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Rafinacija aluminijevih gnetnih zlitin z uporabo višjih deležev sekundarnih surovin

Melt Refining of Wrought Aluminium Alloy Al-Mg-Si with Increased Fractions of External Scrap

Povzetek

V študiji je bila preučena učinkovitost rafinacije ter čiščenja aluminijeve gnetne zlitine Al-Mg-Si z uporabo tehnologije RFI (rotacijsko injektiranje talil), v odvisnosti od različnih sestav talil ter deležev vgrajenih sekundarnih surovin. Serije litja aluminijevih gnetnih zlitin Al-Mg-Si, modificiranih z Zr, so bile preučene na več različnih stopnjah recikliranja, katere so bile injektirane s talili za potrebe določitve učinkovitosti. Opazili smo učinkovitost odstranjevanja vključkov in alkalijskih kovin pri različnih vsebnostih surovin, pri čemer so uporabili različne deleže sekundarnih surovin in primarnega aluminija, ter uvedli korelacijo s končnimi mehanskimi lastnostmi končnega izdelka.

Izdelane so bile različne šarže z več kot 50 % recikliranega materiala (RC) in 80 % celotne sekundarne sestave ter preostalega deleža primarnega aluminija. Parametri procesa injektiranja talil s tehnologijo RFI so bili uporabljeni s konstantnimi parametri za doseganje ponovljivosti enakomernega dovajanja talila ter kontaktnega časa hitrosti reakcije procesa rafinacije ter čiščenja aluminijeve gnetne zlitine na osnovi Al-Mg-Si. Vzorci za kvantitativno in kvalitativno določanje čistoče taline so bili odvzeti z metodo PoDFA (metoda filtriranja s poroznim diskom). Preiskave in vsebnost nekovinskih vključkov so bili določeni s svetlobno, vrstično elektronsko mikroskopijo ter optično emisijsko spektroskopijo. Narejena je bila korelacija vsebnosti deleža sekundarne surovine napram doseženim mehanskih lastnosti zlitine, pri katerem so bili uporabljene najvišje stopnje rafinacije aluminijeve gnetne zlitine.
Ključne besede: Aluminijeve gnetne zlitine, čiščenje, talila, vključki, rotacijsko injektiranje, RFI

Abstract

In the recent study, the effectiveness of melt refining and cleaning processing using rotary flux injection technology (RFI)was investigated in relation to different charge compositions and different recycling contents. Serial batches of aluminium wrought alloys series Al-Mg-Si modified with Zr, were studied on several recycle rate recipes of dedicated alloy were treated with flux mixture by rotary flux injection technology. The efficiency of inclusions, alkali metals removal, by various charge content, using different proportions of secondary raw materials and primary aluminium was observed, and also the correlation to the final mechanical properties of the final product was introduced.

Input charges consisted of more than 50% of recycling content (RC) and 80% total secondary composition and the remainder of primary aluminium ingots. RFI injection process parameters were applied with constant parameters to achieve repeatability, uniform flux feeding distribution, and the same contact reaction time by optimal set-up of flux injection parameters. Samples for the quantitative and qualitative determination of melt cleanliness were taken using the porous disc filtration apparatus (PoDFA) method. Investigations and content of non-metallic inclusions were determined using light, scanning electron microscopy, and optical emission spectroscopy.

Keywords: aluminium, refinement, flux, cleanliness, non-metallic inclusion, rotary injection, alkali element

Poudarki:
- Industrijska proizvodnja gnetnih aluminijevih zlitin z različnim deležem recikliranih odpadkov
- Postopek čiščenja taline z uporabo RFI (injektiranje talil s pomočjo rotorja)
- Učinkovitosti odstranjevanja kovinskih, nekovinskih vključkov in alkalijskih elementov
- Korelacija med čistočo in mehanskimi lastnostmi za zlitino EN AW 6082 (Al-Mg-Si z Zr)

Highlights:
- Wrought aluminium alloys industrial production with different proportions of recycling scrap rate
- Melt cleaning process using RFI (rotary flux injection)
- Efficiency ratio of removal of metallic, non-metallic inclusions, and alkali elements
- Correlation between cleanliness and mechanical properties for alloy EN AW 6182 (Al-Mg-Si with Zr)

1 Uvod

Sekundarni aluminij ima velike ekonomske in okolijske koristi, saj omogoča do 95 % nižjo porabo energije pri recikliranju v primerjavi z elektroliznim pridobivanjem aluminija. Znatno povečanje deleža aluminijevih odpadkov v celotni proizvodnji aluminija se bo v nadaljnjih letih še naprej povečevalo do 30 Mt celotne svetovne proizvodnje, kar je več kot 50 % izhodnega deleža celotne svetovne proizvodnje aluminija [1]. To narekuje nujno upoštevanje običajne sekundarne uporabe v proizvodnih obratih, medtem ko onesnaževalci iz internih ter eksternih virov zahtevajo dodaten postopek rafiniranja in čiščenja aluminijeve taline, s ciljem doseganja končnih lastnosti aluminijevih izdelkov.

Kovinski in nekovinski vključki prihajajo v talino iz več virov, iz trdnih, čistih ali onesnaženih odpadkov z organskimi ali anorganskimi spojinami, ostankov iz procesa taljenja ali z dodatnim legiranjem

1 Introduction

Secondary aluminium has major economic and environmental benefits, with an impact on lower recycling energy consumption up to 95%, compared to primary production. Significant increase of aluminium scrap content in complete aluminium production will still grow in recent years till up to 30 MT of the total production worldwide, which is more than 50% of the output content of complete global aluminium production [1]. This causes necessary consideration for common secondary usage in production facilities, while the contaminants from internal, external sources require additional refining and cleaning processes of aluminium melt, targeting the final properties of aluminium products.

Metallic and non-metallic inclusions come into the melt from several sources, from solid clean or contaminated scrap with organic or inorganic compounds, residues from the melting process, and ali rafinacijo taline, kar lahko vodi do nastanka kompleksnih aglomeratov v obliki Ti-boridov. Reakcija z vlago tvori aluminijev oksid, hkrati pa poveča količino raztopljenega vodika v talini, kar ima za posledico več učinkov na pojav poroznosti [2].

Gnetne aluminijeve zlitine na osnovi Al-Mg-Si so toplotno obdelane aluminijeve zlitine, ki se pogosto uporabljajo v komercialni, arhitekturni, elektro, vesoljski in avtomobilski industriji. Zlitine serije 6xxx (Al-Mg-Si) vsebujejo masni delež silicija in magnezija v razmerjih, potrebnih za tvorbo utrjevalne faze (Mg_2Si). Ta vrsta zlitin serije ima dobro preoblikovalnost, varivost ter odpornost proti koroziji. Zlitine v tej toplotno obdelani skupini se lahko preoblikujejo v stanju T4 in po oblikovanju utrjujejo do stanja T6 s pomočjo toplotne obdelave [3]. Utrjevanje zlitine na osnovi Al-Mg-Si je predvsem posledica procesa staranja, kot procesa izločevanja faznih struktur. Morfologija kristalne strukture, velikosti, količine in porazdelitev teh faz imajo pomemben vpliv na doseženo trdnost zlitine. Učinkovitost staranja je povezano tudi s kemijsko sestavo, časom staranja in temperaturo, kjer je ključnega pomena mikrostrukturno stanje zlitine [4].

Za izboljšanje kvalitete aluminijevih gnetnih zlitin z višjim deležem recikliranja, je potrebno poiskati različne metode za optimizacijo in zmanjšanje vpliva sekundarnih surovin na končne specifične lastnosti zlitine. Eden od konvencionalnih načinov čiščenja taline je rafiniranje z anorganskimi spojinami različnih mešanic kloridov in fluoridov, ki se dovajajo v aluminijevo talino, kar zagotavlja nizko vsebnost nečistoč, visok izkoristek kovine in dodatno zaščito pred oksidacijo [5].

Obdelava taline z različnimi talili znižujejo vsebnost alkalijskih in zemeljsko-alkalijskih kovin, oksidov in drugih kovinskih

with additional alloying or grain refining process, which can lead to form complex agglomerates, observed as Ti-borides. The reaction with moisture forms aluminium oxide, simultaneously increasing dissolved hydrogen in molten aluminium, resulting in several porosity effects [2].

Wrought aluminium alloys series Al-Mg-Si are heat-treatable aluminium alloys, widely used for commercial, architectural, electrical, aerospace, and automotive industries. Alloys in the 6xxx series (Al-Mg-Si) contain silicon and magnesium approximately in the proportions required for the formation of magnesium silicide (Mg_2Si). This type of series alloy has good formability, weldability, machinability, and corrosion resistance. Alloys in this heat-treatable group may be formed in the T4 temper and strengthened after forming to full T6 properties by precipitation heat treatment [3]. The strengthening of the alloy is mainly due to the small aging strengthening phase (i.e., the second phase) precipitated during the aging process. Therefore, the morphology, size, quantity, and distribution of the aging strengthening phase have important effects on the strength. The precipitation of the aging strengthening phase is also related to the chemical composition, aging time-temperature, where the microstructure state of the alloy is crucial [4].

Improving the quality of aluminium melt whith high-grade secondary content is necessary to optimize and explore methods to reduce complete waste. One of the convencional ways for the melt cleaning process is refining with inorganic compounds of different chloride and fluoride mixtures feeding into the aluminium melt, ensuring low content of impurities, high metal recovery, and additional protection to form oxidation [5].

in nekovinskih vključkov. Odstranjevanje nečistoč lahko znatno izboljša mehanske lastnosti končnega izdelka [6]. Mešanice talil v granulirani, praškasti ali briketirani obliki se lahko v staljeni aluminij vnesejo na več možnih načinov v procesu ročnega dodajanje na površini in mešanja v talino ali običajno potopitev talila na dno taline z dodatnim vpihovanjem argona ali dušika. Najučinkovitejše metode za postopek vnašanja talila v talino se izvajajo z uporabo rotacijskega injektiranja talila (RFI) z mešanjem rotorja, kjer se talilo enakomerno dovaja neposredno v talino. RFI tehnologija običajno uporablja granulirane mešanice talil, kot dobro uveljavljeno tehnologijo za učinkovito pripravo in obdelavo taline v livnih pečeh. Različne vrste pokrivnih talil, talil za čiščenje taline ali talil za obdelavo žlindre, so hkrati indirektno pomembne za doseganje različnih namenov uporabnosti priprave in obdelave zlitin [7, 8, 9, 10].

Uporaba hibridnega rotorja s specifično geometrijo dodatno izboljša učinkovitost obdelave taline z RFI, saj ustvarja optimalen radialni pretok taline in omogoča boljše mešanje taline pri injektiranju talila s pomočjo inertnega plina. Povečan učinek mešanja izboljša hitrost odstranjevanja alkalij in skrajša potreben čas obdelave [11].

