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Preiskava reciklirane zlitine AlSi9Cu3(Fe)

Investigation of Recycled AlSi9Cu3(Fe) Alloy

Izvleček

Zaradi zakonodaje Evropske unije in težav, s katerimi se v zadnjem času soočajo proizvajalci ulitkov, se vse več pozornosti namenja surovinam. Surovine se nahajajo na začetku vseh industrijskih vrednostnih verig. Te kritične (CRM) in strateške surovine (SRM) so pogosto nepogrešljive za številne strateške sektorje, vključno z obnovljivimi viri energije, digitalno industrijo, vesoljskim in obrambnim sektorjem ter zdravstvenim sektorjem, ki so vsi povezani s kovinsko industrijo. Aluminij in njegove zlitine so pomembne kritične in strateške surovine. Standardna aluminijeva zlitina AlSi9Cu3(Fe) (EN AC 46000) se pogosto uporablja v avtomobilski industriji in sektorju prevoza. Glavne prednosti zlitine AlSi9Cu3(Fe) so vrhunske mehanske lastnosti, kot so trdnost in trdota ter raztezek in odpornost proti koroziji.

Funkcionalne in uporabne lastnosti aluminijevih zlitin so odvisne od kemijske sestave, obdelave taline, hitrosti strjevanja, postopka litja in morebitne toplotne obdelave. Večina jih je odvisna od razvoja mikrostrukture. V tem članku je raziskan potencial recikliranja zlitine AlSi9Cu3(Fe) z uporabo popolnoma povratnega materiala brez dodatkov ali prečiščevanja. Prisotnost širokega spektra legirnih elementov zlitin AlSi9Cu3(Fe) kaže na razvoj α-$Al_{15}Si_2M_4$ (M= Cr, Fe, Mn, Mo), β-AlFeSi, Al_2Cu in še bolj kompleksnih, kot je $AlCu_2Mg_9Si_7$, z uporabo teoretičnega modeliranja. Kompleksna pot strjevanja kaže na primarni aluminij α_{Al}, evtektično fazo (α_{Al} + β_{Si}), intermetalno fazo na železovi osnovi v obliki AlFeSi in morfologijo »kitajske pisave«, intermetalno fazo na osnovi magnezija in bakra, kot sta Mg_2Si in Al_2Cu, ter kompleksne intermetalne faze, kot sta $AlMg_3FeSi_2$ in $Al_5Mg_8Si_2Cu_2$. Termodinamični učinki interakcije elementov med strjevanjem pomembno vplivajo na potek in način strjevanja. Čeprav preučevani vzorci ohranijo visoko natezno trdnost in raztezek, rahlo poslabšanje kemijske sestave in s tem termodinamičnega učinka pomembno vplivata na razvoj mikrostrukture. Kljub degeneraciji kemijske sestave je bila dobljena mikrostruktura pravilna in je zato upravičeno dosegla odlične mehanske lastnosti. Zato je na podlagi preučevanja termodinamičnih in mikrostrukturnih lastnosti sekundarne zlitine AlSi9Cu3(Fe) navedeno, da je surovina kakovosten polnilni material z dobrim potencialom za uporabo in recikliranje.

Ključne besede: zlitina AlSi9Cu3(Fe), strjevanje, termodinamika, mikrostruktura

Abstract

Due to European Union legislative and recently the difficulties faced by casting manufacturers, more and more attention is focused on raw materials. Raw materials are found at the beginning of all industrial value chains. These critical (CRMs) and strategic raw materials (SRMs) are often indispensable inputs for a wide set of strategic sectors including renewable energy, the digital industry, the space and defence sectors, health sector all connected to the metal industry. Aluminium and its alloys plays an important CRMs and SRMs. Standard aluminium alloy AlSi9Cu3(Fe) (EN AC 46000) is widely used in the automotive and transport industry. High mechanical properties such as strength and hardness, as well as elongation and corrosion resistance are the main advantages of AlSi9Cu3(Fe) alloy.

The functional and useful properties of aluminium cast alloys are dependent from the chemical composition, melt treatment, solidification rate, casting process and potential heat treatment. Most of them are conditioned by the microstructural development. This paper investigates the recycling potential of AlSi9Cu3(Fe) alloy using completely return material without any additions or refining. The presence of wide range of alloying elements AlSi9Cu3(Fe) alloys indicates development α-$Al_{15}Si_2M_4$ (M= Cr, Fe, Mn, Mo), β-Al_5FeSi, Al_2Cu and even more complex one such as $Al_3Cu_2Mg_9Si_7$ using theoretical modelling. Complex solidification path indicates primary aluminium α_{Al}, eutectic phase $\alpha_{Al}+\beta_{Si}$, intermetallic phase on the iron base in Al_5FeSi and "Chinese script" morphology, intermetallic phase on the magnesium and copper base such as Mg_2Si and Al_2Cu, and complex intermetallic such as $Al_8Mg_3FeSi_2$ and $Al_5Mg_8Si_2Cu_2$ phases. Thermodynamic effects of elements interaction during solidification sequence significantly influence on solidification path and manner. Although the investigated samples maintain high tensile strength and elongation, slight degradation in chemical composition and therefore in thermodynamic effect, significantly influence on microstructure development. In despite of chemical composition degeneration, obtained microstructure was correct and therefore justified achieved high mechanical properties. Therefore, on the base of thermodynamic and microstructural investigation of the secondary AlSi9Cu3(Fe) alloy indicated raw material as a quality charge material with good application and recycling potential.

