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Karakterizacija lastnosti tlačno ulite inovativne zlitine AlSi9MgMn

Characterization 9f Innovative High Pressure Die Casting AlSi9MgMn Alloy Properties

Izvleček

Zaradi nenavadne kemične sestave smo preiskali novo večkomponentno zlitino AlSi9MgMn. Zlitina AlSi9MgMn je prva aluminijeva zlitina z malo železa in večjim deležem mangana, ki so jo razvili za tlačno ulite avtomobilske dele in sestave. Za to zlitino so značilne izboljšane mehanske lastnosti pri hitrem ohlajanju ulitkov, kot sta duktilnost in žilavost, zaradi nastajanja kroglaste intermetalne faze $Al_xMn_yFe_zSi_u$. Karakterizacija nove večkomponentne hitro ohlajane zlitine AlSi9MgMn za tlačno ulite dele kaže, da nastajajo kroglaste intermetalne faze, ki neposredno vplivajo na izboljšane mehanske lastnosti.

Raziskava je odkrila nastanek značilnih mikrostrukturnih sestavin glede na morfologijo in sestavo: primarni aluminij (α_{Al}) z mešano dendritno-kroglasto morfologijo, kompleksno kroglasto/poliedrično intermetalno fazo $Al_xMn_yFe_zSi_u$ in glavnim evtektikom (α_{Al} + β_{Si}) v meddendritnih prostorih. Kompleksna intermetalna faza $Al_xMn_yFe_zSi_u$, ki nastaja pri velikih hitrostih ohlajanja, je kroglasta ali poliedrična, kar kaže na njeno neodvisno nastajanje v prvih fazah strjevanja. Lokalne podhladitve in tekoče stanje omogočata neposredno nukleacijo ravnotežne faze v talini tako, da nastajajo in rastejo posamezna zrna ali se debelijo že preje nastala zrna, ki jih je prinesla difuzija v talini.

Morfologija evtektika je mešana lamelno-vlaknata. Dobljene mehanske lastnosti so bile zelo visoke v primerjavi z navadnimi aluminijevimi avtomobilskimi zlitinami. Pomembno razliko smo ugotovili pri povečanju ohlajevalne/strjevalne hitrosti z vzorci različnih premerov. Vzorci, ki so se zaradi svoje geometrije (manjši premer) hitreje ohlajali, so imeli višje napetosti tečenja, natezne trdnosti in raztezke zaradi drobnejše mikrostrukture, dobro vidne kroglaste mikrostrukture primarnega aluminija, intermetalne faze $Al_xMn_yFe_zSi_u$ in popolnoma modificiranega vlaknatega evtektika.

Ključne besede: zlitina AlSi9MgMn, razvoj mikrostrukture, mehanske lastnosti, tlačno ulivanje

Abstract

Novel multicomponent AlSi9MgMn alloy has been investigated due to unusual chemical composition. An AlSi9MgMn alloy is the first aluminum alloy with low iron and intentionally high manganese content developed for structural automotive casting parts and sets produced by high pressure die casting process. This alloy has been characterised by enhanced mechanical properties of castings such as ductility and toughness at high cooling rates due to evolution of intermetallic $Al_xMn_yFe_zSi_u$ phase in globular manner. Characterization of novel multicomponent AlSi9MgMn alloy at high cooling rate related to high pressure die casting indicates evolution of fine intermetallic phases with globular morphology which directly influence on development of enhanced mechanical properties.

Investigation revealed evolution of characteristic microstructural constituents on the base of their morphology and chemical composition: primary aluminum (α_{Al}) with mixed dendrite and globular morphology, complex intermetallic phase $Al_xMn_yFe_zSi_u$ in globular / polyhedron morphology, main eutectic in interdendritic spaces ($\alpha_{Al} + \beta_{Si}$). Complex intermetallic phase $Al_xMn_yFe_zSi_u$ evaluated at high cooling rate reveals globular or polyhedron morphology which indicates independently evolution in early stages of solidification, due to both local undercooling and liquid composition which allow direct nucleation of the equilibrium phase in the liquid by individual nucleation and growth or by increase in thickness of that originated previously, that have been transported mainly by diffusion in the liquid.