2 Metode in materiali

Industrijska baza podatkov je bila analizirana na aluminijevih zlitinah Al-Mg-Si, modificiranih z Zr (EN AW 6182). Kemijske sestave analiziranih zlitin so bile v skladu s standardom EN 573-3, z mejnimi vrednostmi razlik za različne elemente in z vsebnostjo Zr do 0,15 mas. % (tabela 1).

Klasifikacija za različne recepture vhodnega vložka je sestavljena iz različnih vrst surovin:

Salt fluxes treatment of molten aluminium removes alkali and alkali-earth metals, oxides, and other metallic, nonmetallic inclusions. The removal of impurities can significantly improve the mechanical properties of the final product [6]. Flux mixtures in granular, powder, or briquettes form can be introduced to molten aluminium in a few possible principles, such as manual addition to the surface distribution and stirred into the melt, or typically submerged into the melt bottom with additional argon, nitrogen stirrer blowing agent. Most efficient methods for the fluxing process are the use of rotary degasser and flux injection with direct stirring process, where fluxes are constantly fed directly into the molten bath. RFI (Rotary flux injector) generally uses a granulated flux mixture as a well-established technology for efficient furnace metal preparation and treatment. Different types of cover fluxes, melt cleaning fluxes, or drossing fluxes require technology that is relevant for different aluminium purposes [7, 8, 9, 10].

The new hybrid rotor additionally improves the performance of RFI processing, which generates optimal radial metal flow, favours the melt shearing of the injected gas and fluxing salts. The increased shearing effect improves the alkali removal rates and reduces the required fluxing period [11].

This recent study investigates the different recycling ratio compositions with RFI cleaning efficiency and their impact on the final mechanical properties of the wrought aluminium alloys 6xxx modified with Zr. Quantity and quality evaluation of inclusions were represented with porous disc filtration apparatus (PoDFA), spectral chemical analysis, light and electron microscopy. The main goal of the research was to test cleaning efficiency through different secondary content to achieve the

Tabela 1. Kemijska sestava preiskovanih modificiranih zlitin Al-Mg-Si (v mas. %).

Table 1. Chemical compositions of the investigated modified Al-Mn-Si alloys (in wt. %).

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Pb	Zr
1.20	up to	up to	0.55	0.80	0.12	up to	up to	up to	up to
1.30	0.25	0.1	0.70	0.90	0.15	0.2	0.05	0.05	0.15

Interni odpadki - krožni: Surovina, ki nastaja v internih proizvodnih obratih pri predelavi končnega pol-izdelka in se vrne v proces pretaljevanja v čisti obliki, brez drugih nečistoč (čisti Al trakovi, folija, profili, livarniški čisti odpadki,…).

Sekundarni odpadki (Pre-Consumer): Surovina, ki nastaja iz sekundarnega odpadnega procesa med proizvodnim procesom različnih obdelav in predelav do končnega izdelka. Med te uvrščamo ponovno uporabljene sekundarne surovine iz procesa predelav, ponovne priprave (šrediranje/mletje) ali odpadki, ki jih je mogoče predelati v istem procesu, v katerem so nastali. Takšne surovine prihajajo predvsem iz zaprtih zank procesne predelave končnega izdelka (ostanki od kovanja, ostanki folij od lakiranja/barvanja,…)

Sekundarni odpadki (Post-Consumer): Surovina, ki se vrača v proces recikliranja iz gospodinjstev ali komercialnih, industrijskih ali drugih procesov, pri katerem končni izdelek ni več uporaben ali funkcionalen za namene uporabe in jih kot takega ni več mogoče uporabiti za prvotno načrtovan namen. Ta surovina vključuje tudi materiale iz distribucijskih verig, surovine iz zunanjega eksternega vira z delno onesnaženimi odpadki in z možnostjo kontaminacije različnih organskih in anorganskih snovi kot so olje, emulzija, folije, laki in barve. Med te surovine uvrščamo barvne profile, ISO profile, Offset plošče, pločevinske in druge kontaminirane frakcije.

Primarni Al: Surovina v obliki različnih dimenzijskih formatov, kot so highest mechanical properties of the final products.

2 Methods & Materials

An industrial database of complete traceability parameters of batches, raw material composition was analysed on aluminium alloys Al-Mg-Si, modified with Zr (EN AW 6182). Chemical compositions of analysed alloys were according to standard EN 573-3, with different limits for various elements and with Zr content up to 0,15 wt. % (Table 1).

Several secondary raw material recipes content were prepared for the charge and re-melted in the multi-chamber furnace, capacity of 50 t (SMS-Hertwich). Recycling content (RC) of Pre consumer and Post consumer aluminium scrap was variate from 12,5% – 52,8% of composition charge content, where classification for input charge recipes consists from different types of raw materials:

Internal clean raw material-scrap: Raw material comes from internal round production steps in clean form and with no other contamination, such as billets end/front cut, clean extruded profile, sheets.

Pre-consumer scrap: Raw material from the waste stream during a manufacturing process. Reutilized raw material is excluded, such as rework, regrind, or scrap generated in a process and capable of being reclaimed within the same process that generated it. Such raw material comes mainly from internal closed loop as clean

RSI-sekundarni ingoti ter primarni ingoti standarne kakovosti P0610 in P1020.

Za vložek je bilo pripravljenih več različnih receptur sekundarnih surovin, ki so bile staljene v več-komorni peči s kapaciteto 50 t (SMS-Hertwich). Delež recikliranja (RC) Pre-Consumer in Post-Consumer sekundarnih odpadkov se je gibal med 12,5 % in 52,8 % sestave vložka.

Skupna količina 26,5 t staljenega aluminija je bila prelita v enokomorno peč (Sistem-Teknik), kjer je bila izvedena korekcija končne kemijske sestava in izveden postopek rafiniranja/čiščenja z RFI prikazano na sliki 1.

Ustrezna predpriprava talila (tabela 2) je bila izbrana na podlagi ustrezne granulacije, kemijskih specifik za doseganje najboljše reaktivnosti odstranjevanja vodika, alkalij (natrija, kalcija), nizke gostote, viskoznosti, najnižje evtektične točke in učinkovitosti zmanjšanja površinske napetosti med staljenim aluminijem in talilom. Tako so eksperimentalne študije talila na osnovi $MgCl_2$ in 46 % KCl pokazale, da je sestava talila eno najučinkovitejših pri zmanjševanju vsebnosti natrija, kalcija in odstranjevanju vključkov. Talilo je sestavljeno iz majhnih belih granul velikosti do 3 mm, enakomerne

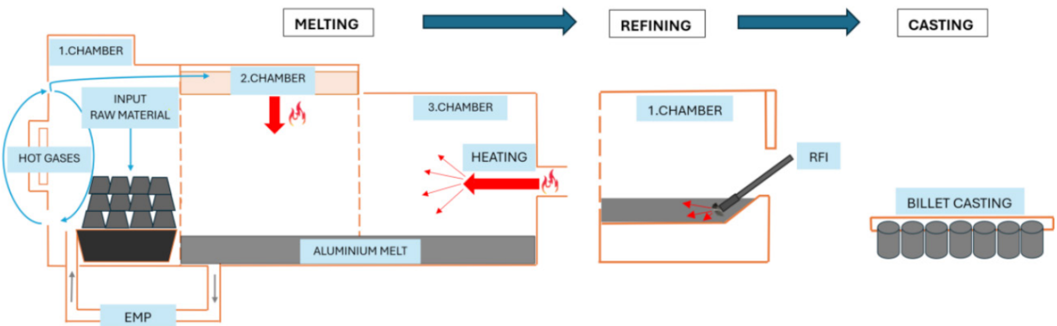
scrap, mainly remaining scrap residue coming from forging productions.

Post-consumer scrap: Raw material from households or commercial, industrial, and institutional facilities as end-users of the product, which can no longer be used for its intended purpose. This includes returns of material from the distribution chain. Such raw material from an external source also includes partly contaminated scrap with up to 1 mas. % possible organic (oil, emulsion, paint and other contaminated surface) depollutes.

Primary Al: Raw material in form of RSI-remelt secondary ingot and primary ingot, related to standard quality P0610 and P1020.

Total charge capacity of 26,5 t of molten aluminium were transferred to the one chamber furnace (Sistem-Teknik), where final chemical composition and refining/ cleaning process were done with RFI shown in Fig. 1.

The composition of the salt flux (Table 2) was selected based on granular mesh size, lower melting points, reactivity for removing hydrogen, alkalines (sodium, calcium), density, viscosity, lower eutectic point, and surface tension efficiency



Slika 1. Postopek sekundarne reciklaže aluminijevih gnetnih aluminijevih zlitin s procesno verigo priprave in rafinacije ter čiščenja taline s postopkom RFI.

Fig. 1. Industrial melt processing steps with related re-melting, refining, cleaning, and billet casting process.

obarvanosti in z do 95 % porazdelitve delcev brez prašne frakcije. Takšno rafinacijsko talilo je sestavljeno iz treh glavnih komponent: binarne soli ($KMgCl_3$), karnalita ($KMgCl_3 \times 6H_2O$) in bišofita ($MgCl_2 \times 6H_2O$) s tališčem med 487 in 530 °C ter dinamično viskoznostjo 3,05–3,34 cP pri 700 °C [12].

Tabela 2. Kemijska sestava talila (v mas. %).

Table 2. Chemical composition of fluxes (in wt. %).

Oznaka / Designation	Povprečna kemijska sestava (mas. %) / Average chemical composition (wt.%)
Sestava talila / Salt Composition	Cl = 45, K = 15, Mg = 11, O = 25, H = ostalo / Remain (mas/weight %; 54 % $MgCl_2$+46 % KCl)

Primarna reakcija z $MgCl_2$ reducira alkalije v talini na podlagi ternarnega diagrama KCl–NaCl–$MgCl_2$, vendar je zaradi previsoke temperature taljenja pri 714 °C omejen kot zanesljiv reaktant. Z dodatkom mešanice KCl (40 %) se doseže evtektična temperatura 467 °C, kar znatno zniža temperaturo ponovnega taljenja soli v talini aluminija [16].

Talilo v obliki granulata je bilo injektirano v talino s pomočjo RFI naprave (dobavitelja STAS) v količini 15 kg/šaržo, pri konstantni hitrosti dodatka talila 1 kg/min. Temperatura aluminijeve taline med obdelavo s fluksom je bila 750 ± 10 °C. Kotni položaj rotorja in hitrost vrtenja sta bila določena z uporabo modela pretoka brezmrežne metode [17] z eksperimentalnim testiranjem sistema RFI v livarski peči. Enakomerno vbrizgavanje soli v talino je mogoče doseči s kotom rotorja 45 ° in hitrostjo vrtenja 410 min^{-1} ter z uporabo grafitnega rotorja s premerom 300 mm. Med mešanjem je bil za razplinjevanje uporabljen argon s pretokom 200 l/min. Po obdelavi taline s talilom je bil v talino dodan modifikator na osnovi AlTiB, da je bila dosežena končna sestava

reduction between molten aluminium and flux. Thus, experimental studies as flux based on MgCl2 and 46% KCl flux composition showed one of the most effective in reducing the content of sodium, calcium, and inclusions removal. The flux consists of small white granules with a uniform coloration, measuring up to 3.0 mm in size and up to 95% particle distribution size without dust fraction. Such refining flux consists of three main components: Binary salt (KMgCl3), Carnallite (KMgCl3×6H2O), and Bischofite (MgCl2×6H2O), with a melting point between 487 – 530 °C and dynamic viscosity 3.05-3.34 cP at 700 °C [12].

