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Vpliv skandija na mikrostrukturo in lastnosti aluminijeve livne zlitine A356

Effect of scandium on the microstructure and properties of the aluminium casting alloy A356

Povzetek

V članku je podan pregled stanja o vplivu skandija na lastnosti aluminijevih livnih zlitin. Prikazana je mikrostruktura predzlitine AlSc2 in mikrostrukture zlitine A356 (AlSi7Mg0,3) v litem stanju in po toplotni obdelavi T6. Predstavljeni so tudi prvi rezultati vpliva majhnega dodatka skandija na trdoto zlitine A356.
Ključne besede: aluminijeva zlitina, skandij, mikrostruktura, fazna analiza, trdota

Abstract

This article gives a short overview regarding the effects of scandium on the properties of aluminium casting alloy. The microstructure of the master alloy AlSc2 and the microstructures of the alloy A356 (AlSi7Mg0,3) in the as-cast condition and after T6 heat treatment are presented. Effects of small additions of Sc on the hardness of the alloy A356 were also evaluated.
Keywords: aluminium alloy, scandium, microstructure, phase analysis, hardness

1 Uvod

Skandij je srebrno-bela prehodna kovina. Pogosto ga uvrščamo, skupaj z itrijem in petnajstimi lantanoidi, v skupino elementov redkih zemelj. Njegov ugodni učinek na aluminijeve zlitine je bil odkrit v sedemdesetih letih prejšnjega stoletja. Zlitine Al-Sc se v glavnem uporabljajo v letalski in vesoljski industriji; uporabljene so bile v sovjetskih vojaških letalih in raketah [1]. Pred nekaj leti so razvili zlitino Al-Mg-Sc, ki se imenuje Scalmalloy. Izdeluje se z litjem na vrteče kolo (angl. melt spinning), pri katerem se doseže hitro strjevanje. Nato se trakovi toplo iztiskajo ter na koncu toplotno obdelajo. Zlitina ima odlične

1 Introduction

Scandium is a silvery-white transition metal. It is often classified as a rare earth element (REE), together with yttrium and the fifteen lanthanides. The positive effects on aluminium alloys were discovered in the 1970's. The main application of scandium is in aluminium-scandium alloys for selected aerospace industry components. Initially, they were used in the Soviet military aircraft and missiles [1]. A few years ago, an Al-Mg-Sc alloy, called Scalmalloy, has been developed. It is produced by melt spinning, consolidated by warm extrusion and finally heat treated. It has excellent mechanical properties and corrosion resistance. The trdnostne in korozijske lastnosti. V zadnjem času se deli iz te zlitine izdelujejo tudi z različnimi dodajalnimi tehnologijami, kot je med drugim tudi selektivno lasersko taljenje [2]. Toda ker je letna proizvodnja skandija le okoli deset ton, je težko pričakovati, da bi lahko izdelali velike količine te zlitine. Poleg tega je skandij tudi zelo drag [1].

Uporaba skandija v livnih aluminijevih zlitinah je zelo redka. Pri dosedanjih raziskavah so ugotovili, da več kot 0,4 mas. % Sc lahko močno udrobni kristalna zrna v zlitinah Al-Mg [3]. Muhammad in sodelavci [4] so poročali, da lahko dodatek do 0,4 mas. % Sc zlitini A357 zmanjša velikost kristalnih zrn za 80 %, medtem ko se natezna trdnost in trdota povečata za 28 % in 19 %. Hkrati se poveča tudi razteznost za kar 165 %. Xu in sodelavci [5] so odkrili, da 0,5 mas. % Sc bistveno udrobni mikrostrukturo in oplemeniti evtektični silicij. Pretvorba lamel v vlakna omogoči sferoidizacijo evtektskega silicija pri toplotni obdelavi. Izboljšanje mehanskih lastnosti je izviralo iz oplemenitenja evtektskega silicija in izločanja disperzoidov Al3(Sc, Zr).

V gnetnih aluminijevih zlitinah tvori skandij disperzoide, ki preprečijo rast kristalnih zrn med rekristalizacijo in zagotovijo drobna podzrna, kar prispeva k večji trdnosti tako pri sobni temperaturi kot tudi pri povišanih temperaturah. Omogoča tudi superplastičnost številnih aluminijevih zlitin [6]. V livnih zlitinah pa lahko skandij povzroči udrobnitev kristalnih zrn, oplemenitenje evtektskega silicija ter tudi nastanek disperzoidov, ki lahko povečajo trdnost pri povišanih temperaturah. Toda zaradi interakcije skandija z zlitinskimi elementi, ki so v livnih zlitinah praviloma v večjih koncentracijah kot v gnetnih, se lahko pojavijo tudi nezaželeni stranski učinki, ki pa še niso temeljito raziskani. Cilj tega prispevka je raziskati vpliv skandija na mikrostrukturo Al-zlitine A356 pri litju

parts from this alloy have also been produced by additive manufacturing technologies [2]. Since the annual world production of scandium is not more than ten tonnes, it is hard to expect large quantities of this alloy. Also, scandium is very expensive [1].