Eutectic posses mixed lamellar and fibrous morphology. Obtained mechanical properties were very high when compared to common aluminium automotive alloys. A significant differentiation has been established due to increasing of cooling / solidification rate obtained by several sample diameters. Test samples exposed to higher cooling rate due to their geometry (smaller diameter) show increase in yield and tensile strength and elongation due to finer microstructure, prominent globular microstructure of primary aluminium, intermetallic $Al_xMn_yFe_zSi_u$ phase and completely modified fibrous eutectic.

Characterization of novel multicomponent AlSi9MgMn alloy indicates applicability of this material for safety automotive parts due to obtained high values of mechanical properties.

Key words: AlSi9MgMn alloy, microstructure development, mechanical properties, high pressure die casting.

1 Uvod

Ker se aluminijeve zlitine zelo široko uporabljajo v številnih industrijah, se zahteve po kakovosti usmerjajo na izboljšane mikrostrukture in mehanske ter tehnološke lastnosti. Nova večkomponentna zlitina AlSi9MgMn je prva z majhnim deležem železa in namensko povečanim deležem mangana, ki je bila razvita za konstrukcijske tlačno ulite avtomobilske ulitke. Značilnosti te tehnologije so, da ugodno vpliva na razvoj mikrostrukture zaradi nastajanja kroglaste/ poliedrične intermetalne faze $Al_xMn_yFe_zSi_u$, kar izboljšuje mehanske lastnosti ulitkov, kot sta duktilnost in žilavost.

Ker ta zlitina ni standardizirana z mednarodnim standardom, ne EN niti AA, ampak le kratko opisana v internem standardu proizvajalca [1], predstavlja izziv za razumevanje mehanizma strjevanja. Dodatek posebnih zlitinskih elementov, kot

1 Introduction

Since aluminium alloys have found their wide application in numerous industries, quality requirements allocated new features regarding microstructural, mechanical and technological properties. Novel multicomponent AlSi9MgMn alloy is the first one with low iron and intentionally high manganese content developed for structural automotive casting produced by high pressure die casting process. Characteristics of this technology favourably affect the microstructure development through evolution of intermetallic $Al_xMn_yFe_zSi_u$ phase in globular / polyhedron manner and thus enhance mechanical properties of castings such as ductility and toughness.

Since this alloy has not been classified in international standard, neither EN nor AA, only briefly described in manufacturer norm [1], it represents challenge for understanding sta magnezij in tudi mangan ter železo, lahko izboljša mehanske in tehnološke lastnosti ulitka [2-12].

Ker ta zlitina ni standardizirana z mednarodnim standardom, ampak le kratko opisana v internem standardu proizvajalca, predstavlja izziv za razumevanje mehanizma strjevanja. Delež prehodnih elementov in njihova razmerja imajo pomemben vpliv na nastanek faze Al-(Mn,Fe)-Si.

Primerjavo kemične sestave zlitine AlSi9MgMn z velikim deležem Mn, kar zahteva proizvajalčev standard [1] in dejanskega vzorca, daje razpredelnica 1.

Primerjava kemične sestave ni pokazala odklona od vrednosti, ki jih zahteva proizvajalčev standard. Deleža železa in mangana se občutno razlikujeta od deležev v navadnih aluminijevih zlitinah in zato nakazujeta nastajanje kompleksne faze $Al_xMn_yFe_zSi_u$.

of its solidification mechanism. Addition of particular alloying elements such as magnesium as well as manganese and iron can improve mechanical and technological properties of casting [2-12].

Since this alloy has not been classified in international standard, only briefly described in manufacturer norm, it represents challenge for understanding of its solidification mechanism. Transition elements content and there ratio have significant influence on evolution of the Al-(Mn,Fe)-Si phase.

Compared overview of chemical composition of AlSi9MgMn alloy with high Mn content required by manufacturer norm [1] and real sample is given in table 1.