Based on the ternary diagram KCl–NaCl–$MgCl_2$, the $MgCl_2$ primary reaction reduces alkali, but due to its high melting point at 714 °C is limited as a reliable reactant. With a KCl (40%) mixture addition composition reaching eutectic temperature of 467 °C, which significantly reduces the remelting temperature of the salt in the aluminium melt [16].

The solid salt flux was injected with RFI (from STAS manufacturer) in an amount of 15 kg/charge, was added into a vessel with a constant feeding rate of 1 kg/min. The temperature of the aluminium melt during flux treatment was 750 ± 10 °C. Angle position of the rotor and rotation speed were determined using a mesh-less flow model [17] by experimental testing of the RFI system in the casting furnace. Uniform salt injection into the melt can be achieved by the rotor angle of 45° and the rotation speed of 410 min^{-1}, using a graphite impeller 300 mm in diameter. During mixing, argon was used for degassing, with a flow rate of 200 L/min. After fluxing, the melt was grain refined with AlTi3B1 grain refiner to achieve the final composition 0.025–0.030 wt.% Ti in the melt. The melt was additionally melt-refined and degassed with SIR-Siphon

0,025–0,030 mas. % Ti v talini. Talina je bila dodatno razplinjena z napravo SIR - Siphon Inert Reactor (Hycast). Končna filtracija aluminijeve taline je bila izvedena skozi keramični penasti filter (CFF) s 50 ppi in ulita s tehnologijo Hot-Top Air-Slip v drogove premera 279 mm. [18]. Uliti drogovi so po toplotni obdelavi (homogenizaciji) bili iztiskovani v palice s premera 46 mm. Mehanske lastnosti so bile izmerjene na Zwick 250 v skladu s pripravljeno epruveto v skladu s standardom DIN 50125 z D_0 = 10 mm ter izmerjene pri doseženih pogojih T6.

Čistost zlitine je bila analizirana s pomočjo PoDFa (Porous Disc Filtration Apparatus) naprave (ABB) [19] na način, da se vzorec staljene taline 30 minut po končani obdelavi s talili filtrira skozi porozni disk filtra naprave. Vzorci za kvalitativno vsebnost vključkov so bili analizirani s svetlobnim mikroskopom (Axio Observer, Zeiss) in vrstičnim elektronskim mikroskopom (SEM Jeol JSM 6610LV, Jeol), opremljenim z energijsko disperzivnim spektrometrom (EDS). Kvantitativno število vključkov je bilo pridobljeno z merjenjem površine vključkov, deljene z maso filtrirane taline izražene v mm^2/kg.

Kemijska analiza zlitine, vključno z vsebnostjo alkalijskih elementov (Na, Ca), je bila izvedena z uporabo instrumenta Spectro S101, SPECTRO Analytical Instruments GmbH (Nemčija). Vzorci svetlobne (LM) in vrstične elektronske (SEM) mikroskopije so bili mehansko brušeni z uporabo SiC papirjev z granulacijo od 320 do 4000 in polirani z diamantno pasto velikosti 9 µm, 6 µm in 3 µm. EDS analize so bile izvedene s poliranimi vzorci, medtem ko je svetlobna mikroskopija zahtevala kemično jedkanje z Weckovim reagentom, ki je vseboval 2 g KMnO4, 1 g NaOH in 50 ml destilirane vode. Velikost zrn ulitih drogov je bila določena v skladu s standardom ASTM E112-24.

Inert Reactor (Hycast). Final aluminium melt filtration was done through 50 ppi ceramic foam filter (CFF) and cast with Hot-Top Air-Slip Technology in 279 mm billets in diameter. [18]. Homogenized billets were extruded to 46 mm bars diameter. Mechanical properties were measured on Zwick 250 according to a prepared probe related to standard DIN 50125 with D_0 = 10 mm and measured in T6 condition.

The alloy cleanliness was tested using the PoDFA (Porous Disc Filtration Apparatus) method (ABB) [19]. A sample of molten metal was taken from the melt 30 minutes after finishing flux injection and filtered through a porous disc to capture inclusions. The samples for qualitative inclusions content were analysed using a light microscope (Axio Observer, Zeiss), scanning electron microscope (SEM Jeol JSM 6610LV, Jeol) equipped with an energy dispersive spectrometer (EDS). A quantitative number of inclusions was obtained by measuring the area of inclusions, divided by the mass of filtered melt, present in mm^2/kg.

The chemical analysis of the alloy, including the contents of alkali elements (Na, Ca), was carried out using Spectro S101, SPECTRO Analytical Instruments GmbH, Germany. The light (LM) and scanning electron (SEM) microscopy samples were mechanically ground using SiC papers with granulations of 320 to 4000 and polished using 9 mm, 6 mm, and 3 mm diamond paste. EDS analyses were carried out using polished samples, while light microscopy required chemical etching with Weck's reagent, consisting of 2 g $KMnO_4$, 1 g NaOH, and 50 mL of distilled water. The grain size of the cast billets was determined according to the standard ASTM E112-24.

3 Rezultati in diskusija

3.1 Mikrostruktura

V aluminijevi zlitini Al-Mg-Si sta Mg in Si glavna legirna elementa, ki skupaj tvorita intermetalno spojino Mg_2Si. Zlitine Al-Mg-Si so tipične zlitine za utrjevanje z izločanjem, kjer se učinek utrjevanja običajno doseže z izločki β′ in β″, ki predstavljajo metastabilne ravnotežne faze Mg_2Si [13]. Topnost Mg in Si v trdni raztopini aluminija (α-Al) je do 0,5 mas. %. Fe in Mn sta prisotna v različnih intermetalnih fazah. Na robovih ulitih palic iz aluminijeve zlitine EN AW 6182 prevladujejo intermetalne spojine Mg_2Si (oblika kitajske pismenke), faze z Fe (kot so: Si (Al-Fe-Si), …) in faze z Fe in Mn (kot so: Al-Mn-Fe-Si, …). Oblika in porazdelitev intermetalnih faz se spreminjata po prerezu palice.

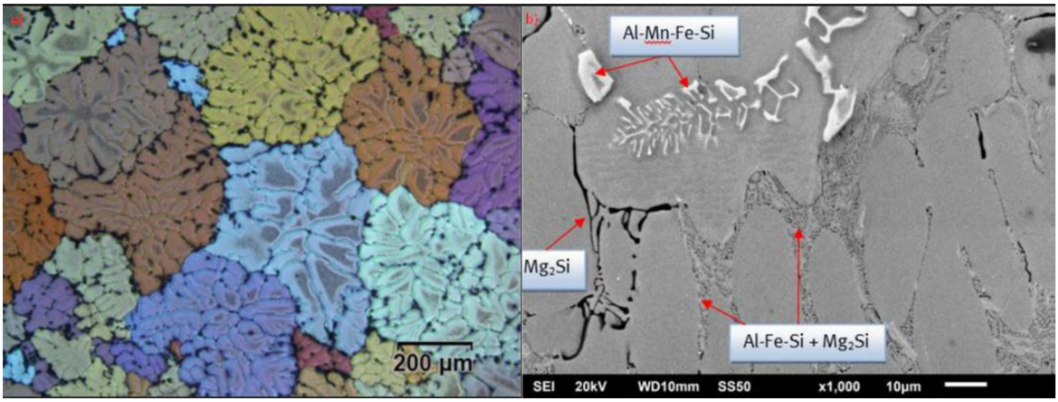
Za zlitine Al-Mg-Si z vsebnostjo Mn in/ali Cr se med segrevanjem ulitih zlitin, na temperaturo homogenizacije, s hitrostjo segrevanja 3 K min^{-1} na iglastih fazah β′-Mg_2Si tvori vmesna faza, imenovana „u-faza“. Z nadaljnjim postopkom toplotne obdelave se Mn in Mn + Cr disperzoidi,

3 RESULTS AND DISCUSSION

3.1 Microstructure

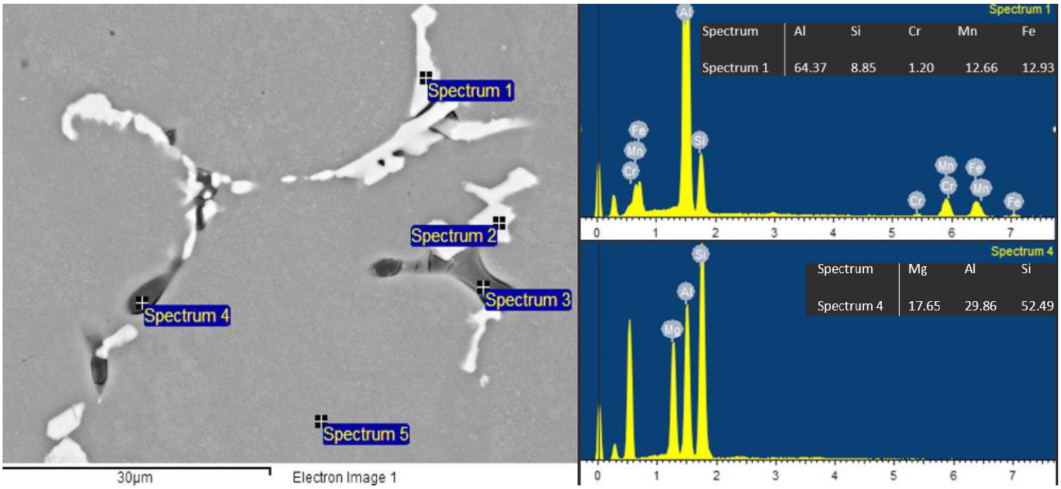
In the Al-Mg-Si aluminum alloy, Mg and Si are the main alloying elements, which together form the intermetallic compound Mg_2Si. Al-Mg-Si alloys are typical precipitation hardening alloys, where the strengthening effect is usually achieved through β′ and β″ precipitates representing metastable variants of the equilibrium Mg_2Si phase [13]. The solubility of Mg and Si in the solid solution of aluminum (α-Al) is up to 0.5 wt. %. Fe and Mn form or are present in various intermetallic phases. At the edges of cast billets of the EN AW 6182 aluminum alloy, the intermetallic compounds Mg_2Si (Chinese character shape), phases with Fe (such as: Si (Al-Fe-Si),…), and phases with Fe and Mn (such as: Al-Mn-Fe-Si, …) dominate. The shape and distribution of the intermetallic phases varies across the cross-section of the cast billets.