The application of Sc in the cast Al-alloys is very rare. The addition of more than 0.4% (mass fraction) Sc can cause a remarkable grain refining effect in Al-Mg alloys [3]. Muhammad et al. [4] reported that the addition of up to 0.4% (mass fraction) Sc to A357 alloy decreased the grain size by 80% while ultimate tensile strength and hardness are increased by 28% and 19%, respectively. Moreover, along with the growth in strength, elongation to failure is also increased up to 165%. Xu et al. [5] found that 0.5% Sc addition could refine the microstructure significantly and modify the morphology of eutectic Si from platelike to fibrous, which promotes the spheroidization of eutectic Si during heat treatment. The improvement of mechanical properties was attributed to microstructural refinement, particularly the modification of eutectic Si and precipitation of nanoscale Al3(Sc, Zr) dispersoids.

In the wrought alloys, scandium forms dispersoids that prevent grain growth during recrystallization and provide fine subgrain structure, which provides low-temperature and high-temperature strength. Scandium also allows the superplasticity of many aluminium alloys [6]. In the casting alloys, scandium can cause grain refinement, modification of the eutectic silicon, and also the formation of dispersoids, which can increase the high-temperature strength. However, due to the interaction of scandium with alloying elements, which are present at higher levels than in the wrought alloys, several undesired effects can occur, which have not yet been examined in detail. The main goal of this article is to study the v bakreno kokilo, kjer se dosežejo večje ohlajevalne hitrosti.

2 Eksperimentalno delo

Raziskali smo osnovno zlitino A356 (AlSi7Mg0,3) in zlitino z dodatkom 0,4 % Sc (tabela 1). Skandij smo dodali s predzlitino AlSc2. Da bi zlitina s Sc vsebovala podoben delež silicija in magnezija kot osnovna zlitina, smo ji dodali ustrezni količini AlSi20 in tehnično čistega magnezija.

Tabela 1: Kemijska sestava preiskanih zlitin

Table 1: The chemical compositions of the investigated alloys

Al	Si	Mg	Fe	Sc
92,11	7,25	0,47	0,17	-
91,71	7,46	0,31	0,11	0,40

Talino s temperaturo 750 ºC smo ulili v bakreno kokilo pri sobni temperaturi. Livna votlina je imela takšno obliko, da smo dobili valjčke s premeri 2,5; 4; 6; 10 in 16 mm. Izvedli smo toplotno obdelavo T6 (topilno žarjenje 8 ur pri 536 ºC, gašenje v vodi ter staranje 3 ure pri 156 ºC).

Vzorce smo metalografsko pripravili in opazovali na svetlobnem mikroskopu (SM) Nikon Neophot 300, vrstičnem elektronskem mikroskopu Sirion 300 NC, FEI, kemično sestavo faz smo ugotavljali z energijskodisperzijsko (EDS) analizo rentgenskih žarkov (INCA 350, Oxford Analytical). Izmerili smo tudi trdoto vseh vzorcev (HV 1) na prečnem prerezu valjčkov s premerom 6 mm z merilnikom mikrotrdote Zwick 3212.

Rentgensko fazno analizo (XRD) smo izvedli v sinhrotronu Elettra (Sincrotrone Elettra, Trst, Italija). Poskuse smo izvajali na končni postaji XRD1, valovna dolžina

scandium effect on the microstructure of the aluminium alloy A356 during casting into a copper mould, where higher cooling rates can be achieved.

2 Experimental work

The basic A356 alloy A356 (AlSi7Mg0,3) and the alloy with 0.4% Sc were investigated, Table 1. Scandium has been added in the form of the $AlSc_2$ master alloy. Adequate amounts of $AlSi_20$ and technically pure Mg were also added in order to retain approximately the same amounts of Si and Mg in the modified alloy

The melt with a temperature of 750 ºC was cast into a copper mould at room temperature. The shape of the mould enabled us to obtain cylinders with diameters of 2.5, 4, 6, 10 and 16 mm. The samples were heat treated by T6 treatment (solution annealing at 536 ºC for 8 h, water quenching and artificial aging at 156 ºC for 3 h).

The samples were metallographically prepared. They were investigated using a light microscope (LM) Nikon Neophot 300, scanning electron microscope Sirion 300 NC, FEI, the chemical composition of phases were determined using energy dispersive X-ray spectroscopy EDS (INCA 350, Oxford Analytical). The Vickers hardness HV 1 of the samples was tested on the lateral cross-sections of the cylinders with a diameter of 6 mm (microhardness tester Zwick 3212).

The X-ray phase analyses (XRD) were carried out at synchrotron Elettra (Sincrotrone Elettra, Trieste, Italy). The experiments were performed at the beamline XRD1. The wavelength of the X-rays was 0.1 nm. The X-rays were collected by a detector Dectris Pilatus 2M. Afterwards, the results were transformed from 2D images to X-ray patterns intensity vs. 2Θ using a uporabljenih rentgenskih žarkov je bila 0,1 nm. Rentgenske žarke smo zajemali z detektorjem Dectris Pilatus 2M. Rezultate smo pretvorili iz 2D-posnetkov v diagrame intenziteta – 2*Θ* s programom Fit2D. Na osnovi teh diagramov smo s pdf-karticami (pdf je kratica za powder diffraction file) identificirali faze v predzlitini $AlSc_2$ ter v stanjih T6 obeh zlitin.