Comparison of chemical composition values has not brought out any deviation from values requested by manufacturer norm. Iron and manganese values,

Razpredelnica 1. Kemična sestava zlitine AlSi9MgMn

Table 1. Chemical composition of the AlSi9MgMn alloy

Vzorec / Sample	Element (mas. %) / (%, mass fraction)			
	Si	Fe	Mn	Mg
Standard proizvajalca [1] / Manufacturer norm [1]	9,5 - 11,5	0,15	0,50 - 0,80	0,10 - 0,50
Preiskovani vzorec / Investigated sample	10,568	0,0858	0,6192	0,2399

Razpredelnica 2. Potek strjevanja zlitine AlSi9MgMn [13,14,15]

Table 2. Solidification sequence of the AlSi9MgMn alloy [13,14,15]

Št. r. / R. No.	Reakcija Reaction	T/°C TCW	T/°C DSC
1	$L \rightarrow L_1 + Al_3Fe/(Al_6Mn) \leftrightarrow Al_xMn_yFe_zSi_u$	612,85	>612
2	$L_1 \rightarrow L_2 + Al_xMn_yFe_zSi_u + \alpha_{Al}$	589,85	588
3	$L_2 \rightarrow L_3 + \alpha_{Al} + Al_xMn_yFe_zSi_u + Al_5FeSi$	573,85	573,4
4	$L_3 \rightarrow L_4 + \alpha_{Al} + \beta_{Si}$	565,85	571,5
5	$L_4 + Al_5FeSi \rightarrow L5 + Al_8Mg_3FeSi_6$	-	566,7
6	$L_5 \rightarrow \alpha_{Al} + Mg_2Si$	489,85	553

Numerično modeliranje ravnotežnega faznega diagrama (TCW), diferencialna vrstična kalorimetrična analiza (DSC) in enostavna termična analiza (STA) so se usklajeno uporabili pri preiskavah mikrostrukture za ugotavljanje zaporedja nastajanja faz pri strjevanju zlitine AlSi9MgMn, kar kaže razpredelnica 2 [13,14,15].

Termodinamični izračun poteka strjevanja je razkril naslednje zaporedje nastajanja faz: izločanje visokotemperaturne faze $Al_xMn_yFe_zSi_u$, nastanek primarne dendritne mreže, glavna evtektična reakcija in končno nastanek sekundarne evtektične faze Mg_2Si.

Iz taline neodvisno izločena faza $Al_xMn_yFe_zSi_u$ in njene mikrostrukturne značilnosti zaradi velike ohlajevalne hitrosti zelo močno vplivajo na mehanske lastnosti. Kroglasto-poliedrična morfologija predstavlja potencial za izboljšanje mehanskih lastnosti in s tem za varnost kritičnih sestavnih delov. Cilj prispevka je bil karakterizirati novo večkomponentno tehnično zlitino AlSi9MgMn z velikim deležem Mn in ustrezne vrednosti mehanskih lastnosti, ki jih omogoča tlačno ulivanje.

2. Materiali in metode

Vzorce zlitine AlSi9MgMn smo že predhodno preiskali z več metodami, da smo ugotovili potek in mehanizme strjevanja [13,14,15]. Priprava taline je obsegala razplinjevanje in modificiranje s predzlitino AlSr10. Indeks končnega razplinjenja je bil 1,330 % in delež stroncija 0,0096 mas. %.

Simulacija ulivanja in strjevanja v posebej narejeni kokili je potekala po standardnem postopku. Ulivanje in strjevanje ulitkov/preizkušancev smo simulirali z računalniško opremo MAGMASoft. Celotna 3D-geometrija kokile je bila izdelana s programom CATIA,

significantly differ from those in common aluminium alloys, and therefore indicate formation of complex $Al_xMn_yFe_zSi_u$ phase.

Numerical modelling of equilibrium phase diagram (TCW) and performed differential scanning calorimetry (DSC) analysis and simple thermal analysis (STA) correlated to microstructure investigations resulted in solidification sequence determination of AlSi9MgMn alloy, as follows in table 2 [13,14,15].

Thermodynamic calculation revealed solidification sequence with corresponded temperatures as follows: precipitation of high temperature $Al_xMn_yFe_zSi_u$ phase, development of primary dendrite network, main eutectic reaction, and finally secondary eutectic phase Mg_2Si.