For alloys Al-Mg-Si containing Mn and/or Cr, it was shown that during the heating of the as-cast alloys to homogenization



Slika 2. Mikrostruktura Al-Mg-Si litega droga a), SEM posnetek z dendritnimi kristalnimi zrni in intermetalnimi fazami - Al(Mn,Fe)Si, Mg_2Si b).

Fig. 2. A crystal grain structure of an Al-Mg-Si in as-cast billet a) and SEM with dendritic crystal grains with reach intermetallic phases-Al(Mn,Fe)Si, Mg_2Si in as cast billet b).



Slika 3. Mikrostrukturni posnetek BEC in spektralna analiza v mas. % na intermetalnih fazah Al(Mn,Fe)Si, Al(Mn–CrFe)Si, Mg_2Si v homogeniziranem drogu.

Fig. 3. BEC field image and dedicated spectrums in wt. % on intermetallic phases Al(Mn,Fe)Si, Al(Mn-Cr,Fe)Si, Mg2Si in homogenized billets.

heterogeno tvorijo na izločkih „u-faze“ in so prisotni vse do končnega raztapljanja v aluminijevi matrici. Nukleacijska mesta za disperzoide s Cr niso bila dokončno identificirana. V zlitinah, ki vsebujejo Mn in/ali Cr, se disperzoidi imenujejo izločki faz na osnovi Al(Mn–CrFe)Si [36].

Med homogenizacijskim žarjenjem pod temperaturo solidus, se kemijska sestava dendritnih kristalnih zrn α-Al izenači, intermetalne spojine Mg_2Si pa se raztopijo v trdni raztopini α-Al. Intermetalne faze na osnovi Fe in Mn ter Al_3Zr se ne raztopijo in ostanejo morfološko nespremenjene. Modificirana zlitina 6082 z Zr, kaže v gašenem stanju povečanje trdnosti za 28 MPa v primerjavi z osnovno zlitino. Disperzoidi običajno prispevajo k povečanju trdnosti z Orowanovim zorenjem zaradi tipičnih velikosti, ki preprečujejo, da bi jih dislokacije pri gibanju prerezale. Umetno staranje povzroči nadaljnje povečanje napetosti tečenja (17 MPa), kar ustvari skupno povečanje natezne trdnosti za 45

temperature at a heating rate of 3 K min^{-1}, an intermediate phase, referred to as the ‘u-phase’, nucleated on the β′-Mg_2Si needles. With continued annealing, dispersoids containing Mn and Mn + Cr nucleated heterogeneously on the ‘u-phase’ precipitates before these precipitates dissolved. The nucleation sites for the dispersoids with Cr were not conclusively identified. In alloys containing Mn and/or Cr, the dispersoids are referred to as the Al(Mn-CrFe)Si phase precipitates [36].

During homogenization annealing, which takes place below the solidus temperature, the chemical composition of the dendritic α-Al crystal grains is equalized, and the intermetallic compounds Mg_2Si dissolve in the α-Al solid solution. The intermetallic phases based on Fe and Mn and Al_3Zr do not dissolve and remain morphologically unchanged. In the as-quenched state, 6082, which is modified by Zr-addition only, shows a strength increase of 28 MPa compared to the base

MPa v popolnoma utrjenem stanju T651 v primerjavi z zlitino 6082 [14].

3.2 Vključki

Vključki v talini in posledično v izdelkih se lahko pojavljajo v obliki kompleksnejših spojin in struktur, katerih poglaviten vpliv imajo na mehanske in druge fizikalne lastnosti aluminijevih zlitin. Dokazano je, da vključki poslabšajo mehanske lastnosti ulitkov, povečajo nagnjenost k utrujanju in poslabšajo duktilnosti, saj predstavljajo mikro lokacije koncentracije napetosti v kristalni strukturi [15].

Vključke lahko razdelimo v tri glavne skupine:

Nekovinski vključki:

- Al_2O_3, MgO in kompleksni oksidi v klasterjih
- aglomerati TiB_2
- soli (kovinski kloridi)
- materiali iz ognjevzdržne obloge
- karbidi

Kovinski vključki:

- Cr, Cr-Mn in Al_3Ti (Zr)
- intermetalne faze Fe-Si-Mn
- neraztopljeni legirni elementi

Oksidni filmi:

- Al_2O_3
- MgO
- špineli $MgAl_2O_4$

Na obnašanje nekovinskih vključkov v aluminijevih talinah vplivajo različni mehanizmi, kot so konvekcija, privlačne sile, magnetna polja, vzgon in Brownovo gibanje. Velikost vključkov se lahko giblje do nekaj sto mikronov in jih je mogoče opaziti v obliki posameznih delcev, klasterjev in aglomeratov. Vključki lahko vplivajo tako na mehanske lastnosti kot tudi na kakovost površine izdelkov [20].

alloy. Dispersoids typically contribute to a strength increase via Orowan hardening, due to typical sizes, which prevents them from being cut by dislocations. Artificial aging causes a further increase in yield strength (17 MPa), which generates a total increase of 45 MPa in the fully hardened T651 state compared to 6082 [14].

3.2 Inclusions

Inclusions are undesirable phases incorporated into the final casting, which on the whole, are detrimental to the required mechanical, fatigue, electrical, or thermal properties. Inclusions have been shown to degrade the mechanical properties of castings, primarily fatigue and ductility, primarily as stress concentrators or crack initiators within the casting [15]. Inclusions can be listed in three main groups:

Non-metallic inclusions:

- Al_2O_3, MgO, and spinel in compacts or clusters
- TiB_2 agglomerates
- Salt (metal chlorides)
- Material from the refractory lining
- Carbides

Metallic inclusions:

- Cr, Cr-Mn, and Al_3Ti (Zr)
- Fe-Si-Mn intermetallic
- Undissolved alloying elements

Oxide films:

- Al_2O_3
- MgO
- Spinel

The behaviour of non-metallic inclusions in aluminium melts is influenced by different mechanisms such as convection, attractive forces, magnetic fields, buoyancy, and Brownian motion. The size of inclusions may vary from a few hundred microns, and they can be observed in the form of single

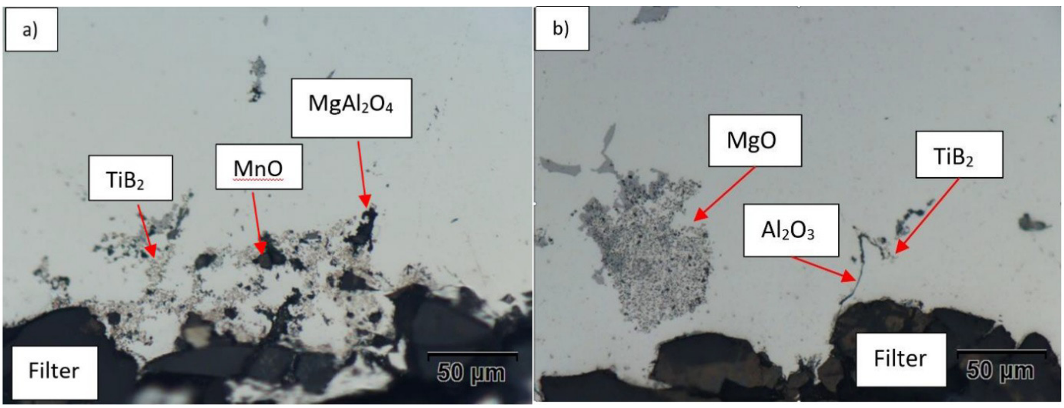
Špinel nastane z reakcijo aluminijeve taline z MgO, ki izvira iz ognjevzdržne obloge in/ali stika med oksidom Al_2O_3 ter talino z visoko vsebnostjo Mg, pri čemer nastane kompleksna faza $MgAl_2O_4$. TiB_2 delci so prisotni kot del modifikatorja kristalnih zrn Al-Ti-B v odpadni sekundarni surovini materiala. Al_4C_3 je bil zaznan v zanemarljivem deležu in lahko nastane z reakcijo taline Al z organskimi snovmi [21, 22] in MgO z raztopljenim magnezijem ter prostim kisikom. Delci MnO/FeO so lahko prisotni kot del onesnaženega vira legirnih elementov, kar je na splošno vzrok za oksidirane delce prahu, zaznane v predzlitinah.

Z metodo filtracije PoDFA je mogoče slediti identifikaciji vrst in količin nekovinskih vključkov. Analiza filtrirne pogače za določitev kakovosti taline je bila opazovana s svetlobno mikroskopijo in SEM. Slika 4 prikazuje tipično svetlobno mikrografijo nekovinskih vključkov in oksidov pred in po obdelavi taline s talili.

V tabeli 3 in 4 so prikazani rezultati kvantitativne analize PoDFA, ki prikazujejo vsebnost vsakega posameznega nekovinskega vključka pred in po obdelavi

particles, clusters, and agglomerates. Inclusions can influence both the mechanical properties and the surface quality of products [20].

Formation of spinel was introduced as an aluminium molten reaction with MgO, which comes from refractory lining and/or interface between Al_2O_3 and molten metal with high Mg content, to form a complex $MgAl_2O_4$ phase. TiB_2 was part of the Al-Ti-B grain refiner present in the scrap. Al_4C_3 was detected in negligible proportion and can be formed by the reaction of Al melt with organic substances [21, 22] and MgO with the dissolved magnesium and oxygen from the atmosphere. MnO/FeO particles can preferably be contaminated from the external alloying process source, generally causes oxidized dust particles to be detected in master alloys. With the PoDFA filtration method the identification of nonmetallic inclusion types and quantities can be traced. Analysis of filter cake to determine melt quality was observed with a light microscopy and SEM. Figure 4 shows a typical light micrograph of non-metallic inclusions and oxides before and after melt treatment with fluxes.



Slika 4. Optična mikroskopija vključkov v filtru PoDFA: pred a) in po obdelavi taline s talili b).

Fig. 4. Optical microscopy of non-metallic inclusion in PoDFA filter: before a) and after melt treatment with fluxes b).

rafiniranja kovinskega aluminija z RFI. Aglomerirani delci TiB_2, ki izhajajo iz modifikatorja kristalnih zrn in so prisotni še dodatno v odpadni surovini, predstavljajo največji delež nekovinskih vključkov in v povprečju predstavljajo več kot 50 % celotne količine vključkov. Delež vključkov je bil pred obdelavo taline vedno višji, kar kaže na učinkovitost čiščenja taline s

Tables 3 and 4 give the results of the quantitative PoDFA analysis, showing the content of each individual non-metallic inclusion before and after aluminium metal refining treatment with RFI. The agglomerated TiB_2 particles, arising from the grain refiner and the scrap, present the largest fraction of the non-metallic inclusions, and it was achieved an average

Tabela 3. Vsebnost vključkov določena s PoDFA pred postopkom RFI (Batch = št. šarža).

Table 3. Contents of non-metallic inclusions determine with PoDFA before RFI.