Ravnotežne faze in strjevanje skladno s Scheilovim modelom smo izračunali s programom Thermo-Calc. Pri tem smo uporabili banko podatkov TCAL4.

3 Rezultati in diskusija

Slika 1 prikazuje mikrostrukturo predzlitine $AlSc_2$. V predzlitini $AlSc_2$ je skandij navzoč v obliki delcev Al_3Sc, ki imajo praviloma kockasto obliko, medtem ko so nekateri dendritne oblike. Z rentgensko fazno analizo smo ugotovili, da ima *α*-Al mrežno konstanto *a* = 0,40479 nm, ter Al_3Sc *a* = 0,40980 nm, kar je zelo blizu vrednostim za čisti Al (številka pdf-kartice 04-0787) in Al_3Sc (števila pdf-kartice: 000-17-0412). Mrežni konstanti obeh faz sta podobni, zato je lahko faza Al3Sc koherenta z *α*-Al, ko so delci majhni, pri večjih velikostih pa postane fazna meja nekoherentna [7].

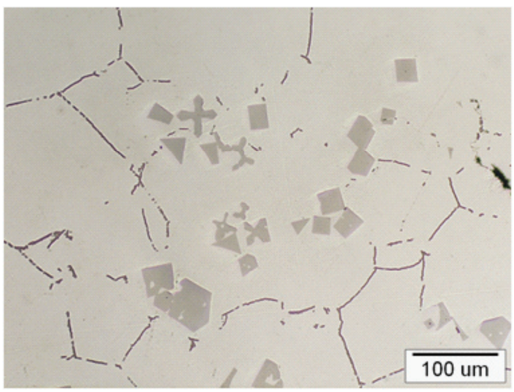
Slika 2 prikazuje mikrostrukturi zlitin v litem stanju, v valjčku s premerom 6 mm. V mikrostrukturi prevladujejo dendriti trdne raztopine *α*-Al, v meddendritnem prostoru pa je evtektik (*α*-Al + *β*-Si). V meddendritnem prostoru je bila tudi faza bogata z železom in silicijem, najverjetneje Al_3FeSi. Zaradi sorazmerno hitrega strjevanja sta tako *α*-Al kot tudi evtektični silicij zelo drobna, pa tudi razlika med obema mikrostrukturama je zelo majhna.

software Fit2D. These X-ray patterns were used to identify phases in the $AlSc_2$ master alloy, and both alloys in T6-state by using pdf cards (pdf is an acronym for powder diffraction file).

The equilibrium phases and solidification according to the Scheil model were calculated using software Thermo-Calc, and the thermodynamic database TCAL4.

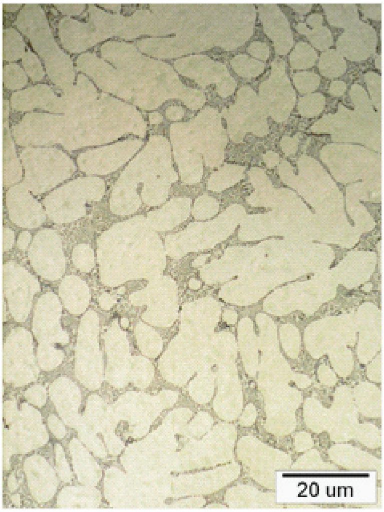
3 Results and Discussion

Figure 1 shows the microstructure of the master alloy $AlSc_2$. In the master alloy AlSc2, scandium is mainly present in the form of Al_3Sc-particles, having a cuboidal shape predominantly, while some have a dendritic morphology. XRD showed that the lattice constant of *α*-Al was *a* = 0.40479 nm, and that of Al_3Sc was *a* = 0.40980 nm. These values were close to values of pure Al (pdf 04-0787) and Al_3Sc (pdf 000-17-0412). The lattice constants of both phases are very similar. Thus, the interface between Al_3Sc and *α*-Al can be coherent when the particles are small but can become incoherent when the size of Al_3Sc particles increases [7].