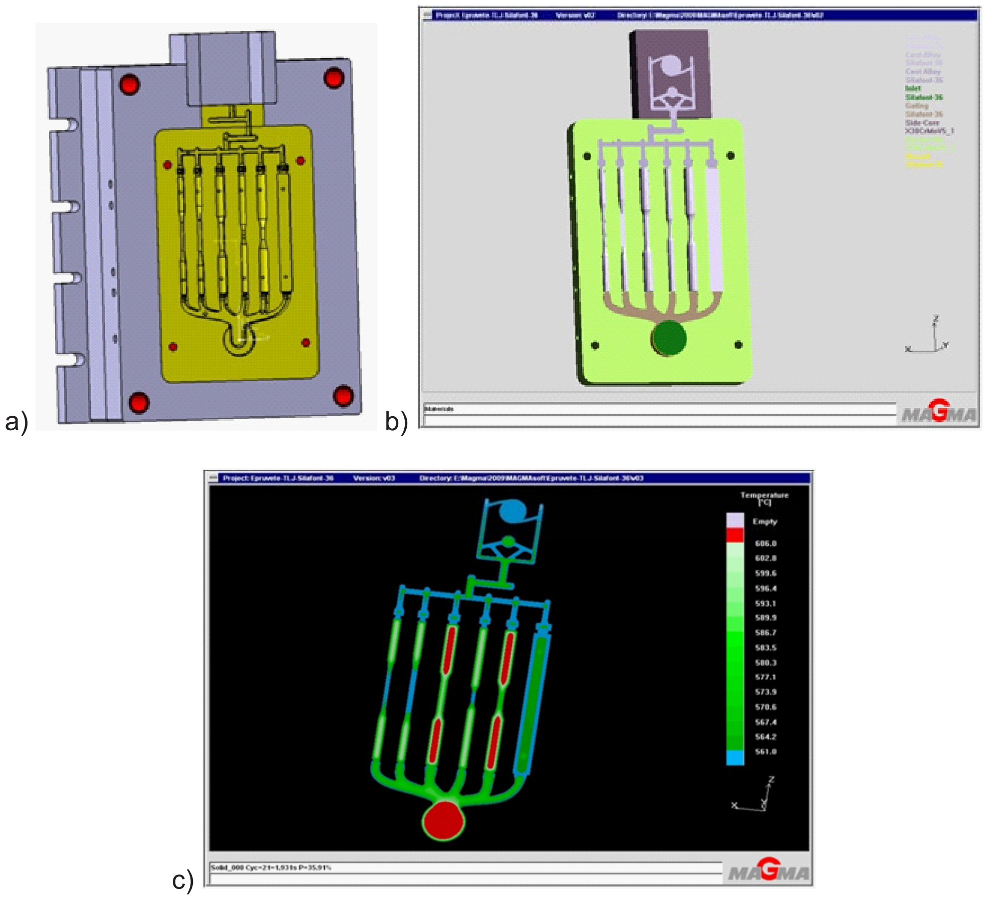
Independently precipitated $Al_xMn_yFe_zSi_u$ phase from bulk liquid, and its microstructural features, due to high cooling rate, strongly influences on mechanical properties development. Its globular / polyhedron morphology made a potential for increasing of mechanical properties, and therefore an application for safety critical parts. The aim of this article was to characterise novel muticomponent technical AlSi9MgMn alloy with high addition of Mn and corresponded mechanical values produced by high pressure die casting.

2. Materials and Methods

AlSi9MgMn alloy samples was previously investigated by multidisciplinary approach in order to determine solidification sequence and mechanism [13,14,15]. Melt preparation included degassing and modification by AlSr10 master alloy. Final degassing index was 1,330 % and strontium content 0,0096 %.

Pouring and solidification simulation in specially designed die was performed pretvorjena v STL-format in uvožena v MAGMA-predprocesor. Ustrezne skupine materialov in ustrezne lastnosti, ki so bile izbrane iz podatkovne baze, smo označili z ulitek, ulivni sistem, napajalnik, peščena forma (slika 1a). Simulacijo smo napravili, da bi napovedali potek ulivanja in strjevanja in potrdili ustrezen tehnološki nastanek ulitka (slika 1b, 1c).

