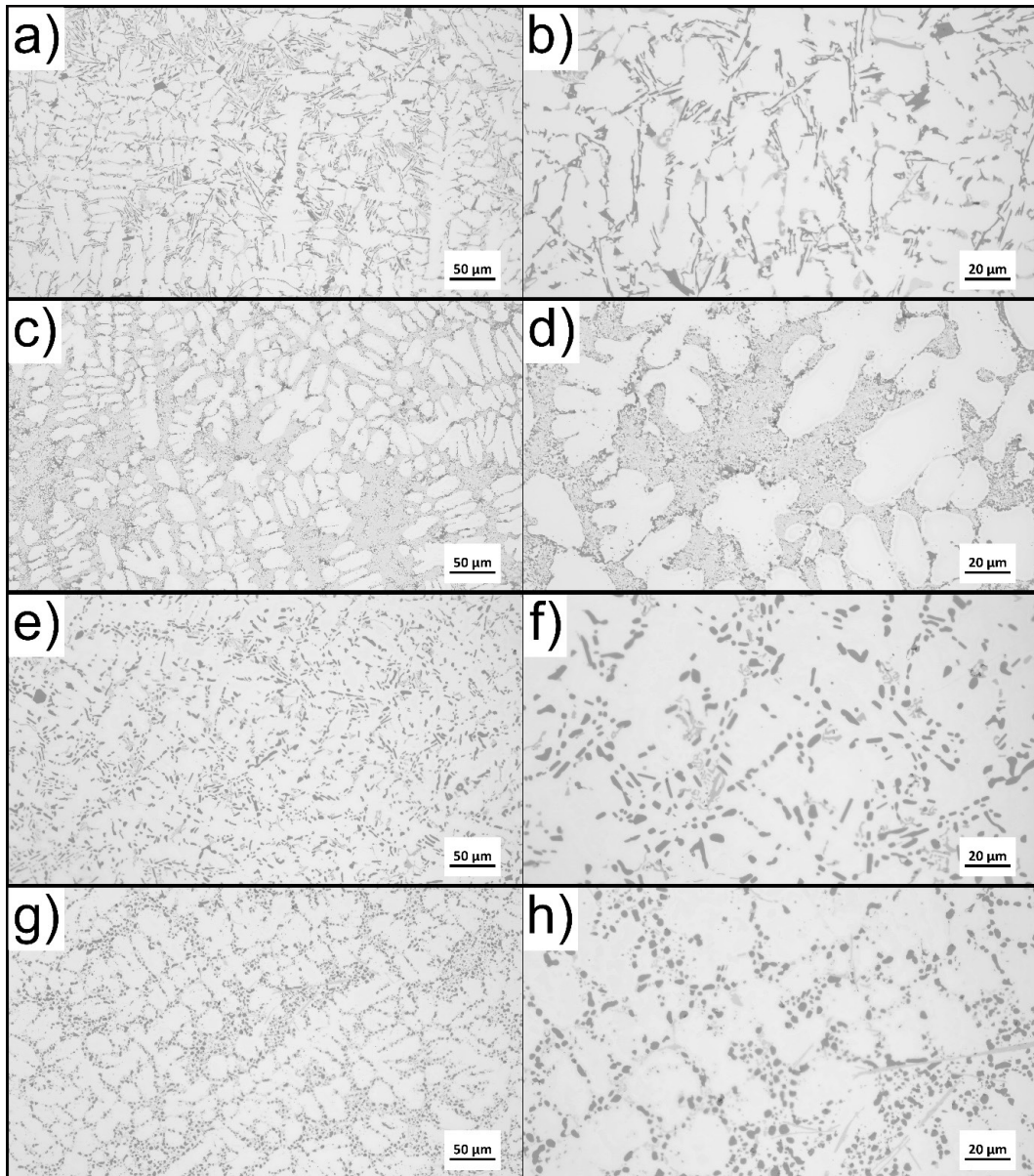
Mikrostruktura zlitine AISi9Cu3 po toplotni obdelavi T6 (toplotna obdelava, gašenje in umetno staranje) je predstavljena na sliki 3 e) in f) in kaže, da se je predhodno lamelni β_{Si} pretvoril v skoraj sferično obliko. Dokaj podobno mikrostrukturo kaže tudi zlitina AISi9Cu3 z dodatkom 0,012 mas. % Sr po toplotni obdelavi T6, ki je predstavljena na sliki 3 g) in h) in razkriva sferično oblikovane kristale β_{Si} .