Keywords: recycling potential, AlSi9Cu3(Fe) alloy, solidification, thermodynamics, microstructure

1 Uvod

Ogljični odtis evropskega primarnega proizvodnega procesa znaša 6,8 kg emisij CO_2 v primerjavi s svetovnim povprečjem 16,1 kg CO_2 na kg proizvedenega aluminija [1]. Surovine veljajo za izvor vseh industrijskih vrednostnih verig. Te kritične surovine (CRM) so nepogrešljiv vhodni material za strateške sektorje, kot so obnovljivi viri energije digitalna industrija, vesoljski in obrambni sektor ter zdravstveni sektor, ki so večinoma povezani s kovinsko industrijo. Pridobivanje in obdelava kritičnih surovin lahko, odvisno od uporabljenih metod in postopkov, negativno vplivata na okolje in družbo. Z najpomembnejšimi

1 Introduction

The carbon footprint of Europe's primary production process is 6,8 kg of CO_2 emissions compared to the global average of 16,1 kg CO_2 per kg of aluminium produced [1]. Raw materials are considered as an origin of all industrial value chains. These critical raw materials (CRMs) represent an indispensable input for a strategic sector such as renewable energy, the digital industry, the space and defence sectors and the health sector, most of them connected to metal industry. Extraction and processing of CRMs can have negative environmental impacts, depending on the methods and processes used, as well surovinami, kot so navadne kovine, npr. aluminij, baker, svinec, nikelj, kositer in cink, se trguje na borzah. V zadnjem času razvoj gospodarstev v vzponu in širjenje ključnih omogočitvenih tehnologij narekujeta povpraševanje po surovinah. Proizvajalci se odzivajo na razpoložljivost kritičnih (CRM) in strateških surovin (SRM) ter na nihanja cen z ustvarjanjem zalog, pogajanji o dolgoročnih pogodbah ali varovanjem pred tveganjem cen. V nedavni študiji o kritičnih surovinah za EU iz leta 2023 [3] je predstavljena ocena teh surovin za EU: 70 surovin kandidatk, ki vključujejo 67 posameznih materialov, in tri skupine materialov: deset težkih (HREE) in pet lahkih (LREE) redkih zemeljskih elementov

as social impacts. The most important raw materials like base metals such as aluminium, copper, lead, nickel, tin and zinc are traded on stock exchanges. Recently, development of emerging economies and the diffusion of key enabling technologies dictate the demand for raw materials. Producers respond to availability of CRMs and Strategic Raw Materials (SRMs) as well as on the price fluctuations by stockpiling, negotiating of long-term contracts or price hedging. The recent Study on the critical raw materials for the EU 2023 [3] presents assessment of the critical raw materials for the EU: 70 candidate raw materials comprising 67 individual materials and three materials groups: ten heavy (HREEs) and

Preglednica 1. Uporaba aluminija, deleži uporabe in uporaba v sektorjih NACE2 [2]

Table 1. Aluminium application, uses shares and NACE2 sectors assignment [2]

Uporaba / Application	Delež / Share %	Sektor NACE / NACE sector
Gradbeništvo / Construction	21 %	C25 – Proizvodnja kovinskih izdelkov, razen strojev in naprav / C25 - Manufacture of fabricated metal products, except machinery and equipment
Avtomobilska industrija / Automotive industry	19 %	C29 – Proizvodnja motornih vozil, prikolic in polprikolic / C29 - Manufacture of motor vehicles, trailers and semi- trailers
Transportna oprema / Transport equipment	19 %	C30 – Proizvodnja drugih vozil in plovil / C30 - Manufacture of other transport equipment
Embalaža / Packaging	15 %	C25 – Proizvodnja kovinskih izdelkov, razen strojev in naprav / C25 - Manufacture of fabricated metal products, except machinery and equipment
Visokotehnološki inženiring / High tech engineering	11 %	C28 – Proizvodnja drugih strojev in naprav / C28 - Manufacture of machinery and equipment n.e.c.
Trajno potrošniško blago / Consumer durables	5 %	C25 – Proizvodnja kovinskih izdelkov, razen strojev in naprav / C25 - Manufacture of fabricated metal products, except machinery and equipment
Ognjevzdržni materiali / Refractories	3 %	C23 – Proizvodnja nekovinskih mineralnih izdelkov / C23 - Manufacture of other non metallic mineral products
Cement / Cement	3 %	C23 – Proizvodnja nekovinskih mineralnih izdelkov / C23 - Manufacture of other non metallic mineral products
Brusi / Abrasives	2 %	C23 – Proizvodnja nekovinskih mineralnih izdelkov / C23 - Manufacture of other non metallic mineral products

ter pet kovin iz platinske skupine (PGM), skupaj 87 posameznih surovin. Aluminij in boksit sta bila ocenjena v sinergiji [2].

Kritičnost aluminija je ocenjena za dve različni fazi življenjskega cikla, pridobivanje in rafiniranje. Uporaba aluminija, deleži uporabe in uporaba v sektorjih iz statistične klasifikacije gospodarskih dejavnosti v Evropski skupnosti (NACE) so prikazani v preglednici 1 [2].

Strateški pomen za gospodarsko rast ter trajnost evropskega gospodarstva in družbe, vključno s prehodom na podnebno nevtralnost in digitalno gospodarstvo, pri čemer je zagotovljena skladnost z načelom, da se ne škoduje bistveno, kot je navedeno v evropskem zelenem dogovoru, obravnava trajnostno pridobivanje in predelavo surovin, kjer [3]:

1. prispevajo h gospodarski rasti in socialno-ekonomskemu napredku skupnosti, vključno z avtohtonim prebivalstvom, ki je povezano s postopki pridobivanja in predelave ali je zaradi njih prizadeto;
2. se izvajajo za zagotavljanje dolgoročne trajnosti in ekonomske upravičenosti za razvoj in zadovoljevanje potreb sodobne družbe po mineralih in kovinah;
3. spodbujajo inovacije in uvajanje digitalnih tehnologij za varnejše, čistejše in stroškovno učinkovitejše proizvodne procese;
4. se izvaja krožno gospodarstvo in na učinkoviti rabi virov osnovane tehnološke vrednostne verige, ki temeljijo na mineralih, za spodbujanje predelave odpadkov ter omogočanje energetskega prehoda in
5. elektrifikacijo.