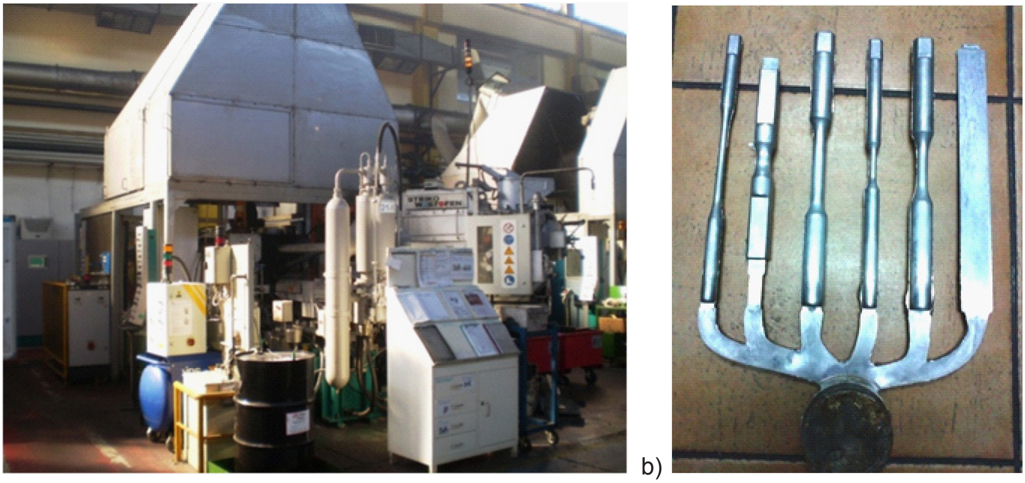
by standard procedure. Pouring and solidification of castings/test samples were accompanied by numerical simulation by MAGMASoft. Complete mould 3D geometry was prepared in CATIA and converted in STL format and afterwards imported in MAGMA pre-processor. Corresponded group of materials and corresponded properties selected from data base have



Slika 1. a) 3D model gibljivega dela kokile, konstruiran z računalniško opremo ″CATIA″, b) Geometrija gibljivega dela v ″MAGMA-postprocesorju″, c) Numerična simulacija strjevanja tlačno ulitih preskušancev po času t =1,93 s

Figure 1. a)˝3D model of moving part of die designed in ″CATIA″ software, b) Geometry of moving part in ″MAGMA post-processor″, c) Numerical simulation of solidification of test samples cast by high pressure die casting technology after t=1,93 s

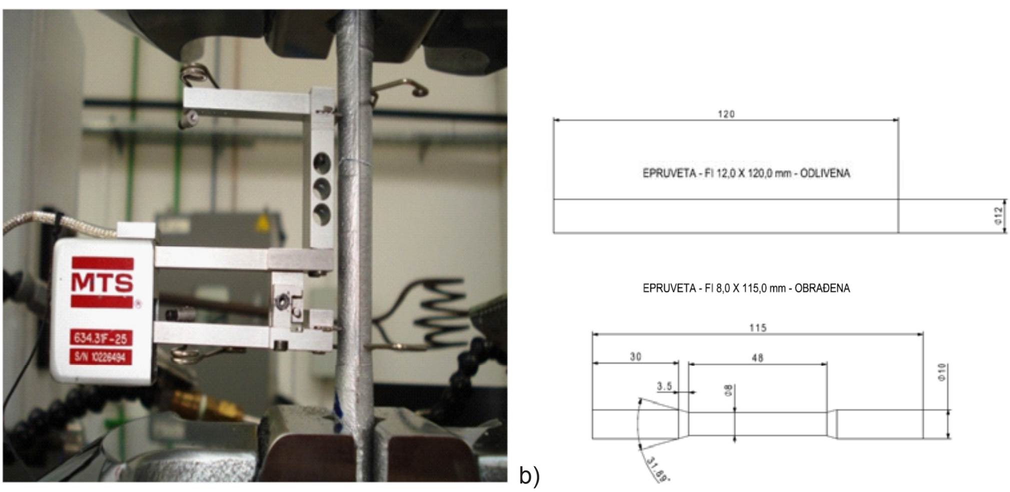
a) b)