V nasprotju s toplotno obdelavo T5 toplotna obdelava T6 vključuje štiriurno raztopno žarjenje pri 520 °C. Pri teh temperaturah je difuzija dovolj hitra, da lahko poteka proces sferoidizacije. Zato primerjava s Sr modificirane in nemodificirane zlitine AISi9Cu3 po toplotni

Microstructure of the alloy AISi9Cu3 after the heat treatment T6 (solution heat treatment, quenching and artificial aging) is presented in Figure 3 e) and f) and shows that previously lamellar β_{Si} converted into an almost spherical shape. Rather similar microstructure also shows the alloy AISi9Cu3 with the addition of 0.012 wt. % of Sr after the heat treatment T6 which is presented in Figure 3 g) and h) and reveals spherically shaped crystals of β_{Si} .

In contrast to heat treatment T5, heat treatment T6 includes solution heat treatment at 520 °C for four hours. At these temperatures the diffusion is fast enough to enable the spheroidization process to take place. Therefore, comparison of Sr modified and unmodified alloy AISi9Cu3 after the T6 heat treatment indicates almost negligible differences in morphology of eutectic β_{Si} . This means that modification process in castings which will be after the casting heat treated by solution heat treatment at moderate durations and high temperatures is not so crucial.

Heat treatment processes also affect the mechanical properties of this alloy among which the hardness is most indicative. Vickers microhardness HV0.01 was measured in the regions of the primary α_{Al} and the results are presented in Table 2.



Slika 3. LM posnetki mikrostrukture zlitine AISi9Cu3 po toplotni obdelavi T5 a), b), z dodatkom Sr po toplotni obdelavi T5 c), d), po toplotni obdelavi T6 e), f) in z dodatkom Sr po toplotni obdelavi T6 g), h).

Figure 3. LM images of the microstructure of the AISi9Cu3 alloy after T5 a), b), with the addition of Sr after T5 c), d), after T6 e), f) and with the addition of Sr after T6 g), h).

obdelavi T6 kaže skoraj zanemarljive razlike v morfologiji evtektičnega β_{Si} . To pomeni, da modifikacijski proces pri ulitkih, ki bodo po ulivanju toplotno obdelani z ustrežno dolgim raztopnim žarjenjem, ni tako ključen.

Postopki toplotne obdelave vplivajo tudi na mehanske lastnosti te zlitine, med katerimi je najbolj indikativna trdota. Mikrotrdota po Vickersu HV0.01 je bila izmerjena v območjih primarnega α_{Al} , rezultati pa so predstavljeni v tabeli 2. Najnižja mikrotrdota je bila ugotovljena pri vzorcih v litem stanju in vzorcih po toplotni obdelavi T5, medtem ko ima modificirana zlitina Sr-T5 znatno višjo trdoto. Še višja mikrotrdota je bila ugotovljena pri nemodificiranih vzorcih T6 in modificiranem Sr-T6.

Baker je v tej zlitini pomemben zlitinski element, ki bistveno vpliva na mehanske lastnosti. Zato smo izmerili tudi sestavo območij primarne faze α_{Al} . Ti rezultati so predstavljeni tudi v tabeli 2. Rezultati kažejo, da sta vsebnosti bakra in cinka višje v primeru vzorcev T6 in Sr-T6 v primerjavi z vsemi ostalimi.