Ker aluminij (in njegove zlitine) spada v skupino zelenih materialov in ker je njegov pomen prepoznan v kritičnih in strateških surovinah, je možnost njegove uporabe kot sekundarne surovine

five light (LREEs) rare earth elements, and five platinum-group metals (PGMs), and 87 individual raw materials in total. Aluminium and bauxite have been evaluated in synergy [2].

The criticality of aluminium is assessed for two different life cycle stages, the extraction and refining. Aluminium application, uses shares and NACE sectors assignment are shown in Table 1 [2].

Strategic importance for economic growth and the sustainability of Europe's economy and society including the transition to climate neutrality and a digital economy while complying with the principle of do no significant harm as stated in the European Green Deal deals with sustainable raw materials extraction and processing in which they [3]:

1. contribute to the economic growth and the socio-economic advancement of communities, including indigenous people, associated with or affected by extraction and processing operations;
2. are carried out to ensure long-term sustainability and economic viability to develop and meet the needs of modern society for minerals and metals;
3. facilitate innovation and encourage the uptake of digital technologies for safer, cleaner and cost-effective production processes.
4. implement circular economy and resource efficiency driven mineral-based technology value chains to promote waste recovery, and enable energy transition and
5. electrification.

Since aluminium and its alloys belong to the group of green materials and due to its recognizes significance in the CRMs and SRMs, the potential of its' use as a secondary raw material is enormous. Usual application of secondary raw material in conventional foundries was dedicated to ogromna. Običajna uporaba sekundarnih surovin v konvencionalnih livarnah je bila namenjena lastnemu ponovnemu pridobivanju (odpad) [4–5]. Nadzorovane lastnosti, kot sta kemična sestava in stopnja nečistoč, omogočajo dodajanje večjih količin odpadnega aluminija pri proizvodnji aluminijevih zlitin [6–7].

Večkratno ponovno taljenje je pomemben vidik pri podaljševanju življenjske dobe materiala. Pri običajni uporabi določenega deleža sekundarnih surovin v vložku je bilo ugotovljeno, da kemijska sestava zlitine ustreza tisti, ki jo zahteva standard [8], vendar tudi z določenim zmanjšanjem mehanskih lastnosti [9–10].

Zlitine iz skupine Al-Si igrajo zaradi visoke trdnosti pri sobnih in povišanih temperaturah pomembno vlogo v avtomobilski industriji pri različnih varnostno kritičnih delih [11–12]. Razumevanje razvoja mikrostrukture med strjevanjem je splošnega pomena zaradi zahtev, povezanih z mehanskimi, tehnološkimi in korozijskimi lastnostmi materiala [13–14]. Poleg obdelave taline, hitrosti ohlajanja in toplotne obdelave je odvisna predvsem od kemijske sestave in možnih interakcij prisotnih elementov med postopkom strjevanja [15]. Med postopkom strjevanja je prišlo do številnih interakcij. Modelirani ravnotežni fazni diagram omogoča napovedovanje poteka strjevanja v ravnotežnem in neravnotežnem načinu [15]. Mikrostrukturne preiskave vzorcev z optično in vrstično elektronsko mikroskopijo potrjujejo prisotnost naslednjih faz: primarni razvoj aluminija (α_{Al}), faze na osnovi železa (Al_5FeSi, $Al_x(Fe, Mn, Cu)_ySi_z$ in/ali $Al_x(Fe, Mn)_yMg_zCu_uSi_w$), primarni evtektik ($\alpha_{Al} + \beta_{Si}$), sekundarni evtektik v obliki intermetalnih faz, kot so $Al_5Mg_8Si_6Cu_2$, Al_2Cu, in nazadnje $Al_{15}Cu_2Mg_8Si_6$.

own return (scrap) [4-5]. Controlled features such as chemical composition and level of impurities enables addition of higher amount of aluminium scrap in production of aluminium alloys [6-7].

Multiple remelting is an important aspect in extending the material end of life. In the conventional application of a certain share of secondary raw material in the charge material it has been noticed that chemical composition of an alloy corresponds to those required by norm [8], but also with certain reduction in mechanical properties [9-10].

Alloys from the Al-Si group have an important role in automotive industry for various safety critical parts due to their high strength at room and elevated temperatures [11-12]. Understanding of microstructure evolution during solidification is of general importance due to requirements related to mechanical, technological and corrosion properties of material [13-14]. Beside melt treatment, cooling rate and heat treatment it is mainly dependent from the chemical composition and possible interaction of present elements during solidification process [15]. Numerous interaction occurred during solidification process. Modelled equilibrium phase diagram enables solidification sequence prediction in equilibrium and non-equilibrium mode [15]. Microstructural investigation of samples by optical and scanning electron microscopy confirms the presence of following phases: primary aluminium evolution (α_{Al}), iron base phases (Al_5FeSi, $Al_x(Fe,Mn,Cu)_ySi_z$ and/or $Al_x(Fe,Mn)_yMg_zCu_uSi_w$), primary eutectic phase ($\alpha_{Al}+\beta_{Si}$), secondary eutectic phases in form of intermetallic phases like $Al_5Mg_8Si_6Cu_2$, Al_2Cu and finally $Al_{15}Cu_2Mg_8Si_6$.