Šarža / Batch No.	MgO	Spinel	Al_2O_3	Fe/Mn oksidi / oxides	TiB_2
	mm²/kg	mm²/kg	mm²/kg	mm²/kg	mm²/kg
Batch #1	0.770	0.357	0.206	0.019	0.526
Batch #2	0.444	0.277	0.305	0.014	0.347
Batch #3	1.072	0.852	0.247	0.027	0.550
Batch #4	0.206	0.506	0.075	0.225	0.862
Batch #5	0.202	0.321	0.174	0.028	0.193
Batch #6	0.249	0.430	0.263	0.042	0.402
Batch #7	1.029	0.995	0.583	0.137	0.686
Batch #8	0.886	0.790	0.192	0.120	0.407
Batch #9	0.057	0.407	0.066	0.000	0.417
Batch #10	0.039	0.212	0.048	0.000	0.666

Tabela 4. Skupni vključki in delež redukcije vključkov, določena s PoDFA pred in po RFI (Batch = št. šarža).

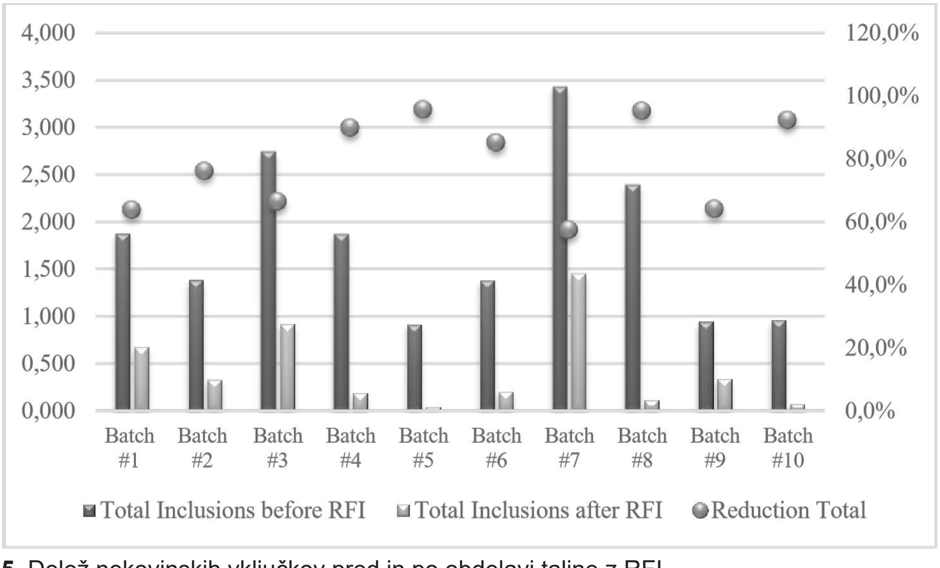
Table 4. Total inclusions and reduction ratios of non-metallic inclusions determining with PoDFA (before and after RFI).

Šarža / Batch No.	Skupni vključki pred RFI / Total Inclusions before RFI	Skupni vključki po obdelavi RFI / Total Inclusions after RFI	Redukcija / Reduction TiB_2	Redukcija oksidi / Reduction Oxides	Redukcija skupna / Reduction Total
	mm²/kg	mm²/kg	mas. %	mas. %	mas. %
Batch #1	1.877	0.679	66.5	62.9	63.9
Batch #2	1.386	0.330	59.4	82.3	76.2
Batch #3	2.748	0.922	63.1	67.3	66.5
Batch #4	1.874	0.190	90.5	89.3	89.9
Batch #5	0.918	0.040	89.6	97.2	95.7
Batch #6	1.386	0.205	85.8	85.1	85.2
Batch #7	3.432	1.455	38.5	62.4	57.6
Batch #8	2.395	0.113	84.8	97.5	95.3
Batch #9	0.947	0.339	56.8	69.8	64.2
Batch #10	0.965	0.074	91.7	93.6	92.3

talilom in doseženo učinkovitost zniževanja vsebnosti vključkov od 57,6 % do 95,7 %. Skupna vsebnost vključkov pred postopkom rafiniranja z RFI je bila najvišja pri serijski proizvodnji serije št. 7, s 3,432 mm²/kg vključkov v talini, kar je povezano z nizko vsebnostjo kovinskih vključkov iz priprave surovine. Učinkovitost rafiniranja in čiščenja taline s postopkom RFI je doseglo 95,7 % odstranitve vseh vključkov.

Slika 5 prikazuje deleže vključkov pred in po obdelavi taline z RFI v odvisnosti od njihove učinkovitosti odstranitve. Količina nekovinskih vključkov pred in po obdelavi taline je močno odvisna od začetnega deleža. Zmanjšanje nekovinskih vključkov je bilo v povprečju doseženo za več kot 78,7 %, v vsaki poskusni šarži pa med 57,6 in 95,7 %. Zaradi zaporednega števila poskusov in dodatnih spremenljivk, ki se pojavljajo v industrijskem okolju, je bila učinkovitost zmanjšanja različnih stehiometrij vključkov zelo visoka in je v vseh vzorcih vedno dosegla najmanj 73 % of more than 50% of complete inclusions amount. The inclusion fraction was always higher before the melt treatment, indicating the efficiency of the fluxes and the achieved refining efficiency from 57.6% to 95.7% of the inclusion's removal. The total inclusion's content before the RFI refining process was highest at serial batch production Batch#7, with 3.432 mm²/kg inclusions in the melt, and related to low metal inclusion content from the raw material preparation, the efficiency of RFI refining showed a total 95.7% of non-metallic inclusion and oxides removal.

Figure 5 shows the fractions of the non-metallic inclusions before and after RFI melt treatment in dependence on their efficiency of removal and shows that the amount of non-metallic inclusion before and after melt treatment strongly depends on the initial fraction. Reduction of non-metallic inclusions was reached in average more than 78.7% and in every trial charge between 57,6 – 95,7%. Due to the serial



Slika 5. Delež nekovinskih vključkov pred in po obdelavi taline z RFI.

Figure 5. The fractions of the non-metallic inclusions before and after RFI melt treatment.

uspešnost redukcije. Najvišjo učinkovitost je bila analizirana pri zmanjšanju količine špinela, kjer je bila povprečna učinkovitost rafinacijske soli skupaj 82 %.

Dodaten vpliv na vsebnost vključkov po rafiniranju z RFI je povezan tudi s časom odstajanja taline po obdelavi, ki lahko prispeva k boljši odstranitvi vključkov zaradi zadostnega časa fluktuacije vključkov na površino ali posedanja glede na specifične gostote vključkov (Stokesov zakon). Tudi prevelika količina vbrizgane mešanice talila v talino aluminija igra pomembno vlogo pri povečanem deležu nekovinskih vključkov, saj preostale nečistoče izvirajo iz komponent mešanice soli, zato je mogoče v talini aluminija zaslediti tudi preostanke talil, kar povečuje delež nekovinskih vključkov [23]. Celotna industrijska pot za predelavo kovin in zmanjšanje vključkov lahko prispeva k dodatni obdelavi taline aluminija pred litjem, vključno s filtracijskimi sistemi CFF tik pred litjem [24].

3.3 Odstranjevanje alkalij in alkalijskih elementov

Alkalijski in zemljoalkalijski elementi so zelo pogosto prisotni v gnetnih Al-zlitinah. Ena glavnih funkcij procesa rafinacije taline s talili je odstranjevanje elementov, ki znatno poslabšajo mehanske in druge lastnosti aluminijeve zlitine. Razmerje odstranjevanja alkalijskih/zemljoalkalijskih elementov (Na, Ca, Li,…) ni le kemično omejeno s hitrostjo reakcije, temveč je omejeno tudi s prenosom mase taline, reakcijsko površino, delci talila in površino taline.

Reakcijo med aluminijevo talino in talilom je predstavljena z diferencialno enačbo (1) in (2) [25, 26]:

$$\frac{dC}{dt} = -\frac{kA}{V}\,(C - C^{*}) \qquad (1)$$

kjer je:

number of experiments and additional variables occurring in the industrial environment, the efficiency of including different stoichiometry reduction was very high and always reached a minimum of 73% in all samples. The highest efficiency was observed by spinel level quantities reduction, where in average, efficiency of refining salt was 82% in total.

Additional influence on the inclusions content after RFI refining is also linked to the holding time, which can contribute to better removal of inclusions due to sufficient time to either sink to the furnace bottom or float to the melt surface, depending on their density (Stoke's law). Also, overdosing the flux injection mixture quantity to aluminium metal plays a significant role to the increased fraction of non-metallic inclusions, as the remaining impurities come from salt mixture components, so in addition, fluxes could be traced in the aluminium melt, increasing the fraction of non-metallic inclusions [23]. Complete industrial path for metal processing and inclusions reduction can contribute to additional aluminium melt processing before casting, including with CFF filtration systems just before casting to reduce the fraction of non-metallic inclusions [24].

3.3 Removal of alkali and alkaline elements

Alkali elements and alkaline earth elements are very often present in wrought Al-alloys. One of the main functions of the flux refining process is to remove elements that substantially deteriorate the mechanical and other properties of aluminium alloy. The ratio of removal of alkaline/alkaline earth elements (Na, Ca, Li,…) is not only chemically limited, while fast reaction, but is also limited by mass transfer of metal,

C(t) = koncentracija nečistoče (Na/Ca) v talini v času t (npr. ppm ali mas. %),
C* = površinska koncentracija
k = koeficient prenosa mase (m/s) za specifično interakcijo (mehurčki, dispergirani delci soli, kontaktna površina),
A = efektivna kontaktna površina med kovino in reaktivno fazo – npr. skupna površina mehurčkov ali skupna površina dispergiranih kapljic talila
V = volumen rafinacijske taline (m³)

Redukcija alkalij in elementov v sledovih je opisana z eksponentno odvisnostjo, prikazanega v enačbi (2): Pri veliki površini je koncentracija C* = 0 zaradi neposrednega stika koncentracije soli/taline:

$$C(t) = C_0 e^{-k_{eff} t} \; ; \; k_{eff} = \frac{kA}{V} \; ; \quad (2)$$

kjer: k_{eff} = koeficient razmerja med efektivnim stikom in volumnom rafinirane taline

Mešanica soli z $MgCl_2$ ima najpomembnejšo vlogo pri odstranjevanju Na in Ca v talini z naslednjimi kemijskimi reakcijami [27]:

1. $MgCl_2$ (l) + 2[Na] = 2NaCl (l) + [Mg] (3)
2. $MgCl_2$ (l) + [Ca] = $CaCl_2$ (l) + [Mg] (4)

kjer: (l) = pomeni tekoče stanje, [Na, Ca] pa raztopljeni element v talini Al.