Slika 2. a) Kompletna celica za tlačno ulivanje BUHLER-42D, opremljena z vakuumsko napravo ″PROVAC″, b) Ulit grozd 6 preskušancev za mehanske preskuse po standardu ISO 377

Figure 2. a) Complete cell for high pressure dies casting BUHLER-42D eguipped with ″PROVAC″ vacuum device, b) Cast cluster with six test samples for mechanical invetigation according to ISO standard 377

a) b)



Slika 3. Ugotavljanje mehanskih lastnosti; a) preiskava na licu mesta, b) preskušanec pred strojno obdelavo in po njej

Figure 3. Mechanical properties investigation; a) investigation "in situ", b) test sample prior and after mechanical treatment for mechanical properties investigation

Mehanski preskušanci so bili uliti s strojem "BUHLER 42D" v skladu s procesnimi parametri (slika 2a). Preskušanci

been assigned: casting, pouring system, feeder, sand mould (Figure 1a). Simulation was performed in order to predict the so bili tlačno uliti v standardnem orodju v skladu s standardom ISO 377:1997 (slika 2b). Pred ulivanjem se je orodje priključilo na vakuumsko napravo »PROVAC«, da bi ulivanje potekalo brez zračnega upora in brez naplinjenja, ki bi povzročilo plinsko poroznost in nezveznost preskušancev.

Povprečna ohlajevalna hitrost celotnega ulitka se je izračunala iz numerične simulacije in je bila r_c = 63 K/s.

Mehanske lastnosti tako pripravljenih preskušancev smo ugotavljali z univerzalnim strojem MTS 810, opremljenim z elektronskim merilnikom raztezkov (slika 3). Ugotavljali smo natezno trdnost, napetost tečenja in raztezek preskušancev v ulitem stanju iz obdelane taline.

Trdoto po Brinellu HB5/250/15 smo ugotavljali z merilnikom trdote WOLPERT DIA TESTOR 3a

Za metalografsko analizo smo uporabili preskušance po mehanskih preskusih. Metalografski obrusi so bili pripravljeni po standardnem postopku brušenja in poliranja za aluminijeve zlitine. Mikrostrukturo smo odkrili z jedkanjem vzorcev v 0,5 % HF. Za metalografsko analizo ugotavljanja posameznih mikrostrukturnih sestavin smo uporabili svetlobni mikroskop Olympus GX 51. Mikroposnetke smo naredili z digitalno kamero Olympus DP70 ter jih obdelali pri različnih povečavah z računalniško opremo Analysis®MaterialsResearchLab. Mikrostrukturna preiskava je odkrila porazdelitev in morfologijo posameznih

pouring and solidification path and confirm adequate technological development of casting (Figure 1b, 1c).

Samples for mechanical testing were cast on “BUHLER 42D” machine according to determined specific process parameters (Figure 2a). Casting of test specimens was performed in the standard tool for high pressure die casting in accordance to ISO 377:1997 standard (Figure 2b). Prior the pouring the “PROVAC” vacuum device was used in order to secure casting without resistance and air entrapment and to prevent the formation of gas porosity and discontinuity occurrence in the test samples.

Calculation of average cooling rate for entire casting obtained by numerical simulation indicates the following cooling rate r_c = 63 K/s.

Investigation of mechanical properties of prepared samples was performed on universal testing machine MTS 810 equipped by electronic extensimeter (Figure 3). Tensile strength, yield strength and elongation of test samples in both, as-cast and melt-treated state were determined.

Also, Brinell hardness was established HB5/250/15 on hardness tester WOLPERT DIA TESTOR 3a.

Metallographic analysis was performed on test samples after mechanical properties investigation. Metallographic samples were prepared by standard procedure

Razpredelnica 3. Kemična sestava ulitkov iz zlitine AlSi9MgMn

Table 3. Chemical composition of AlSi9MgMn alloy castings.

Preiskovan vzorec / Investigated sample	Elementi (mas. %) / Elements (%, mass fraction)										
	Si	Fe	Cu	Mn	Mg	Zn	Ti	Ni	Cr	Pb	Sr
Tlačni ulitki / HPDC	10,568	0,0858	0,0005	0,6192	0,2399	0,0064	0,0491	0,0021	0,0041	0,0032	0,0096

faz. Določene faze so se ugotavljale s kemično sestavo, ugotovljeno z vrstičnim elektronskim mikroskopom Tescan Vega z EDS-napravo.