In this work, the influence of completely return (secondary raw material - scrap) material as the only charge material

V tem delu je bil raziskan vpliv v celoti ponovno pridobljenega materiala (sekundarne surovine – odpad) kot edini vložek za proizvodnjo zlitine AlSi9Cu3(Fe) na razvoj mikrostrukture zaradi termodinamičnih interakcij prisotnih elementov. Ocena kakovosti vložka je temeljila na poslabšanju kemijske sestave zaradi ponovnega taljenja, morebitni spremembi poteka strjevanja in/ali temperatur ter posledično vplivu na druge funkcionalne lastnosti končnih izdelkov.

2 Materiali in metode

Novejša praksa v livarnah tlačnega litja (HPDC) je priprava vložka s 50 % povratnih surovin in 50 % novih surovin (konvencionalni vložek – CCM). V tem delu je bil vložek za taljenje pripravljen iz 100-odstotno, tj. popolnoma iz povratnega materiala (RCM).

Posebno zasnovano orodje za vlivanje preskusnih vzorcev zlitine AlSi9Cu3(Fe) v skladu s standardi ISO 377, ISO 6892-1 in ISO 1099 je bilo izdelano s tehnologijo HPDC na stroju BUHLER 53D. Litje in robotizirano nanašanje vodotesnih premazov je potekalo v popolnoma avtomatiziranih ciklih, vzorci pa so se hladili na zraku. Pridobljeni vzorci so bili pregledani glede mehanskih lastnosti s preskusnim strojem MTS 810 pri sobni temperaturi T = 20 °C v skladu s standardom EN 10002-1 [14].

Analiza kemijske sestave je bila opravljena z optičnim emisijskim spektrometrom ARL-3460. Termodinamični izračuni ravnotežnega in neravnotežnega faznega diagrama s Scheil-Gulierjevim modelom za zlitino AlSi7MgCu so bili opravljeni s programom Thermo-Calc TCW 5.0 s podatkovno bazo TTAL7 [15]. Opravljena je bila primerjava dobljenih rezultatov z rezultati simultane termične

for AlSi9Cu3(Fe) alloy production on microstructure development due to thermodynamic interactions of present elements was investigated. Quality assesment of the charge material was based on the degeneration of chemical composition due to remelting, possible change in solidification sequence and/or temperatures and consequently influence at other functional properties of final products.

2 Materials and methods

Recent practice in High Pressure Die Casting (HPDC) foundries is designing the charge materials with 50% of return and 50% of new raw materials (conventional charge material – CCM). In this work, the charge material for melting was prepared from 100% i.e. completely return material (return charge material - RCM).

Specially designed tool for casting of AlSi9Cu3(Fe) alloy test samples according to ISO 377, ISO 6892-1 and ISO 1099 standards were produced using HPDC technology at BUHLER 53D machine. Casting and robotised coating with watertight coatings were carried out in a fully automated cycles and samples were cooled in the air. Obtained samples undergone the mechanical properties investigations performed on testing machine MTS 810, at room temperature T = 20 °C in accordance to EN 10002-1 [14].

Chemical composition analysis was performed using optical emission spectrometer ARL-3460. Thermodynamic calculations of equilibrium and Scheil–Gulliver non-equilibrium phase diagram of AlSi7MgCu alloy have been performed by Thermo-Calc software TCW 5.0, with database TTAL7 [15]. Obtained results were compared with those from simultaneous thermal analysis performed on STA 449 analize, opravljene na analizatorju STA 449 Jupiter. Simultana termična analiza omogoča določanje značilnih temperatur in toplotnih učinkov posameznih dogodkov med taljenjem in/ali strjevanjem.

Mikrostrukturo smo pregledali s svetlobnim OLYMPUS BX51 in vrstičnim elektronskim mikroskopom, opremljenim z energijsko disperzijskim spektrometrom JEOL-5610.

3 Rezultati in razprava

3.1 Analiza kemijske sestave

Kemijska sestava zlitine AlSi9Cu3(Fe) je navedena v Preglednici 2. Primerjava kemijske sestave preskusnih vzorcev s certificiranimi podatki ni pokazala odstopanj od vrednosti, ki jih zahteva standard EN 1706.

Primerjava zahtev in preskušenih vzorcev iz običajnega vložka (CCM 50 %) ter povratnega materiala (RCM 100 %) je pokazala, da so vse dobljene vrednosti pomembnih elementov skladne s standardi, vendar nižje pri 100 % povratnem materialu. Zaradi visokih vrednosti bakra in nizke vsebnosti magnezija se pričakuje nastanek intermetalnih faz Al_2Cu in $AlMg_8Si_2Cu_2$. Glede na ustrezno vsebnost železa in

Jupiter. STA enables determination of characteristic temperatures and thermal effect of particular events during melting and/or solidification.

The microstructure was examined with a light OLYMPUS BX51 and scanning electron microscope equipped with energy dispersive spectrometer JEOL-5610.

3 Results and Discussion

3.1 Analysis of Chemical Composition

The chemical composition of AlSi9Cu3(Fe) alloy is given in Table 2. The comparison of the chemical composition of tested samples with certified data showed no deviations from the values required by the standard EN 1706.

Comparison of requirement and tested samples in common charge material (CCM 50%) and recycled – return charge material (RCM 100%) revealed that all obtained values for important elements are consequent with the norm but lower in return charge material. Due to the high values of copper and low content of magnesium the formation of Al_2Cu and $Al_5Mg_8Si_2Cu_2$ intermetallic phases is expected. With respect to the corresponding content of iron and manganese in the tested RCM

Preglednica 2. Primerjava kemijske sestave zlitine EN AB AlSi9Cu3 po standardu EN 1706:2010, sestava zlitine iz običajnega vložka sestavljenega iz 50 % povratnega materiala, zlitina pridobljena iz 100 % povratnega materiala.