Višja koncentracija bakra je posledica raztopnega žarjenja pri 520 °C, ki omogoča, da se vsa faza Al_2Cu , ki je prisotna v zlitini po strjevanju, raztopi v trdni raztopini. To je prikazano na sliki 4, ki prikazuje

Lowest microhardness was found to be in as-cast and T5 samples while modified alloy Sr-T5 reveals significantly higher hardness. Even higher microhardness' were found in unmodified T6 and modified Sr-T6 samples.

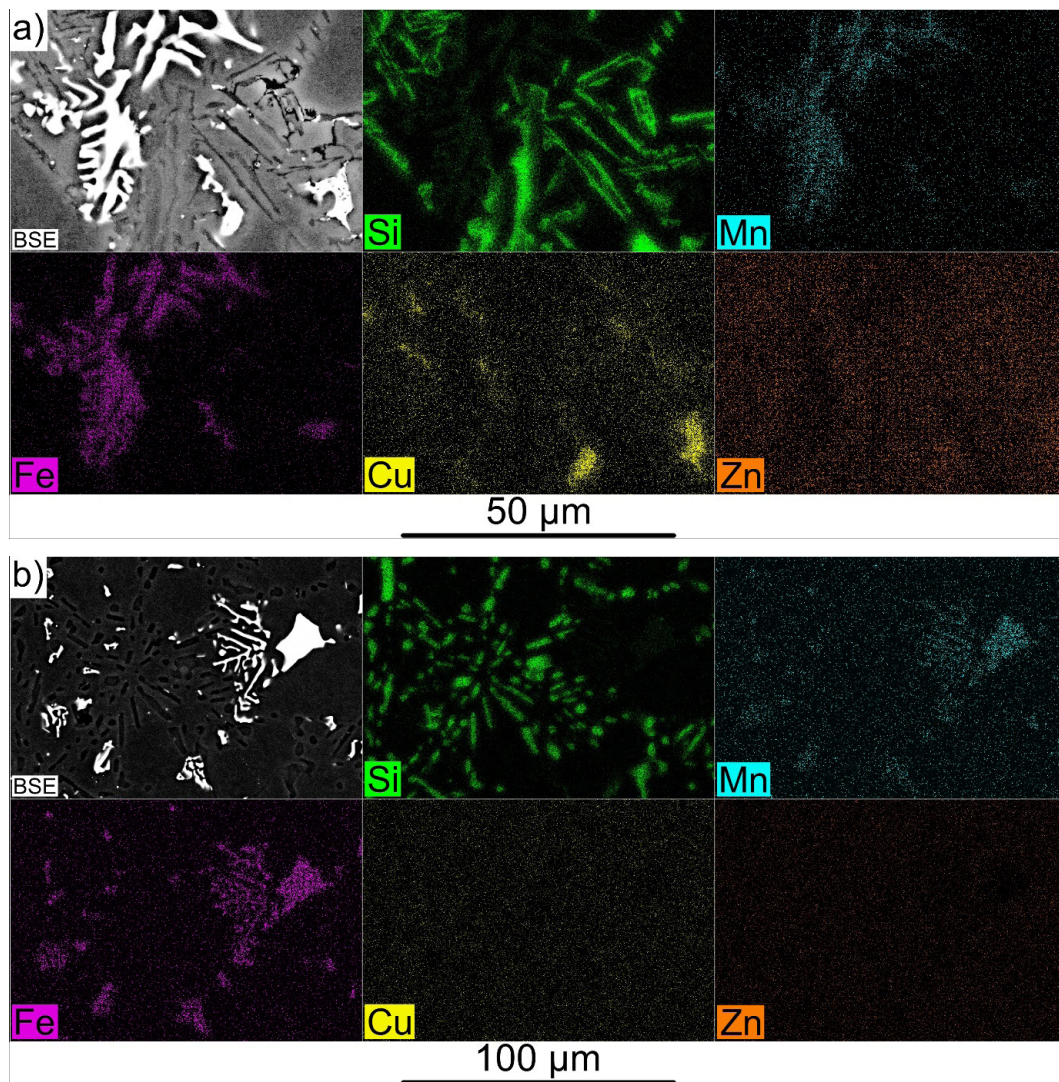
Copper is an important alloying element in this alloy which significantly affects the mechanical properties of this alloy. Therefore, we also measured the composition of the regions of primary α_{Al} phase. These results are also presented in Table 2. Results indicates that the content of copper and zinc are higher in the case of the T6 and Sr-T6 samples compared to all other.