3 Rezultati in razprava

Kemično sestavo zlitine AlSi9MgMn kaže razpredelnica 3.

Mikrostrukturo zlitine AlSi9MgMn smo preiskovali s svetlobnim in vrstičnim elektronskim mikroskopom. Svetlobna mikroskopija je omogočila vizualno razpoznavanje posameznih faz na osnovi morfologije in barve s primerjanjem v atlasu mikrostruktur. Značilne mikrostrukture pri dveh povečavah in za različne premere vzorcev, od katerih je bila odvisna hitrost ohlajevanja/strjevanja, so prikazane na sliki 4.

Mikrostrukturna analiza je omogočila prepoznavanje značilnih faz, ki so prisotne v zlitini AlSi9MgMn: primarni aluminij (α_{Al}) z mešano dendritno-kroglasto morfologijo, kroglasto-poliedrično kompleksno fazo $Al_xMn_yFe_zSi_u$, glavni evtektik (α_{Al} + β_{Si}) v meddendritnih prostorih. Evtektik ima mešano lamelasto-vlaknato morfologijo. Pri preskušancih manjšega premera je zaradi velike hitrosti ohlajanja/strjevanja prevladovala kroglasta morfologija primarnega aluminija in vlaknata oblika evtektika.

Kompleksna intermetalna faza, ki nastaja po reakcijah 1 in/ali 2 (razpredelnica 2) zaradi lokalnih podhladitev in sestave taline, omogoča neposredno nukleacijo ravnotežne faze $Al_xMn_yFe_zSi_u$ v talini; vse sestavine za nastajanje novih delcev faze $Al_xMn_yFe_zSi_u$ se oblikujejo ali z individualno nukleacijo in rastjo delcev, ali z debelitvijo preje nastalih delcev, ki jih prenaša predvsem difuzija v talini.

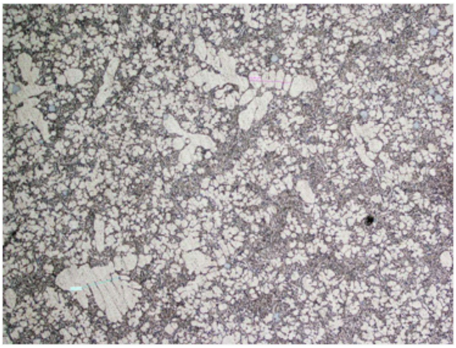
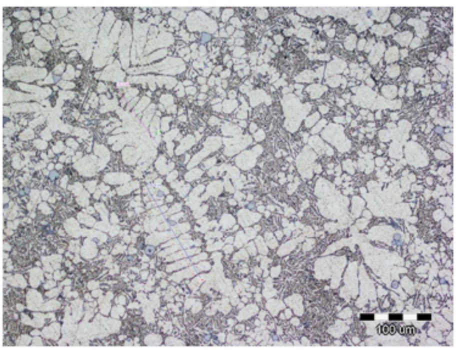
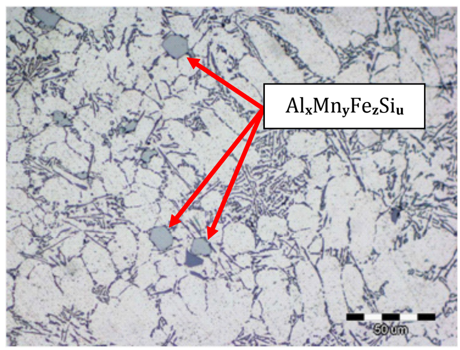
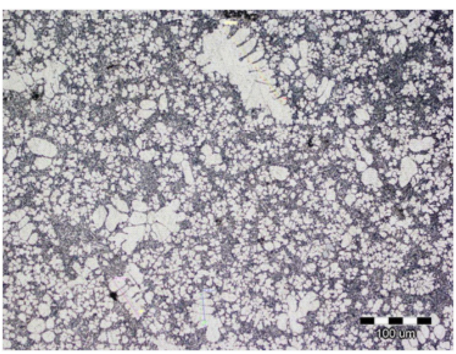
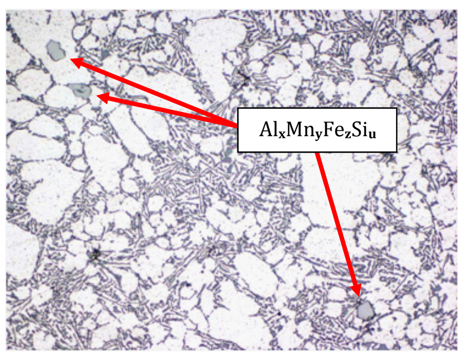
of grinding and polishing for aluminum alloys. For microstructure revealing the etching in 0,5% HF was performed. Metallographic analysis was performed on optical microscope Olympus GX 51 in order to identify particular microstructural constituents. Sample micrographics were acquisitioned by digital camera Olympus DP70, while the analysis was performed by Analysis®MaterialsResearchLab software at different magnification. Microstructural investigation indicated distribution and morphology of particular phase. Particular phases were recognized by chemical composition on scanning electron microscope Tescan Vega by EDS investigation (energy dispersive spectrometry).