Table 2. Comparison of chemical composition of charge material EN AB AlSi9Cu3 by norm EN 1706:2010, conventional charge material consisted from 50% and return charge material consisted form 100% of return charge material

Element w/wt %	Si	Fe	Cu	Mn	Mg	Cr	Zn	Pb	Sn
EN 1706	8,0-11,0	1,0	2,0-4,0	0,55	0,05-0,55	0,15	1,2	0,35	0,25
CCM (50 %)	9,75	0,89	3,26	0,24	0,12	0,04	0,99	0,06	0,012
RCM (100 %)	8,75	0,66	2,91	0,20	0,17	0,04	0,82	0,04	0,004

mangana v preskušeni zlitini RCM in zaradi uporabljene tehnologije HPDC se pričakuje nastanek faze $Al_{15}(MnFe)_3Si_2$. Poleg tega lahko interakcija z magnezijem povzroči nastanek faze $Al_8Mg_3FeSi_2$ [15]. Druge nečistoče, svinec, krom in kositer, so v mejah, ki jih predpisuje standard.

3.2 Rezultati termodinamičnega modeliranja

Termodinamično modeliranje omogoča ravnotežno in neravnotežno napovedovanje poteka strjevanja glede na kemijsko sestavo [15]. Slika 1 prikazuje modelirano obnašanje zlitine iz običajnega vložka in zlitine iz vložka povratnega materiala na podlagi prisotnih termodinamičnih parametrov elementov. Termodinamično modeliranje omogoča napovedovanje in primerjavo poteka strjevanja ter s tem povezanih temperatur transformacije in razvoja faz.

Vrednotenje in primerjava dobljenih ravnotežnih in neravnotežnih faznih diagramov obeh zlitin sta razkrila razlike v poteku strjevanja. Reakcije v poteku strjevanja preskušenih zlitin AlSi9Cu3(Fe), izdelanih iz različnih reciklažnih razmerij v skladu z neravnotežnim Scheilovim diagramom, so navedene v preglednici 3:

Reakcije v poteku strjevanja obeh primerjanih zlitin niso pokazale razlik v reakcijah, pridobljenih fazah in vrstnem redu njihovega pojavljanja. Glavna razlika je v pripadajoči temperaturi in intervalu strjevanja. Običajni AlSi9Cu3(Fe) ima širši interval strjevanja 92,71 °C, medtem ko je pri popolnoma ponovno pridobljenem polnilnem materialu interval 89,10 °C. Modeliranje zaporedja strjevanja zlitine AlSi9Cu3(Fe) za oba je pokazalo nekatere razlike v poteku strjevanja glede značilnih temperatur za intermetalno fazo na osnovi Fe in Cu/Mg kot končne faze strjevanja.

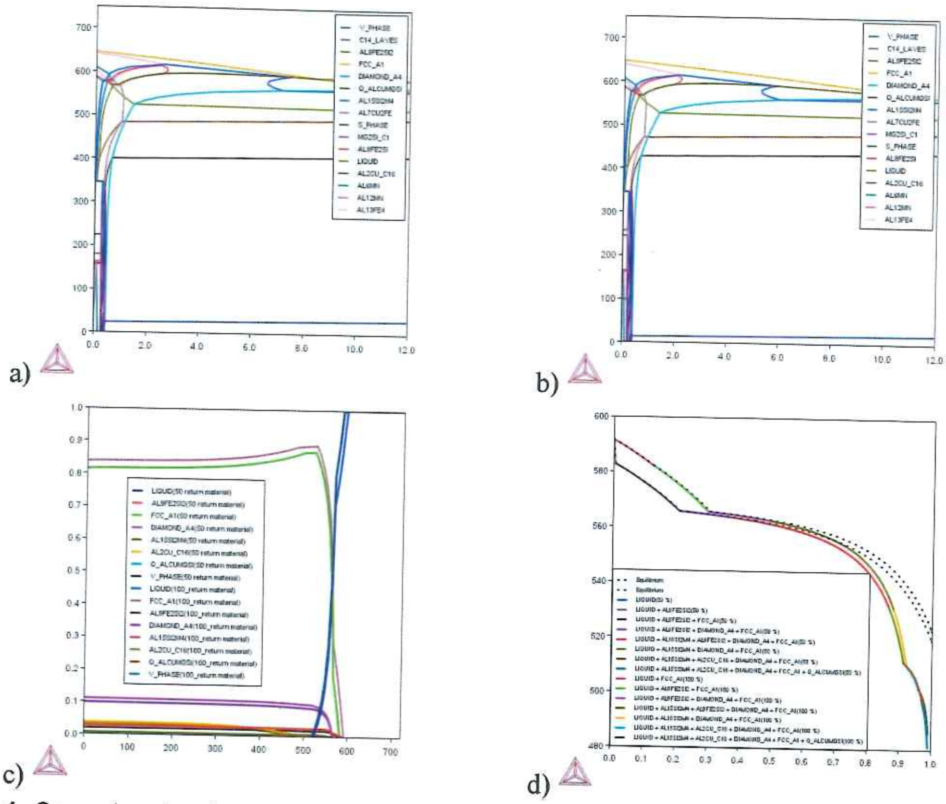
alloy, and due to applied HPDC technology, $Al_{15}(MnFe)_3Si_2$ phase formation is expected. In addition, interaction with magnesium can leads to formation of $Al_8Mg_3FeSi_2$ phase [15]. Other impurities, lead, chrome and tin, are within the limits prescribed by norm.

3.2 Thermodynamic modelling results

Thermodynamic modelling enables equilibrium and non-equilibrium prediction of solidification sequence according to chemical composition [15]. Figure 1 indicate modelled behaviour of conventional and return charge material on the base of thermodynamic parameters present elements. Thermodynamic modelling enables prediction and comparison of solidification sequence and associated temperatures of phases' transformations and evolution.