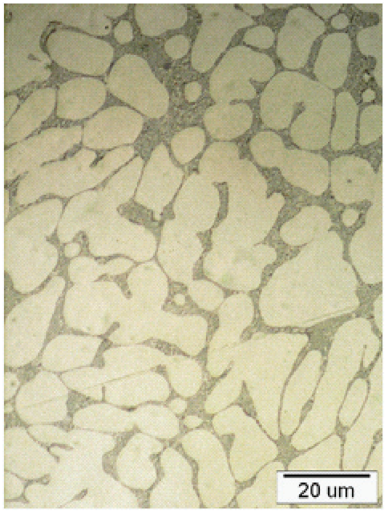


Slika 1: Mikrostruktura predzlitine $AlSc_2$ (SM)

Figure 1: Microstructure of the master alloy $AlSc_2$ (LM)



a) A356



b) A356 + 0,4 % Sc

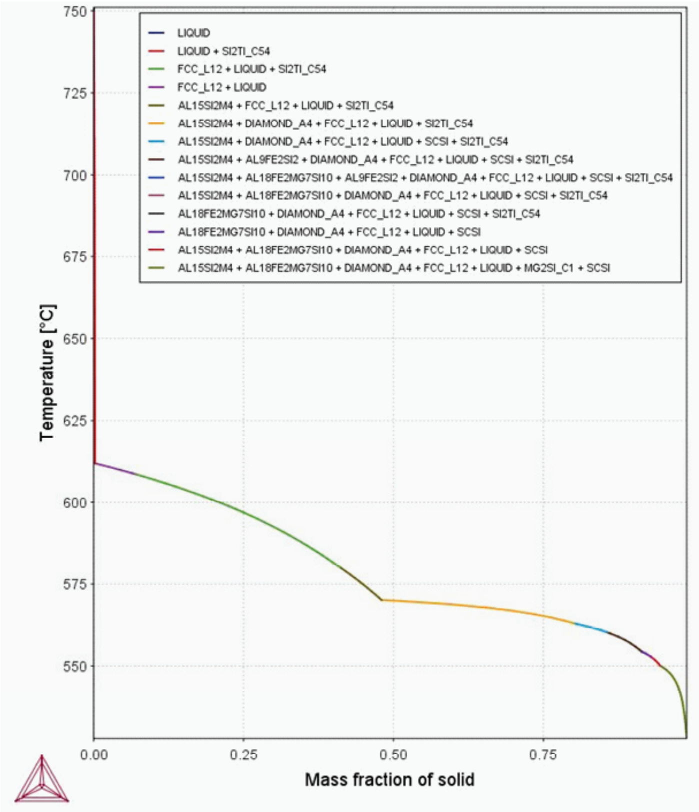
Slika 2: Primerjava mikrostruktur a) osnovne zlitine in b) zlitine z dodatkom 0,4 % Sc v litem stanju v valjčku s premerom 6 mm (SM)

Figure 2: A comparison between micro-structures of the a) basic A356 alloy and b) the alloy with 0.4 % Sc in the as-cast condition, in the cylinder with a diameter of 6 mm (LM)

Obe zlitini sta večkomponentni, zato strjevanje poteka preko številnih reakcij. Na sliki 3 so rezultati izračuna strjevanja po Scheilovem modelu za zlitini A356 z 0,4 % Sc. Ta pokaže, da se strjevanje začne že pri 750 ºC z izločanjem faze Si2Ti. Te faze je sicer le 0,2 mas. %, tako da je v mikrostrukturi nismo odkrili. Faza α-Al začne nastajati pri 612 ºC. Pri približno 570 ºC nastopi kvatrna evtektična reakcija L → α-Al + β-Si + Si_2Ti + AlSiMnFe. Deleža Si_2Ti in AlSiMnFe sta zelo majhna, tako da je mikrostruktura tega evtektika skoraj identična mikrostrukturi binarnega evtektika (α-Al + β-Si). Pri nižjih temperaturah se v okviru večfaznih zlogov izloča tudi faza ScSi. Strjevanje se konča pri približno 525 ºC. Lu in Zhang [8] sta pri termodinamski raziskavi sistema Al-Si-Mg-Sc ugotovila, da se v zlitinah v aluminijevem kotu ne pojavlja faza ScSi, temveč ternarna vmesna spojina $AlSc_2Si_2$, ki pa je ni v banki podatkov TCAL4. Tako naši rezultati niso

Figure 2 shows the microstructure in the as-cast condition, in the cylinder with 6 mm in diameter. The dendrites of α-Al prevail in the microstructure. In the interdendritic region is the eutectic (α-Al + β-Si). In the interdendritic spaces, also a phase rich in Fe was present, probably Al_3FeSi. The rather fast solidification resulted in very fine dendrites of α-Al as well as fine eutectic silicon. In addition, the differences between both microstructures are rather small.

Both alloys were multicomponent. Therefore, solidification took place over several reactions. Figure 3 shows the crystallization sequence according to the Scheil model for the alloy A356 + 0.4 % Sc. The solidification starts at 750 ºC with the formation of Si_2Ti phase, which forms when the alloy has a very small fraction of Ti. The fraction of this phase should be only 0.2%, and we were not able to find it in the microstructure. The α-Al starts to form at