Higer concentration of copper is a consequence of solution heat treatment at 520 °C which enables that all the copper containing phase Al_2Cu which is present in the alloy after the solidification is dissolved in solid solution. This is presented in Figure 4 which shows EDS mappings where we can still observe the Al_2Cu phase in sample T5 – Figure 4a, while on the other hand, no Al_2Cu phase is observed in the sample T6 presented in Figure 4b. During aging this soluble copper enables the formation precipitates which leads to a higher microhardness of these samples. In addition to this the content of zinc was

Tabela 2. Mikrotrdota po Vickersu in kemijska sestava v območjih primarne faze α_{Al} v mas. %, določena z mikroanalizo EDS pri 20 kV za aluminijevo zlitino AlSi9Cu3 v nemodificiranem litem stanju ter nemodificiranem in modificiranem (Sr) stanju po toplotni obdelavi T5 in T6.

Table 2. Vickers microhardness and chemical composition in wt. % of the regions of primary α_{Al} phase determined by EDS microanalysis at 20 kV for an aluminium alloy AlSi9Cu3 in unmodified as-cast state and unmodified and modified (Sr) state after the T5 and T6 heat treatment.

	HV0.01	Al	Si	Cu	Zn
Lito / As cast	77	96,8	1,4	0,7	1,0
T5	76	96,5	1,5	0,9	1,1
Sr-T5	86	96,7	1,6	0,7	1,0
T6	94	95,1	0,9	2,5	1,5
Sr-T6	98	95,1	1,0	2,6	1,4



Slika 4. Posnetki povratno sipanih elektronov (BSE) in porazdelitve Si, Mn, Fe, Cu in Zn v vzorcu T5 a) in vzorcu T6 b) na osnovi EDS.

Figure 4. Backscattered electron images (BSE) and EDS mappings of Si, Mn, Fe, Cu and Zn in sample T5 a) and sample T6 b).

porazdelitev zlitinskih elementov na osnovi EDS, kjer lahko še vedno opazimo fazo Al_2Cu v vzorcu T5 (Slika 4a), medtem ko v vzorcu T6 faza Al_2Cu ni več prisotna (Slika 4b). Med staranjem se baker raztopljen v trdni raztopini izloča, kar vodi do večje

also found to be higher in the samples T6 and Sr-T6. We presume that this fact is simply the consequence of the solution heat treatment performed in these two samples. It is well known that during nonequilibrium solidification zinc segregates to the last

mikrotrdote teh vzorcev. Poleg tega je bila ugotovljena tudi večja vsebnost cinka v vzorcih T6 in Sr-T6. Predvidevamo, da je to posledica raztopnega žarjenja, ki je potekalo pri teh dveh vzorcih. Znano je, da je zaradi neravnotežnega strjevanja koncentracija cinka zaradi porazdelitvenega koeficienta v zadnjih strjenih delih primarne faze največja. Med toplotno obdelavo se razlike v koncentraciji cinka izenačijo, kar pomeni, da se na robovih dendritov koncentracija cinka zmanjša, medtem ko se v osrednjih predelih, kjer smo pretežno izvajali analize, koncentracija poveča. Sicer pa menimo, da cink ne prispeva bistveno k povečanju mikrotrdote.

Rezultati v tabeli 2 prav tako kažejo, da dodatek stroncija v zlitino AlSi9Cu3 vpliva na mikrotrdote pri obeh postopkih toplotne obdelave T5 in T6. Trdota je očitno višja v primerih dodanega stroncija. Ena od razlag za to povečanje je morebitna topnost stroncija v trdni raztopini aluminija. Glede na reference [9,10] ima stroncij najverjetneje zelo majhno topnost v trdni raztopini aluminija. Poleg tega tudi teoretična razlaga mehanizma modifikacije predvideva omejeno topnost v trdni raztopini aluminija [11]. Tudi ta zelo majhna topnost bi lahko povečala trdoto, saj je stroncij z atomskim polmerom 0,2151 nm veliko večji od aluminija, ki ima polmer 0,1432 nm [12].