Evaluation and comparison of obtained equilibrium and non-equilibrium phase diagram of both charge materials revealed differences in solidification sequence. Reactions in solidification sequence of tested AlSi9Cu3(Fe) alloys made from different recycling ratio according to non-equilibrium Scheil diagram are as follows in Table 3.:

Reactions in solidification sequence of both compared charge materials did not revealed differentiations in reactions, obtained phases and its order of appearance. The main difference occurs in belonging temperatures and solidification interval. Conventional AlSi9Cu3(Fe) exhibits wider solidification interval of 92.71°C, while for completely return charge material interval is 89,10°C. Modelling of AlSi9Cu3(Fe) alloy solidification sequence for both charges revealed some differences in solidification path regarding characteristic temperatures for intermetallic on the base of Fe and Cu/Mg as a final solidification phases.



Slika 1. Ocena in primerjava poteka strjevanja zlitine AlSi9Cu3(Fe) iz običajnega vložka in vložka iz povratnega materiala: a) Al-kot zlitine iz običajnega vložka; Al-kot zlitine iz povratnega materiala; c) primerjava poteka strjevanja obeh zlitin v ravnotežnem faznem diagramu; d) primerjava poteka strjevanja obeh zlitin v neravnotežnem Scheilovem diagramu

Figure 1. Evaluation and comparison of solidification sequence of AlSi9Cu3(Fe) alloy from conventional and return charge material: a) Al-corner of conventional charge material; Al- corner of return charge material; c) comparison of solidification sequence for both charge materials in equilibrium phase diagram; d) comparison of solidification sequence for both charge materials in non-equilibrium Scheil phase diagram

3.3 Rezultati simultane termične analize

Simultano termično analizo (STA) smo izvedli na več vzorcih zlitin iz popolnoma povratnega materiala, da bi ocenili skladnost obnašanja pri strjevanju s predhodno modeliranim. Primerjava krivulj ohlajanja je prikazana na sliki 2.

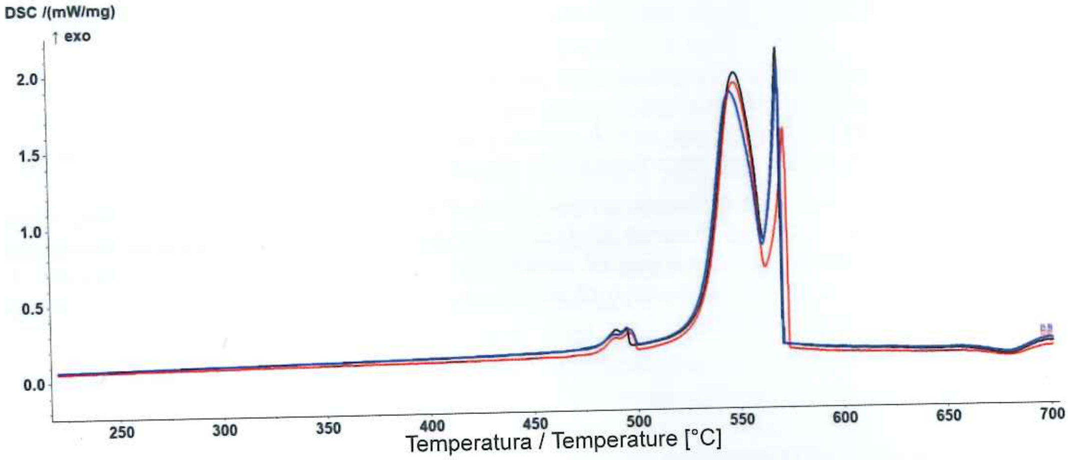
3.3 Simultaneous thermal analysis results

Simultaneous thermal analysis (STA) was performed on several samples of completely return charge material in order to estimate correspondence of solidification behaviour with previously modelled one. Comparison of cooling curves are shown in Figure 2.

Table 3. Comparison of solidification sequence and/or temperatures for both charges of tested AlSi9Cu3(Fe) alloys

Preglednica 3. Primerjava poteka strjevanja in/ali temperatur za obe preskušani zlitini $AlSi_9Cu_3(Fe)$

Vložek / Charge material	Reaction / Reakcija	
Običajni vložek (50 % povratnega materiala) / Conventional charge material (50% return material)	$L + \beta - Al_5FeSi$	590.62
	$L + \beta - Al_5FeSi + \alpha_{Al}$	583.53
	$L + \beta - Al_5FeSi + \alpha_M + \beta_{Si}$	565.80
	$L + \beta - Al_5FeSi + \alpha_{Al} + \beta_{Si} + Al_{15}Si_2M_4$ (M = Cr, Fe, Mn, Mo)	563.77
	$L + \beta_{Si} + Al_{15}Si_2M_4$ (M = Cr, Fe, Mn, Mo)	532.42
	$L + \alpha_{Al} + \beta_{Si} + Al_{15}Si_2M_4$ (M = Cr, Fe, Mn, Mo) + Al_2Cu	512.39
	$L + \alpha_{Al} + \beta_{Si} + Al_{15}Si_2M_4$ (M = Cr, Fe, Mn, Mo) + $Al_2Cu + Al_3Cu_2 + Al_3Cu_2Mg_9Si_7$	497.91
Vožek iz povratnega materiala(100 % povratnega materialaa) / Return charge material (100 % return material)	$L + \alpha_{Al}$	591.62
	$L + \beta - Al_5FeSi + \alpha_{Al}$	582.12
	$L + \beta - Al_5FeSi + \alpha_{Al} + \beta_{Si}$	565.73
	$L + \beta - Al_5FeSi + \alpha_{Al} + \beta_{Si} + Al_{15}Si_2M_4$ (M = Cr, Fe, Mn, Mo)	562.70
	$L + \beta_{Si} + Al_{15}Si_2M_4$ (M = Cr, Fe, Mn, Mo)	531.35
	$L + \alpha_{Al} + \beta_{Si} + Al_{15}Si_2M_4$ (M = Cr, Fe, Mn, Mo) + Al_2Cu	511.32
	$L + \alpha_{Al} + \beta_{Si} + Al_{15}Si_2M_4$ (M = Cr, Fe, Mn, Mo) + $Al_2Cu + Al_3Cu_2Mg_9Si_7$	502.52