Prosti energiji obeh reakcij (3) in (4) sta izjemno negativni z zelo visoko ravnotežno reakcijsko konstanto Kp, ki jo je mogoče izračunati z enačbo (5).

$$\Delta G_0 = -RT\ln(K_p) \quad (5)$$

kjer je:
R = splošna plinska konstanta
T = absolutna temperatura

Dejanska reakcijska konstanta za reakcijo (1) se izračuna:

$$K_p = \frac{a_{NaCl}^2 \cdot a_{Mg}}{a_{MgCl^2} \cdot a_{Na}^2} \quad (6)$$

kjer:
a = aktivnost posameznih elementov/spojine

reaction surface, flux particles, and melt surface. RFI with effective reaction between aluminium melt and flux is present by differential equation 1,2 [25, 26]:

$$\frac{dC}{dt} = -\frac{kA}{V}\,(C - C^*) \quad (1)$$

where:
C(t) = concentration of impurity level (Na/Ca) in the metal at time t (e.g. ppm or wt. %), C∗= surface concentration
k = mass-transfer coefficient (m/s) for specific interaction (bubbling, suspended salt particles, contact area),
A = effective contact area between metal and reactive phase — e.g., total surface area of bubbles or total surface area of suspended flux droplets
V = volume of refining melt (m³)

The reduction of alkalis and trace elements is described by the exponential equation (2): At a large surface area, the concentration C* = 0 due to the direct contact of the salt/melt concentration:

$$C(t) = C_0 e^{-k_{eff} t} \; ; \; k_{eff} = \frac{kA}{V} \; ; \quad (2)$$

where: k_{eff} = coefficient ratio between effective contact and refining melt volume

Salt mixture with $MgCl_2$ contributes to the most crucial role in removing Na and Ca in the melt, by the following chemical reactions [27]:

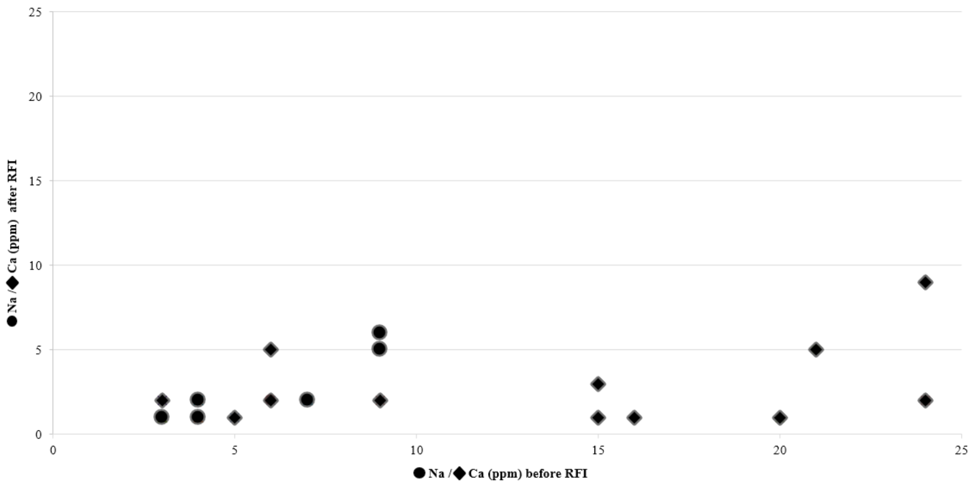
1. $MgCl_2$ (l) + 2[Na] = 2NaCl (l) + [Mg] (3)
2. $MgCl_2$ (l) + [Ca] = $CaCl_2$ (l) + [Mg] (4)

Where: (l) = means the liquid state, and [Na, Ca] dissolved elements in the Al-melt.

The free energies of both reactions (3) and (4) are hugely negative with a very high equilibrium reaction constant K_p, which can be calculated using equation (5).

$$\Delta G_0 = -RT\ln(K_p) \quad (5)$$

where:
R= gas constant
T= absolute temperature



Slika 6. Porazdelitev (ppm) Na in Ca pred in po RFI obdelavi taline s talili.

Figure 6. The distribution (ppm) of Na and Ca before and after RFI shown significant efficiency of flux injections refining process to aluminium melt with final result of both trace elements below 10 ppm.

Aktivnosti je mogoče nadomestiti z njihovimi koncentracijami, povezanimi z nizkimi vrednostmi Na in Mg. Reakcija poteka, dokler je K < Kp. Z dodatkom talila v območju industrijskih poskusov z 1 kg na 1 t taline reakcijski mehanizem neprekinjeno doseže zadostno zmanjšanje teh elementov v sledovih.

Kemijske analize vseh preiskovanih šarž so pokazale, da je bila vsebnost nekaterih alkalij in alkalnih elementov pod kemijsko detekcijsko mejo 1 ppm. Na in Ca sta pokazala zelo nizko vsebnost, njune detekcijske meje pa so bile v območju za Na 1–9 ppm in Ca 1–24 ppm (slika 6).

Po RFI obdelavi taline s talili so vsi vzorci pokazali redukcijo obeh elementov v sledovih, pri čemer vsebnost Ca in Na po postopku rafiniranja z RFI ni presegla 9 ppm. Količine Ca in Na so neodvisne od začetne vsebnosti. Večji potencial za redukcijo je bil opažen pri redukcijskem razmerju za Ca, kjer je bilo minimalno redukcijsko razmerje večje za faktor 2,67 (zmanjšanje iz 24 ppm

The actual reaction constant for the reaction (1) is calculated

$$K_p = \frac{a_{NaCl}^2 \cdot a_{Mg}}{a_{MgCl^2} \cdot a_{Na}^2} \qquad (6)$$

where:

a = activity of each element/compound

Activities can be replaced by their concentrations, related to low values of Na and Mg. The reaction takes place till K < Kp. With the addition of the flux in the range of industrial experiments with 1 kg per 1 t melt reactions mechanism continuously reaches a sufficient decrease of such trace elements.

The chemical analyses of all investigated charges showed that the contents of some alkali and alkaline elements were below the chemical detection of 1 ppm. Na and Ca showed very low content and their detection limits in the range interval for Na 1-9 ppm and Ca 1-24 ppm (Figure 6).

After the RFI refining process was all conducted, samples showed a reduction for both elements, where the content of na 9 ppm). Takšni rezultati kažejo na visoko učinkovitost uporabljene mešanice soli in postopka rafiniranja z RFI.

3.4 Korelacija med različnim deležem uporabe sekundarnih surovin na čistočo taline ter mehanskimi lastnostmi zlitine Al-Mg-Si

Serijska proizvodnja gnetnih aluminijevih zlitin je zahtevala širše raziskave recipročnih spremenljivk v celotnih proizvodnih parametrih in proizvodnih verigah, vključno z veliko količino podatkov o recepturah vhodnih materialov, njihovi kemijski sestavi, stopnji kontaminacije, parametrih procesov pretaljevanja, rafiniranja in modifikacije, parametrov toplotnih obdelav in drugih pogojev, povezanih s tehnološkimi procesi glede na namen izdelave končnega izdelka. Aluminijeva zlitina Al-Mg-Si z Zr je bila razvita za doseganje najvišjih mehanskih lastnosti v avtomobilski industriji, uporabljenih za nadaljnjo predelavo v obliki odkovkov.

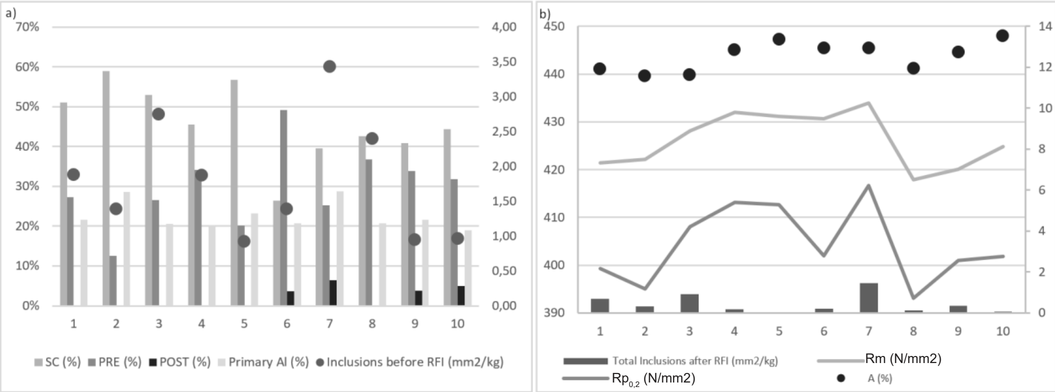
Dodatna preiskava mehanskih lastnosti zlitine EN AW 6182 je bila opravljena za potrebe študije korelacije v odvisnosti rezultata rafiniranja in vsebnostjo sekundardnih odpadnih surovin v različnih recepturah. Na končnih iztiskovanih palicah so bile dodatno analizirane mehanske lastnosti za natezno trdnost. V vseh vzorcih serije so bile mehanske lastnosti končnih ekstrudiranih palic presežene glede na zahtevane meje (za natezno trdnost (UTS ozi. R_m) = min. 380 N/mm^2, napetost tečenja (YS ozi.$Rp_{0,2}$) = min. 360 N/mm^2, raztezek (A) = min. 8 %). Dejansko izmerjene mehanska lastnosti so bile podane z ustreznimi rezultati pripravljenih epruvet z doseženim UTS/R_m = 417,9–433,9 N/mm^2, $Rp_{0,2}$ = 393,1–416,6 N/mm^2, A = 11,6–13,4 % in doseženim povprečjem R_m = 426,2 N/mm^2, $Rp_{0,2}$ = 404,3 N/mm^2 in A = 12,5 % (slika 7). Uporabljena je bila različna

Ca and Na do not reach over 9 ppm after the RFI refining process. The amounts of Ca and Na are independent of the initial content. Higher potential for reduction was observed for the Ca reduction ratio, where the minimum ratio of reduction was greater by a factor of 2,67 (reduction from 24 ppm to 9 ppm). Such results show the high efficiency of the used salt mixture and RFI refining procedure.

3.4 Scrap content correlation to the melt cleanliness and mechanical properties of alloy Al-Mg-Si

Serial production of aluminium wrought alloys required wider investigations of reciprocal variables in complete production parameters and chain production, involving big data mass for input material recipes, their chemical compositions, contamination level, remelting, refining, and modification process parameters, homogenization, and other traced conditions related to final technology downstream data records according to the purpose of the final product. Aluminium alloy Al-Mg-Si with Zr was developed for the highest mechanical properties in the automotive industry as a forged part in assembled chassis main support, which can play a significant important safety issues in the complete lifecycle of car usage.

Additional investigation of the mechanical properties of alloy EN AW 6182 was done to correlate dependence between refining results and charge content recipes. A mechanical probe for ultimate tensile strength (R_m), yield strength ($Rp_{0,2}$) and elongation (A) on final extrusion bars was prepared and analysed. In all batch samples, the mechanical properties of final extruded bars achieved very high



Slika 7. Vsebnost različne vsebnosti sekundarnih surovin glede na količino vključkov pred RFI (a) in končne mehanske lastnosti ekstrudiranih palic v odvisnosti od količine vključkov po RFI (b).