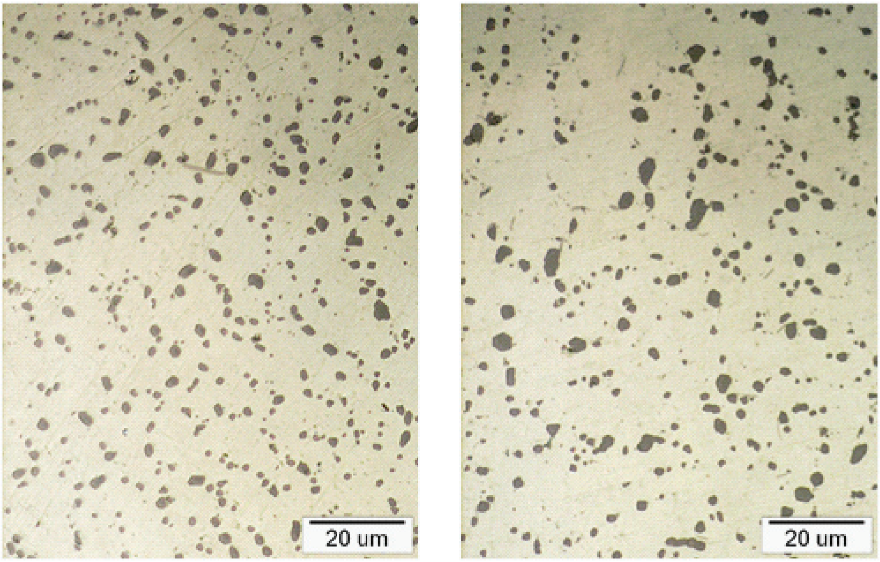
Slika 3: Reakcije pri strjevanju izračunane s Scheilovim modelom (program Thermo-Calc)

Figure 3: The reactions by solidification, calculated by the Scheil model (Thermo-Calc)

povsem pravilni, vendar pa je primerjava rezultati Luja in Zhanga [8] razkrila, da so razlike v temperaturah, pri katerih se pojavi s skandijem bogata faza, zelo majhne.

Slika 4 prikazuje mikrostrukturi po toplotni obdelavi T6. Osnova je α-Al, v kateri so delci β-Si in še nekaterih drugih faz. Med osemurnim topilnim žarjenjem pri 536 ºC se je močno spremenila oblika β-Si. Ta sedaj ni več navzoč v heterogenem zlogu z α-Al, temveč so nastali kroglasti delci, ki imajo premer nekaj mikrometrov. Na posnetkih s svetlobnega mikroskopa so delci faze na osnovi AlFeSi komaj opazni (sivi paličasti delci na sliki 4), medtem ko so dobro vidni na elektronskih mikroposnetkih (svetli delci na sliki 5).

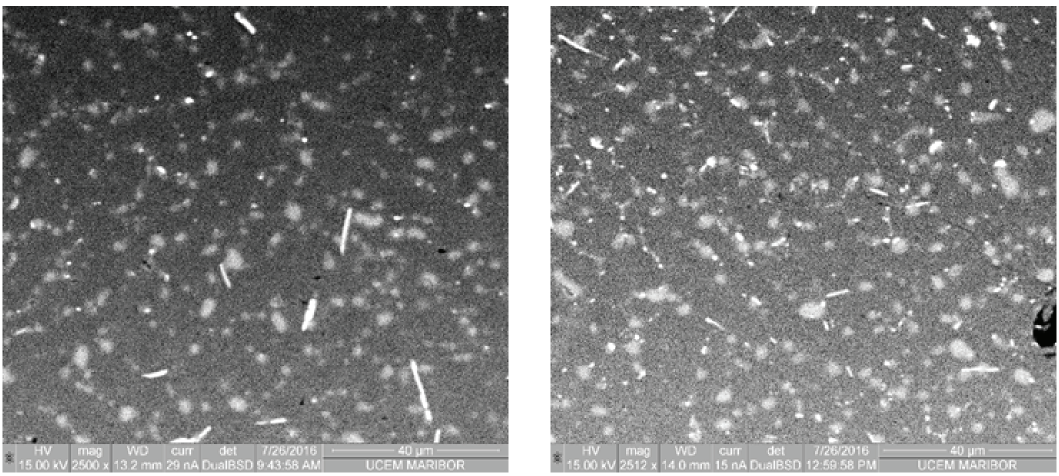
612 ºC. At approximately 570 ºC, initiates the quaternary eutectic reaction L → α-Al + β-Si + Si_2Ti + AlSiMnFe. The fractions of Si_2Ti and AlSiMnFe are very small. Thus the formed microstructure closely resembles the microstructure of the binary eutectic (α-Al + β-Si). At lower temperatures, a scandium-rich phase should form. The Thermo-Calc calculations predict the phase ScSi, which is present as a part of multiphase microstructural constituents. The last melt solidifies at 525 ºC. Recently, have Lu and Zhang [8] carried out a thermodynamic analysis of the quaternary system Al-Si-Mg-Sc. They found out that in the Al-corner a ternary compound $AlSc_2Si_2$ forms and no ScSi. This phase is not included in the



a) A356 b) A356 + 0,4 % Sc

Slika 4: Primerjava mikrostruktur a) osnovne zlitine in b) zlitine z dodatkom 0,4 % Sc v valjčkih s premerom 6 mm po toplotni obdelavi T6 (SM)