4 Zaključki

Raziskovali smo vpliv modifikacije in postopkov toplotne obdelave na mikrostrukturo in mikrotrdoto zlitine AlSi9Cu3.

Rezultati kažejo, da ima mikrostruktura lite in toplotno obdelane zlitine T5 velike dendrite primarnega α_{Al} , večinoma obdane z binarnim eutektikom ($\alpha_{Al} + \beta_{Si}$) in fazo β_{Si} v obliki velikih lamel. Mikrostruktura zlitine AlSi9Cu3 z dodatkom Sr po toplotni

solidified parts of the primary phase due to its partitioning coefficient. During solution heat treatment segregation gets equalized which means that in the edges of dendrites the concentration of zinc decreases while in the central regions, where we predominately performed analysis, concentration increases. However, our opinion is that zinc does not significantly contribute to the increase of microhardness.

Results in Table 2 also indicates that the addition of strontium into an alloy AlSi9Cu3 affects the microhardness results in both T5 and T6 heat treatment processes. Hardness is apparently higher in the cases of added strontium. One explanation for this increase is possible solubility of strontium in solid solution of aluminium. According to references [9,10] strontium has most probably very small solubility in solid solution of aluminium. In addition, theoretical clarification of the mechanism of modification also predicts a limited solubility of strontium in solid solution of aluminium [11]. Even this very small solubility could increase the hardness since strontium with atomic radii of 0.2151 nm is much larger compared to aluminium with 0.1432 nm [12].

4 Conclusions

The influence of the modification and the heat treatment process on the microstructure and microhardness of the AlSi9Cu3 alloy was investigated.

The results show that the microstructure of the as-cast and T5 heat treated alloy has large dendrites of primary α_{Al} , mostly surrounded by binary eutectic ($\alpha_{Al} + \beta_{Si}$), with the β_{Si} phase in the form of large lamellae. The microstructure of the AlSi9Cu3 alloy with Sr addition after heat treatment T5 shows a fine modified eutectic without lamellar

obdelavi T5 kaže droben modificiran eutektik brez velikih lamel β_{Si} . Mikrostruktura nemodificirane in Sr-modificirane zlitine AlSi9Cu3 po toplotno obdelavi T6 kaže podobno mikrostrukturo s silicijem v obliki večjih sferičnih delcev. Mikrotrdota osnove α_{Al} v nemodificirani zlitini se po toplotni obdelavi T5 ne poveča v primerjavi z litim stanjem. Vendar pa ima zlitina, modificirana s Sr, bistveno večjo mikrotrdoto matrice α_{Al} po T5 kot nemodificirana zlitina po T5. Še višje trdote so bile ugotovljene pri nemodificiranih in modificiranih toplotno obdelanih zlitinah T6 in so posledica višje vsebnosti bakra, ki smo jo zaznali z mikroanalizo EDS. Višja mikrotrdota, opažena pri modificiranih zlitinah s Sr pri istem postopku toplotne obdelave, je najverjetnejše posledica zelo nizke topnosti Sr v α_{Al} .

β_{Si} . The microstructure of the unmodified and Sr-modified AlSi9Cu3 alloy after T6 shows a similar microstructure with silicon in the form of larger spherical particles. The microhardness of the α_{Al} matrix in the unmodified alloy does not increase after the T5 heat treatment compared to the as-cast state. However, the alloy modified with Sr has a significantly higher microhardness of the α_{Al} matrix after T5 than the unmodified alloy after T5. Even higher hardnesses were found in unmodified and modified heat-treated T6 alloys and are the result of a higher copper content, which was detected by EDS microanalysis. The higher microhardness observed in Sr-modified alloys in the same heat treatment process could be due to a very low solubility of Sr in α_{Al} .

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