Figure 7. The content of charge mixture in relation to inclusion quantity before RFI (a) and the final mechanical properties of extruded bars in relation of total inclusions after RFI (b) for 10 diferent charges.

mešanica vsebnosti vložka posameznih šarž, kjer je delež interne povratne surovine variral od 26,4 % do 59,0 %, sestava celotne reciklirane surovine (RC) = PRE + POST je variiral od 12,5 % – 52,8 %, sestava celotne sekundarne surovine (SC = interni + RC) je variiral od 71,2 % do 81,1 %, vsebnost primarnega Al v sestavi vložkov pa je znašala v posameznih šaržah od 18,9 % do 28,8 % (slika 7).

V analizo korelacijskih odvisnosti je bilo uporabljenih 121 ustreznih rezultatov populacije v istem terminskem obdobju identične tehnologije izdelave iztiskovanja palic. Višje mehanske lastnosti zlitine Al-Mg-Si z Zr so bile dosežene z različnimi vsebnostmi vložkov in različnimi količinami zaznanih vključkov pred/po RFI. Različen delež sekundarnih surovin v primerjavi z vsebnostjo vključkov po RFI v talini ni pokazal neposredne povezave s končnimi mehanskimi lastnostmi. Ta rezultat je bil povezan z dodatnimi koraki obdelave taline in čiščenja s tehnologijo litja s postopki filtriranja SIR in CFF. Končna

mechanical properties due to required limits (R_m = min 380 N/mm^2, $Rp_{0,2}$ = min. 360 N/mm^2, A = min. 8 %), with related results of Rm = 417,9 - 433,9 N/mm^2, $Rp_{0,2}$ = 393,1 - 416,6 N/mm^2, A =11,6 - 13,4% and in achieved average R_m = 426,2 N/mm^2, $Rp_{0,2}$ = 404,3 N/mm^2 and A =12,5% (Fig. 7). A different charge content mixture was used, where internal clean scrap content charge composition deviates from 26,4% - 59,0%, the total recycle content charge composition (RC) = PRE+ POST = 12,5% – 52,8%, total secondary content (SC = Internal + RC) content charge composition deviates from 71,2% -81,1 %, primary Al content of charge composition deviates from 18,9% – 28,8% (Fig. 7).

Higher mechanical properties of alloy Al-Mg-Si with Zr were achieved by a different charge mixture content and different inclusion detection quantities before/after RFI, were scrap content vs. inclusions content after RFI in the melt didn't show a direct correlation to the final mechanical properties. These results vsebnost vključkov je bila pri vseh najvišjih vsebnostih odpadkov zelo nizka, dosežena raven vključkov pa je bila pod 0,04 mm^2/kg. Mehanske lastnosti so pokazale manjšo korelacijo k višjim mehanskim lastnostim z večjim deležem primarnega aluminija. Še manjši delež šarž z višjo vsebnostjo primarnega vložka (8 %), je pokazal izboljšane mehanskih lastnosti za približno 1,9 %. Prav tako se je raven vključkov TiB_2 povečala z višjim deležem uporabe sekundarne surovine, kar je ključnega pomena za ustrezno kristalizacijo [35]. Višja vsebnost špinelov je bila zaznana tudi z višjim deležem delno kontaminirane sekundarne surovine.

Pearsonova korelacijska metoda je najpogostejša metoda, ki se uporablja za numerične spremenljivke in daje oceno od -1 do +1, pri čemer 1 predstavlja skupno pozitivno linearno korelacijo, -1 pa skupno negativno linearno korelacijo. Korelacijske analize ni mogoče razlagati kot ugotavljanje vzročno-posledičnih povezav. Lahko kaže, kako ali v kolikšni meri so spremenljivke povezane med seboj. Korelacijski koeficient meri le stopnjo linearne povezave med dvema spremenljivkama, kot je prikazano v enačbi [33,34].

$$r = \frac{\sum(x_i - \hat{x})(y_i - \hat{y})}{\sqrt{\sum(x_i - \hat{x})^2} \cdot \sqrt{\sum(y_i - \hat{y})^2}} \qquad (7)$$

kjer:
x_i, y_i = posamezne vrednosti
$\hat{x}$, $\hat{y}$ = povprečje posameznih spremenljivk

Analiza Pearsonovih koeficientov je pokazala, da ni močnejših linearnih povezav med končnimi mehanskimi lastnostmi in različno vsebnostjo uporabljanih sekundarnih surovin odpadkov v vložkih. Koeficient r = 0,247 - 0,260 med vsebnostjo primarnega Al in mehanskimi lastnostmi R_m in $Rp_{0,2}$ kaže na šibko pozitivno korelacijo, kar pomeni, da obstaja rahel

correlated with additional melt treatment and cleaning steps by casting technology with SIR and CFF filtering procedures. Final inclusion content was in the highest scrap content, very low, and achieved inclusion level content below 0,04 mm^2/kg. Mechanical properties show a correlation tendency to higher mechanical properties with increased ration of primary aluminium content. Even a smaller proportion of 8% higher primary mixture charge compounds showed increased mechanical properties for approximately. 1,9%. Also, the inclusion level of TiB_2 was increased with a higher ratio of post-consumer content, which is crucial for the proper crystallization process due to the decrease of refining and modification process [35]. Higher content of spinel inclusions was also detected by a higher ratio of partly contaminated post-consumer usage, but due to size and morphology, it was efficiently removed with no presence in the final melt cleanliness. Furthermore, additional correlation was investigated on 121 charge population results.

The Pearson correlation method is the most common method to use for numerical variables, which produces a score that can vary from − 1 to + 1 and shows 1 as total positive linear correlation, and − 1 is total negative linear correlation. Correlation analysis cannot be interpreted as establishing cause-and-effect relationships. It can indicate how or to what extent variables are associated with each other. The correlation coefficient measures only the degree of linear association between two variables, as shown in equation 7 [33,34].

Pearson correlation coefficient between variables X and Y:

$$r = \frac{\sum(x_i - \hat{x})(y_i - \hat{y})}{\sqrt{\sum(x_i - \hat{x})^2} \cdot \sqrt{\sum(y_i - \hat{y})^2}} \qquad (7)$$

where:
x_i, y_i = individual values

trend med spremenljivkami. Višja vsebnost primarnega aluminija ima pozitiven trend k višjim končnim mehanskim lastnostim iztiskovanih palic. Koeficient r = –0,071 - (-0,002) kaže na zanemarljivo negativno korelacijo, kar pomeni, da spremenljivke sekundarne vsebnosti v recepturi vložka praktično nimajo pomembne povezave z linearno regresijo s končnimi mehanskimi lastnostmi, kljub temu pa imajo skoraj zanemarljiv vpliv na nasprotno napovedno vrednost, kjer višja vsebnost odpadkov znižuje natezno trdnost in napetost tečenja. Sklepamo lahko, da je najvišja stopnja učinkovitosti postopka rafiniranja s solmi RFI in nadaljnja priprava taline, s končnimi kovinskimi vključki pod 0,04 mm²/kg nujna za doseganje visoke čistosti aluminijeve taline, kar vpliva na najvišje mehanske lastnosti končnega izdelka in kjer ni linearne regresijske povezave za razpršenost spremenljivk med vsebnostjo različnih deležev sekundarnih odpadkov in končnimi mehanskimi lastnostmi.

Tabela 5. Rezultati korelacijskih koeficientov glede na vrsto in vsebnost uporabljene surovine ter končne mehanske lastnosti.

Table 5. The correlation coefficient results show two variables comparison to the type of raw material content and final mechanical properties.

	Internal	*PRE consumer*	*POST consumer*	*Primary Al.*
R_m	-0,038	-0,065	-0,033	0,247
$Rp_{0,2}$	-0,023	-0,071	-0,066	0,260
A	-0,066	0,079	-0,002	-0,055

Optimizacija tehnoloških procesov in direktnih spremenljivk pogosto zahteva multivariabilno obdelavo podatkovnih baz. Kadar se za modeliranje procesa ustvarjanja podatkov lahko uporabi večvariatna normalna porazdelitev (MVN), je na splošno na voljo več metod za analizo podatkov in zagotavljanje napovedi, tako

$\hat{x}$, $\hat{y}$ = the means of respective variables

The analysis of the Pearson coefficients showed that there are no stronger linear correlations between final mechanical properties and scrap content of charges. The coefficient r = 0,247 - 0.260 between primary Al content and mechanical properties R_m and $Rp_{0,2}$ indicates a weak positive correlation, which means that there is a slight trend between the variables which resulting. With higher primary aluminium content is a positive trend to higher final mechanical properties of extruded bars. The coefficient r = –0.071 – (-0,002) indicates a negligible negative correlation, which means that the variables of secondary content (internal + pre + post) in charge recipe practically do not significantly connect with linear regression to final mechanical properties, nevertheless has almost negligible impact on opposites prediction value, where higher scrap content lowering Rm and $Rp_{0,2}$. We can conclude that the highest efficiency rate of RFI salt refining procedure and further metal preparation, with final metal inclusions below 0,04 mm²/kg, is mandatory to achieve high purity of aluminium melt, impacting to highest mechanical properties of the final product, and where there is no linear regression connection for dispersed variables results between scrap content correlation and final mechanical properties.

Business and industrial improvement often requires multivariate data. When the multivariate normal (MVN) distribution can be used to model the data-generating process, more methods are generally available for analysing the data and providing predictions, so that deviations from normality imply special causes [37].

Correlation results are a basic part in the prediction model related parameters, variables set-up, and present integration possibilities, as a modern computational example of machine learning (ML). ML, as a da odstopanja od normalnosti pomenijo poseben opis vzroka [37].

Rezultati korelacije so osnovni del nastavitve spremenljivk parametrov, povezanih z napovednim modelom, in predstavljajo možnosti integracije, kot sodoben računalniški primer strojnega učenja (ML). ML kot podmnožica relacije umetne inteligence (UI) lahko zajema širši specifičen pristop, algoritem in nevronske mreže. Močne korelacije med parametri obdelave in končnimi lastnostmi, zlasti napovedmi mehanskih lastnosti izdelkov, so bile že vzpostavljene v proizvodnji jeklarske industrije in tudi pri proizvodnji primarnega aluminija [28, 29].

Primer napovednega modela je mogoče uvesti s transformacijo velikih podatkovnih baz v sofisticirane matematične modele z linearnim regresijskim modelom, logističnim regresijskim modelom in gradientnim logaritemskim modelom izgub [30, 31, 32], kar je prikazano v spodnjih enačbah:

Linearni regresijski model napoveduje podatkovno bazo realne vrednosti (linearni model):

$$f_\theta(x) = \theta_0 \sum_{j=1}^{p} \theta_j x_j \qquad (8)$$

kjer je;
θ_0 = odsek (konstanta)
θ_j = koeficient spremenljivke j
p = število spremenljivk

Učni cilj za min θ ; minimizacija povprečne kvadratne napake (MSE):

$$\hat{\theta} = arg \min_{\theta} \frac{1}{N} \sum_{i=1}^{N} (y_i - f_\theta(x_i))^2 \qquad (9)$$

Logistični regresijski model napoveduje verjetnost vrednosti (klasifikacijski model):

$$\mathrm{P}(y = 1|x;\theta) = \sigma\left(\theta_0 + \sum_{j=1}^{p} \theta_j x_j\right) \qquad (10)$$

Kjer je σ(z) = 1/(1+e^{-z}) logistična funkcija.