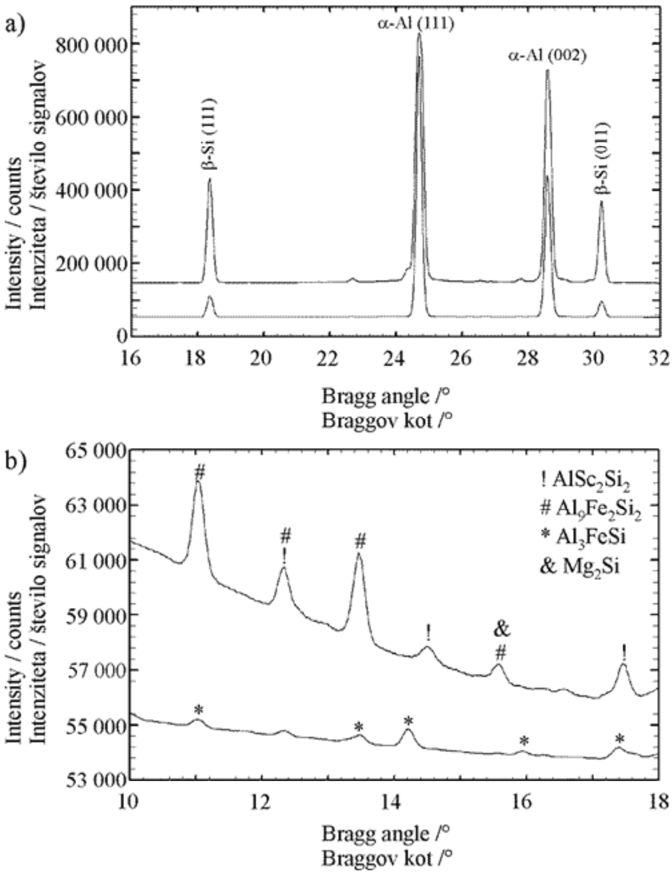
Figure 4: Microstructure comparison of a) the basic alloy and b) the alloy with 0,4% Sc in cylinders with a diameter of 6 mm, in the T6-condition (LM)



a) A356 b) A356 + 0,4 % Sc

Slika 5: Primerjava mikrostruktur a) osnovne zlitine in b) zlitine z dodatkom 0,4 % Sc v valjčkih s premerom 6 mm po toplotni obdelavi T6 (SEM, odbiti elektroni)

Figure 5: Microstructure comparison of a) the basic alloy and b) the alloy with 0,4% Sc in cylinders with a diameter of 6 mm, in the T6-condition (SEM, backscattered electrons)



Slika 6: Difraktograma zlitin A356 in A356 + 0,4 % Sc po toplotni obdelavi T6. a) Prikaz med kotoma 2*Θ* od 16º do 32º, kjer lahko identificiramo α-Al in β-Si, ter b) povečano območje med 10º in 18º, kjer lahko identificiramo fazo Al_3FeSi v zlitini A356, ter faze $AlSc_2Si_2$, $Al_9Fe_2Si_2$ in Mg_2Si v zlitini A356, ki ima 0,4 % Sc.

Figure 6: X-ray diffraction patterns of the alloys A356 and A356 + 0,4 % Sc in the T6-condition. a) The range of 2*Θ* between 16º and 32º, where α-Al and β-Si can be identified, and b) the area between 10º and 18º, where Al_3FeSi in alloy A356, and $AlSc_2Si_2$, $Al_9Fe_2Si_2$ and Mg_2Si in the alloy A356 + 0.4 % Sc can be identified.

Na sliki 6 sta difraktograma obeh zlitin. Slika 6a prikazuje območje med kotoma 2*Θ* 16º in 32º, kjer lahko identificiramo fazi α-Al in β-Si. Opazni so tudi manjši vrhovi, ki pa ne omogočajo zanesljive identifikacije faz. S podrobno analizo ostalih območij difraktograma smo v stanju T6 zlitine A356 identificirali fazo Al_3FeSi. V zlitini A356, ki ima 0,4 % Sc, pa še faze $AlSc_2Si_2$, $Al_9Fe_2Si_2$ in Mg_2Si. Fazi Al_3FeSi in $Al_9Fe_2Si_2$ sta si zelo podobni, saj imata obe monoklinsko kristalno zgradbo. Kristalografski podatki o fazah so zbrani v tabeli 2.

Glede na sliki 4 in 5 in rezultate XRD dodatek Sc spremeni sestavo in mrežne

databank TCAL4. Thus, our results are not completely correct, at least at lower temperatures. However, the comparisons of the results have shown that the differences in the calculated temperatures in the temperature region, where a scandium-rich phase is present, are not significant.