Slika 2. Simultana termična analiza zlitine iz povratnega materiala

Figure 2. STA analysis of completely return charge material of AlSi9Cu3(Fe) alloy

Analiza krivulj segrevanja in ohlajanja pri simultani termični analizi kaže značilne temperature faznih transformacij in razvoja. Te so predstavljene v preglednici 4 skupaj s

Analysis of simultaneous thermal analysis heating / cooling curves indicates characteristic temperatures of phase transformations and evolution. Those are

Preglednica 4. Značilne temperature faznih transformacij in razvoj zlitine AlSi9Cu3(Fe)

Table 4. Characteristic temperatures of phase transformations and evolution of AlSi9Cu3(Fe) alloy

Vzorec / Sample	T_L [°C]	T_E [°C]	T_{Al-Cu} [°C]	$T_{S:Al-Cu-Mg-Si}$ [°C]	AT_{L-S}	Rm [MPa]	A [%]
2	591,0	561,1	500,7	491,9	99,1	316,3	2,50
5	588,7	562,6	500,1	492,2	96,5	311,7	2,30
8	588,2	561,8	497,1	492,1	96,1	329,6	3,00

predhodno raziskanimi natezno trdnostjo in raztezkom.

Preučitev zlitine AlSi9Cu3(Fe) iz povratnega materiala s simultano termično analizo razkriva spremljanje poteka strjevanja, modeliranega s TCW. Opazno je znižanje evtektične in nizkotemperaturne faze. Solidus temperatura T_s je pri 10,62 °C nižja od modelirane, zato je interval strjevanja pri 7,4 °C daljši. Zanimivo je, da ima preiskovani material z višjimi vrednostmi mehanskih lastnosti tudi višjo potrebno energijo za začetek strjevanja in taljenja.

3.4 Rezultati preučitve mikrostrukture

Razvoj mikrostrukture ni pokazal bistvenih odstopanj od poteka strjevanja, razen nekje v morfologiji mikrostrukturnih sestavin, kot je prikazano na sliki 3.

Rezultati optične mikroskopije (OM) in vrstične elektronske mikroskopije (SEM) kažejo značilno mikrostrukturo zlitine AlSi9Cu3(Fe), izdelane s HPDC. Preiskava mikrostrukture je sestavljena iz matrice primarnega aluminija α_{Al}, evtektika (α_{Al} + β_{Si}), intermetalne faze na osnovi železa v pretežno igličasti morfologiji – AlFeSi in tudi v $Al_{15}(Fe, Mn)_3Si_2$.

Morfologija »kitajske pisave«, nekje črna razvejana Mg_2Si, faza intermetalne strukture $Al_8Mg_3FeSi_2$ in faze Al_2Cu ter $Al_5Mg_8Si_2Cu_2$ na osnovi bakra. Bakrovi skupki se izločijo na mejah zrn, medtem

presented in Table 4 along with previously investigated tensile strength and elongation.

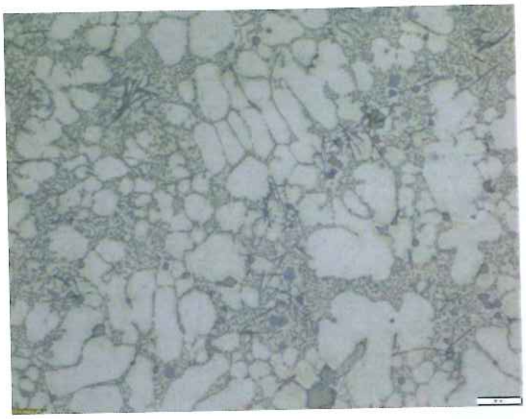
STA investigation of completely return charge material of revealed follow up of the AlSi9Cu3(Fe) alloy reveals follow up of solidification sequence modelled by TCW. The lowering of eutectic and low temperature phase is noticed. Solidus temperature T_S is lower than modelled for 10,62°C, and solidification interval is therefore wider for 7,4°C. It is interesting to notice that the investigated material with higher values of mechanical properties also has a higher required energy for the start of solidification, as well as melting process.

3.4 Microstructure Investigation Results

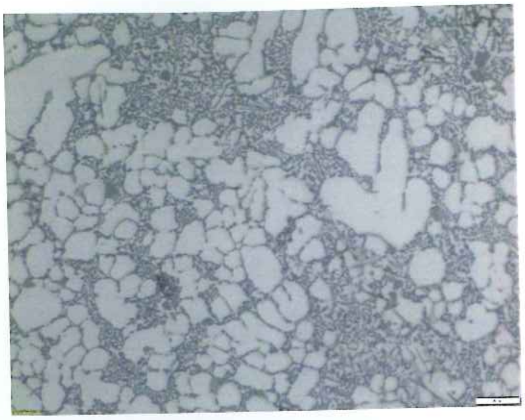
Microstructure development did not indicate any significant deviation from the solidification sequence except somewhere in the morphology of microstructural constituents as shown in Figure 3.