Učni cilj je empirična minimizacija logaritemske funkcije izgub.

$$\hat{\theta} = arg \min_{\theta} \frac{1}{N} \sum_{i=1}^{N} l(\theta; x_i, y_i) \qquad (11)$$

subset relation of artificial intelligence (AI), can overreach that covers a wider specific approach, algorithm, and neural networks. Strong correlations between processing parameters and final characteristics, especially prediction of mechanical properties of the alloys, were already established in the production of the steel industry and also by primary aluminium production [28, 29]. Such a prediction model example can be introduced by big data base transformation into sophisticated mathematical models with linear regression model, logistical regression model, and gradient log-loss model [30, 31, 32] shown in equations below:

Linear regression model predicts the real value data base (linear model)

$$f_\theta(x) = \theta_0 \sum_{j=1}^{p} \theta_j x_j \qquad (8)$$

where;
θ_0 = intercept (constant)
θ_j = coefficient for j and j^th variable
p = number of variables

Learning objective for min θ ; minimization of mean square error (MSE):

$$\hat{\theta} = arg \min_{\theta} \frac{1}{N} \sum_{i=1}^{N} (y_i - f_\theta(x_i))^2 \qquad (9)$$

Logistic regression model predicts value probability (classification model):

$$\mathrm{P}(y = 1|x;\theta) = \sigma\left(\theta_0 + \sum_{j=1}^{p} \theta_j x_j\right) \qquad (10)$$

where; σ(z) = 1/(1+e^{-z}) is a logistics function.

Learning objective empirical minimization of the log-loss function.

$$\hat{\theta} = arg \min_{\theta} \frac{1}{N} \sum_{i=1}^{N} l(\theta; x_i, y_i) \qquad (11)$$

Gradient Log-loss model measures how well probabilities match the actual values (optimization criteria of learning in a neuron mesh):

$$l(\theta) = -\frac{1}{N} \sum_{i=1}^{N} \left[y_i log\sigma(\theta^T x_i) + (1 - y_i) log\left(1 - \sigma(\theta^T x_i)\right) \right] \qquad (12)$$

Gradientni logaritemski model izgub meri, kako dobro se verjetnosti ujemajo z dejanskimi vrednostmi (optimizacijski kriteriji učenja v nevronski mreži):

$$l(\theta) = -\frac{1}{N}\sum_{i=1}^{N}\left[y_i log\sigma(\theta^T x_i) + (1-y_i)log\left(1-\sigma(\theta^T x_i)\right)\right] \quad (12)$$

Zajeta baza podatkov mora biti brez nepravilnih parametrov v zapisih baz. Za ustrezen rezultat validacije modeliranja pa je potrebno navzkrižno preverjanje validacije z distribucijo podatkov, učnim testiranjem in izračunom povprečne metrike, kar zagotavlja zanesljivejšo zmogljivost. Za testiranje na več različnih nepokritih vektorjih podatkov je obvezna ocena enega samega testnega intervala. Takšen model lahko reproducira učenje iz 4/5 uporabnih podatkov in poda napoved na podlagi le 1/5 razpoložljivih podatkov o nastavitvi.

4. Zaključki

Analiza različnih receptur vložka v modificirani aluminijevi gnetni zlitini Al-Mg-Si z Zr, je potrdila ustreznost mešanice talila, sestavljena iz povprečnega masnega razmerja sestave 54 % mas. $MgCl_2$ + 46 % mas. KCl, injektirana s postopkom RFI, kot najučinkovitejšo za potrebe redukcij vsebnosti alkalij (Ca, Na) ter nekovinskih vključkov, vključno z odstranjevanjem bazičnih in kompleksnih oksidov (špinelov). Vsebnost alkalij (Na in Ca) je po obdelavi taline z RFI dosegla zelo nizko vsebnost, vedno pod 10 ppm, kjer je vsebnost Ca pokazala višjo tendenco k redukcijskemu razmerju. Serijsko uporabljene sestave vložka, kljub zelo nizki vsebnosti Ca in Na v staljeni kovini, so v povprečju dosegli več kot 70 % zmanjšanje vsebnosti alkalij po rafiniranju RFI. Stopnja učinkovitosti rafiniranja z RFI je bila zelo visoka, skupaj celo do 95,7 % odstranitve nekovinskih

Suitable data should be clean of irregular parameters in database, records, and for a convenient result of modelling validation is necessary to cross-validation checks with data distribution, training-testing, and calculate the average metric, which gives a more reliable performance. An estimate single test split is mandatory to test on several different uncovered vectors of the data. Such a model can reproduce learning from 4/5 of usable data and give a prediction based on only 1/5% of available setup data, confirmed with several performance evaluation steps.

4 Conclusions

Analysis of industrial charges confirmed the selected flux mixture with RFI injection, consisting of a general composition ratio by 54 wt. % $MgCl_2$ + 46 wt. % KCl is the most effective mix composition for alkali reduction (Ca, Na) and non-metallic inclusions, including basic and complex oxides removal in aluminium alloy Al-Mg-Si modified with Zr. The content of alkalis (Na and Ca), after RFI refining, achieved very low content, always below 10 ppm, where Ca content shown higher tendency to reduction ratio. The serial charges, nevertheless, have very low Ca, Na content in the molten metal, achieved an average of more than 70% reduction of alkali content after RFI refining. The efficiency rate of RFI refining achieved very high level, in total up to 95,7% of non-metallic inclusion and oxides removal. Total measured inclusions content before refining process in the melt was the highest 3.432 mm^2/kg per melt, and on average 2,157 mm^2/kg in the molten melt related to different charge mixture, prepared by max. 52,8% of recycled content and max. 81,1% of the total secondary ratio. The highest quantities reduction was achieved for Spinel vključkov in oksidov. Skupna izmerjena vsebnost vključkov pred postopkom rafiniranja v talini je bila najvišja, 3,432 mm^2/kg in v povprečju 2,157 mm^2/kg glede na različne mešanice vložkov, ki so bile pripravljene z maks. 52,8 % vsebnosti sekundarnih eksternih surovin (RC) in največ 81,1 % celotnega sekundarnega deleža (SC). Največje zmanjšanje količin je bilo doseženo pri zmanjšanju špinela in TiB_2, ki predstavljata tudi več kot 50 % vseh vključkov v talini. Zaradi uporabe zelo čistih vhodnih surovin v poskusnih recepturah se lahko odstopanje med vsebnostjo vključkov nekoliko razlikuje zaradi vzorčenja PoDFA in manipulacije taline, kar lahko vpliva na pojav nekovinskih vključkov, zlasti na dvig deleža oksidov v obliki Al_20_3. Prikazane so bile dodatne preiskave korelacijskih faktorjev med mehanskimi lastnostmi zlitine Al-Mg-Si, rezultati rafiniranja in vsebnostjo vključkov v recepturah. Natezna trdnost končnih iztiskovanih palic presega več kot 410 N/mm^2. Korelacijska analiza ni pokazala neposredne linearnega razmerja med deležem uporabljenih sekundarnih odpadkov in doseženimi mehanskimi lastnostmi, temveč je povezana s končno obdelavo taline in filtracijo v celoti. Serijska izdelava šarž je pokazala na 100-odstotno ponovljivost, kjer končna vsebnost vključkov ni presegla mejne vrednosti 0,04 mm^2/kg, vključno z nizko vsebnostjo alkalij. Pearsonova korelacijska matrika med končnimi mehanskimi lastnostmi je pokazala rahlo linearno tendenco glede na vsebnost primarnega aluminija z kvadratom funkcije r^2 = 6,8 %. Delež uporabljenih sekundarnih odpadkov je pokazal zelo nizko linearno negativno tendenco glede mehanskih lastnosti, kljub temu da so bili uporabljeni zelo visoki deleži recikliranih surovin. Dodatno modeliranje s pomočjo porazdelitve multi-variantnih podatkovnih nizov za ustrezno napovedna sposobnost and TiB_2 reduction, which also represents more than 50% inclusions in molten metal. Due to very clean input raw material usage in trials charge recipes, the deviation between inclusion content may slightly vary due to PoDFA error made by manipulation operation sampling process, which has an impact on counting ratio of non-metallic inclusion, especially for oxides level as Al_20_3. Additional investigation of correlation factors between mechanical properties on alloy Al-Mg-Si, refining results, and charge content recipes was shown. Ultimate tensile strength on final extrusion bars exceeds in all serially produced charges more than 410 N/mm^2 due to the required limits. Correlation analysis showed no direct linear distribution between scrap ratio to mechanical properties limits but linked more to the final metal processing and their cleanliness efficiency in total, while serial production batches showed 100% repeatability, where metal cleanliness achieved the final inclusion content max. 0,04 mm^2/kg including low alkali content. Pearson correlation matrix between final mechanical properties values shows more slightly linear tendency with primary ingot content as positive, with R^2 = 6,8%. Scrap content shows a general very low linear negative tendency to mechanical properties, nevertheless reaches a very high recyclability share, so additional distribution type of multi variate processing data sets of modelling are mandatory, represented in logistic regression and/or gradient probabilities optimization as modern steps to machine learning and AI evolution progress.

Data Availability

The data supporting this study's findings are available from the corresponding author upon reasonable request.

je možno doseči z upoštevanjem logistične regresije in/ali optimizacija gradientnih verjetnosti, katera se uporablja kot sodobni korak k razvoju naprednega strojnega učenja in razvoja umetne inteligence.

Razpoložljivost podatkov
Podatki so na voljo pri avtorju članka.

Author Contribution
Conceptualisation: FZ, UK; Data curation: UK; Investigation: UK; Methodology: FZ; Writing – original draft: UK, Writing – review & editing: UK, Supervision: FZ.

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AKTUALNO / CURRENT

Livarske prireditve 2026

Datum dogodka	Ime dogodka	Mesto in država
15. 04. 2026	Seminar "Bewertung von Simulationsergebnissen" (Schwerpunkt Druckguss)	Aachen, Nemčija
23. – 24. 04. 2026	68. Österreichische Gießereitagung	Gurten, Avstrija
19. – 22. 05. 2026	68. International Technical Fair	Beograd, Srbija
19. – 21. 05. 2026	Deutscher Gießereitag 2026	Göttingen, Nemčija
08. – 09. 06. 2026	Industrijski forum IRT	Portorož, Slovenija
09. – 11. 06. 2026	CastForge 2026	Stuttgart, Nemčija
16. – 18. 09. 2026	66th IFC Portrož 2026	Portorož, Slovenija
18. – 24. 10. 2026	76th World Foundry Congress	Istanbul, Turčija
18. – 19. 11. 2026	FORUM Eisenguss	Aachen, Nemčija
11. 12. 2026	Poljski dan livarjev z 90-letnim jubilejem Poljskega združenja livarjev (STOP)	Krakow, Poljska