Figure 4 depicts the microstructure after T6 heat treatment. The matrix is α-Al, in which particles of β-Si and some other phases are present. The shape of β-Si particles has considerably changed during solution treatment at 536 ºC for 8h. β-Si is not present as a part of eutectic (α-Al + β-Si) anymore but in the form of mainly spherical

Tabela 2: Rezultati rentgenske fazne analize zlitin v stanju T6

Table 2: The results of the XRD of alloys in the condition T6

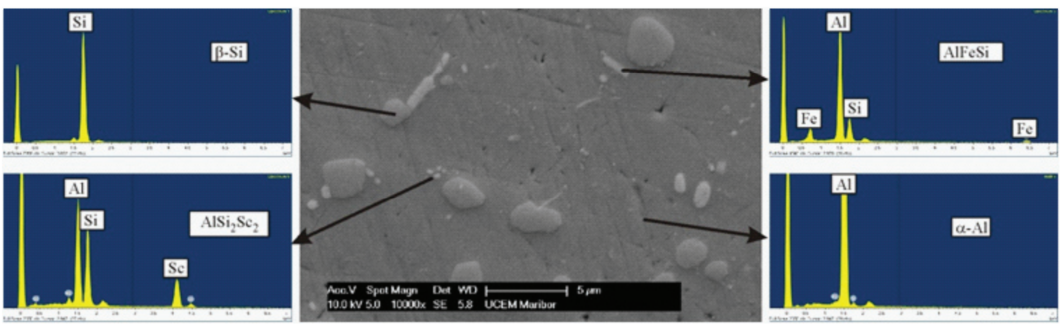
Vzorec	α-Al	β-Si	$AlSc_2Si_2$	Al_3FeSi (α-AlFeSi)	$Al_9Fe_2Si_2$ (α-AlFeSi)
A356T6_2	a = 0,40492	a = 0,54249		*a* = 1,78012 *b* = 1,02516 *c* = 0,88954 *β* = 132,03°	
A356Sc04T6_1	*a* = 0,40486	*a* = 0,54233	*a* = 0, 65977 *b* = 0, 39742		*a* = 2,09031 *b* = 0,62781 *c* = 0,60632 *β* = 89.86°
Referenčni podatki	pdf 04-0787	27-1402	ref. [1]	pdf 20-0032	pdf 54-0376

parametre faze AlFeSi, hkrati pa se zmanjša njena velikost.

Podrobnejša analiza mikrostrukture zlitine A356 + 0,4 % Sc z vrstičnim elektronskim mikroskopom in energijsko-disperzijsko analizo je prikazana na sliki 7. Svetli, podolgovati delci vsebujejo Al, Si in Fe. V njih ni praktično nič Mn, saj je tudi v osnovni zlitini bil v zelo majhni količini. Torej je to gotovo faza $Al_9Fe_2Si_2$ (α-AlSiFe), ki smo jo identificirali tudi z rentgensko fazno analizo. Faza $AlSc_2Si_2$ je navzoča v obliki kroglastih delcev, ki so veliki od nekaj desetink mikrometra do enega mikrometra.

particles. Light and electron micrographs also reveal the presence of a phase based on AlFeSi (Figures 4, 5).

Figure 6 shows the X-ray diffraction patterns of both alloys in T6 condition. Figure 6a illustrates the area between 16º and 32°, where the phases α-Al and β-Si can be identified. There are also smaller peaks present, but they do not allow reliable identification of phases. Careful analysis of other regions revealed the phases Al_3FeSi in A356, and $AlSc_2Si_2$, $Al_9Fe_2Si_2$ and Mg_2Si in A356 + 0.4% Sc. Phases Al_3FeSi and $Al_9Fe_2Si_2$ are very similar since both exhibit



Slika 7: Analiza zlitin A356 + 0,4 Sc v stanju T6 (SEM + EDS)

Figure 7: Analysis of the alloy A356 + 0.4 Sc in the T6-condition.

Izločkov faze Mg_2Si z vrstičnim elektronskim mikroskopom nismo mogli identificirati.

S programom Thermo-Calc smo izračunali tudi ravnotežne faze pri temperaturi topilnega žarjenja. To naj bi bile faze α-Al (92 mol. %), β-Si (6 mol. %), $Al_{15}Si_2(Fe,Mn)_4$ (1,2 mol. %), ter zelo malo faze ScSi. Glede na to, da v banki podatkov ni $AlSc_2Si_2$, njeno mesto nadomešča faza ScSi. V mikrostrukturi pa je zaradi majhne vsebnosti Mn namesto faze $Al_{15}Si_2(Fe,Mn)_4$ navzoča faza $Al_9Fe_2Si_2$.

V tabeli 3 so trdote v litem stanju in po toplotnih obdelavah. Razlike med zlitinama pri premeru 6 mm niso velike. Največje so v stanju T6, morda zaradi nekoliko večje vsebnosti magnezija v osnovni zlitini. Večje razlike bi lahko pričakovali pri večjih premerih, kjer so hitrosti ohlajanja počasnejše. Vsekakor navzočnosti skandija povzroči, da je železova faza bolj drobna, kar bi lahko vplivalo na povečanje duktilnosti zlitine pri nateznem preskusu

Eden izmed ciljev dodajanja skandija je povečanje temperaturne stabilnosti zlitin. Zato je gotovo pomembneje, kako se te zlitine obnašajo pri povišanih temperaturah. To pa je področje raziskav, na katerem bomo v prihodnje intenzivneje raziskovali tovrstne zlitine.