Results of optical microscopy (OM) and scanning electron microscopy (SEI) show the typical microstructure of AlSi9Cu3(Fe) alloy produced by HPDC. Microstructure investigation consists from matrix of primary aluminium α_{Al}, eutectic phase $\alpha_{Al}+\beta_{Si}$, intermetallic phase on the iron base in predominantly needle-like morphology - Al_5FeSi and also in $Al_{15}(Fe,Mn)_3Si_2$

"Chinese script" morphology, somewhere black ramified Mg_2Si, intermetallic script $Al_8Mg_3FeSi_2$ phase,



Light microscopy 500x



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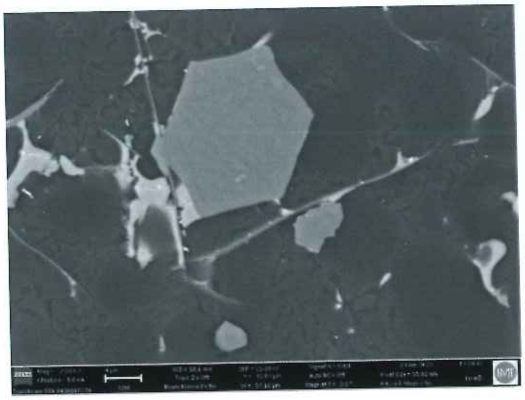
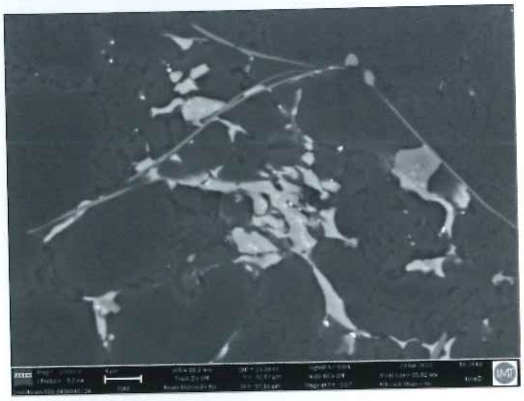


SEI 2000x



SEI 2000x

Slika 3. Razvoj mikrostrukture zlitine AlSi9Cu3(Fe)

Figure 3. Microstructure development of AlSi9Cu3(Fe) alloy

ko se razvejana bakrova faza nahaja v interdendritnih prostorih.

4 Sklepne ugotovitve

V tem delu je bil raziskan vpliv reciklirane (ponovno taljene) zlitine AlSi9Cu3(Fe) na termodinamiko strjevanja in razvoj mikrostrukture. Raziskava je bila opravljena na zlitine AlSi9Cu3(Fe) izdelane iz povratnega materiala.

Preučitev povratnega materiala kot vložek za izdelano zlitino AlSi9Cu3(Fe)

and Al_2Cu and $Al_5Mg_8Si_2Cu_2$ phases on the copper base. Copper clusters are precipitated on the grain boundaries, while ramified copper phase is placed in interdendritic spaces.

4 Conclusions

Influence of recycled (remelted) AlSi9Cu3(Fe) alloy on solidification thermodynamics and microstructure development was investigated in this work.

s simultano termično analizo razkriva spremljanje poteka strjevanja, modeliranega s TCW. Opazno je znižanje evtektične in nizkotemperaturne faze. Solidus temperatura T_s je pri 10,62 °C nižja od modelirane, zato je interval strjevanja širši za 7,4 °C. Zanimivo je, da ima preiskovani material z višjimi vrednostmi mehanskih lastnosti tudi višjo potrebno energijo za začetek strjevanja in taljenja.

Mikrostruktura ni pokazala bistvenih odstopanj pri razvoju glavnih mikrostrukturnih sestavin primarnega aluminija α_{Al}, evtektika (α_{Al} + β_{Si}), intermetalne faze na železovi osnovi v obliki Al_5FeSi in morfologije »kitajske pisave«, intermetalne faze na osnovi magnezija in bakra, kot sta Mg_2Si in Al_2Cu, ter kompleksne intermetalne faze, kot sta $Al_8Mg_3FeSi_2$ in $Al_5Mg_8Si_2Cu_2$. Razvoj mikrostrukture omogoča relativno visoke vrednosti mehanskih lastnosti, kot sta natezna trdnost in raztezek.

Rezultati termodinamičnih in mikrostrukturnih preiskav zlitine AlSi9Cu3(Fe) so pokazali, da je popolnoma povraten material kakovosten vložek z dobrim potencialom za uporabo in recikliranje. Kljub slabšanju kemijske sestave je bil razvoj mikrostrukture pravilen, zato so bile upravičeno dosežene odlične mehanske lastnosti.

Investigation were performed on completely return charge material of AlSi9Cu3(Fe) alloy.

STA investigation of completely return charge material of revealed follow up of the AlSi9Cu3(Fe) alloy reveals follow up of solidification sequence modelled by TCW. The lowering of eutectic and low temperature phase is noticed. Solidus temperature T_S is lower than modelled for 10,62°C, and solidification interval is therefore wider for 7,4°C. It is interesting to notice that the investigated material with higher values of mechanical properties also has a higher required energy for the start of solidification, as well as melting process.

Microstructure did not show significant deviation in development of main microstructure constituent primary aluminium α_{Al}, eutectic phase α_{Al}+β_{Si}, intermetallic phase on the iron base in Al_5FeSi and "Chinese script" morphology, intermetallic phase on the magnesium and copper base such as Mg_2Si and Al_2Cu, and complex intermetallic such as $Al_8Mg_3FeSi_2$ and $Al_5Mg_8Si_2Cu_2$ phases. Microstructure development comprehend to relatively high values of mechanical properties regarding tensile strength and elongation.

Thermodynamic and microstructural investigation results of the AlSi9Cu3(Fe) alloy indicated completely return material as a quality charge material with good application and recycling potential. In despite of chemical composition derogation microstructure development was correct and therefore justified achieved high mechanical properties.

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