Tabela 3: Vrednosti trdot HV 1 valjčkov s premerom 6 mm v različnih stanjih

Table 3: Hardness HV 1 of the cylinders with a 6 mm diameter in different conditions

Zlitina / Alloy	lito / As-cast	Topilno žarjeno + gašeno / Solution annealed + quenched	T6
A356	84	86	106
A356 + 0,4 % Sc	84	77	90

a monoclinic structure. The crystallographic data are collected in Table 2. Thus the addition of Sc to A356 changes the nature of AlFeSi-phase, and also reduces its size (Figures 4, 5).

The detailed analyses of the microstructure of the alloy A356 + 0.4 % Sc using SEM and EDS is shown in Figure 7. The bright and elongated particles contain Al, Si and Fe. They do not contain any Mn since its amount in our alloy was minor. These particles should then belong to the phase $Al_9Fe_2Si_2$ (α-AlSiFe), which was identified by XRD. The $AlSc_2Si_2$ is present in the form of spherical particles. Their sizes range between few tenths of micrometre and one micrometre. The Mg_2Si precipitates have not been identified using SEM.

The equilibrium phases at a temperature of the solution annealing were calculated using Thermo-Calc. These phases should be α-Al (92 mol. %), β-Si (6 mol. %), $Al_{15}Si_2(Fe,Mn)_4$ (1.2 mol. %), and a tiny amount of ScSi. Since the phase $AlSc_2Si_2$ is not in TCAL4, its place is occupied by ScSi. Due to a tiny amount of Mn, the Mn-rich phase was not detected in the microstructure. Instead of it, the phase $Al_9Fe_2Si_2$ appeared.

Table 3 illustrates the hardness in the as-cast and heat treated conditions. Differences in the samples having a diameter of 6 mm are not large. The greatest are in the condition T6. Higher differences could be expected by larger diameters when the cooling rates are much lower. The presence of Sc caused the formation of smaller particles of the Fe-rich phase, which should have a beneficial effect on the ductility of the alloy.

One of the goals by the addition of scandium is to increase temperature stability of the alloys. Therefore, it is more important how these alloys behave at higher

4 Sklepi

Po podatkih iz literature lahko majhen dodatek skandija lahko v aluminijevih zlitinah udrobni kristalna zrna, zmanjša razdalje med dendritnimi vejami, hkrati pa se oplemeniti evtektični silicij. Torej ima skandij večkratni pozitivni učinek, kar je izrazito pri majhnih ohlajevalnih hitrostih. Pri naših preskusih, ko smo zlitino lili v bakreno kokilo, razlike niso bile zelo velike. Trenutno je svetovno proizvodnja majhna in težavna, zato je sorazmerno drag. Pogosto se delno nadomešča z drugimi elementi, predvsem s cirkonijem in itrijem.

V tem delu so predstavljeni tudi začetni rezultati učinka na mikrostrukturo in trdoto zlitine A356, ki je bila ulita v bakreno kokilo. Pri sorazmerno velikih ohlajevalnih hitrostih je vpliv dodatka Sc sorazmerno majhen. Najbolj je bilo očitno zmanjšanje velikosti z železom bogate faze. V zlitini smo identificirali fazo $AlSc_2Si_2$, ki se pojavlja v zlitinah Al-Si namesto faze Al_3Si. Zato bo potrebno to fazo vključiti v banko termodinamskih podatkov, da bodo rezultati termodinamskih izračunov ustreznejši.

Podoben učinek skandija na zlitino A356 kot je bil ugotovljen v tej raziskavi, lahko pričakujemo tudi v primeru tlačnega litja. Ta na mikrostrukturo in lastnosti ne vpliva v zelo veliki meri, vendar pa bo bolj bistveno ugotoviti, kako Sc vpliva na povečanje temperaturne stabilnosti zlitin.

5 Zahvala

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Izvedba XRD analiz je bila omogočena z odprtim dostopom do sinhrotrona Electra,

temperatures. This is the area, where we intend to continue research in the future.

4 Conclusions

A small addition of scandium can refine the grain sizes, decrease the distances between the secondary dendrite arms, and modify the eutectic silicon in aluminium alloys. Thus, scandium can have multiple effects. At the moment, the world production of scandium is very small, and consequently, its price is very high. Zirconium and yttrium frequently replaced it.

In this work, we present our initial results regarding the effect of scandium on the microstructure and hardness fo the alloy A356, which has been cast into a copper mould. At higher cooling rates, the effect of scandium is rather small. It mainly decreases the size of iron-rich phase in all conditions. In the investigated alloy, we identify the phase $AlSc_2Si_2$, which is present in Al-Si alloy instead of Al3Si. Therefore, $AlSc_2Si_2$ should be incorporated into thermodynamic databases, in order to improve the reliability of thermodynamic modelling in Al-Si alloys.

A similar effect of scandium as it was detected in this investigation can be expected by high-pressure die casting. Its effect on microstructure and properties is not very large. However, it will be more important to determine the effect of Sc on increase of the temperature stability of Al-Si alloys.

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