3 Results and Discussion

Chemical composition of AlSi9MgMn alloy castings is shown in table 3.

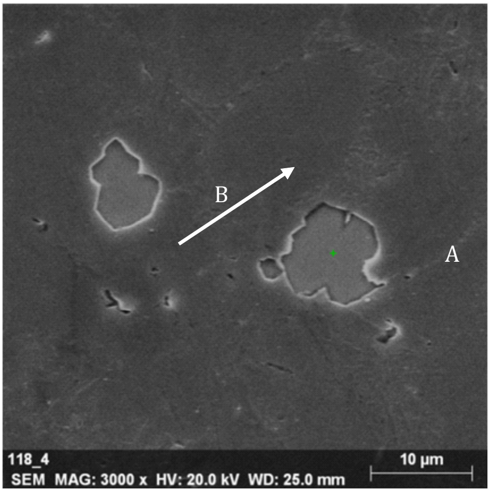
Microstructural investigation of AlSi9MgMn alloy was performed in optical and scanning electron microscope. Optical microscopy enables visual recognition of particular phases on the base of their morphology and colour by comparison with those in atlas of microstructure. Characteristic microstructure in comparative magnification overview related to test sample diameter i.e. cooling / solidification rate are shown in Figure 4.

Microstructural analysis enable visual recognition of characteristic phases present in AlSi9MgMn alloy: primary aluminum (α_{Al}) with mixed dendrite and globular morphology, complex intermetallic phase $Al_xMn_yFe_zSi_u$ in globular / polyhedron morphology, main eutectic in interdendritic spaces (α_{Al} + β_{Si}). Eutectic posses mixed lamellar and fibrous morphology. Smaller test sample diameter promotes globular morphology of primary aluminum as well

Premer vzorca / Test sample diameter Φ, mm	povečava / magnification 200 x	povečava / magnification 500 x
6,4		
9,0		
11,0		

Slika 4. Mikrostrukturna analiza preskušancev s primerjalnim pregledom, pri ustrezni povečavi in označitvijo značilne faz

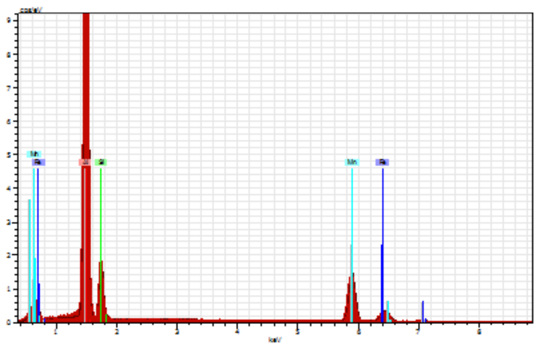
Figure 4. Microstructural analysis of test samples in comparative overview with corresponded magnification with labelled characteristic $Al_xMn_yFe_zSi_u$ phase: a) 200x, b) 500x



Slika 5.EDS-preiskava določenih intermetalnih sestavin; A) $Al_xMn_yFe_zSi_u$, B) linijska analiza

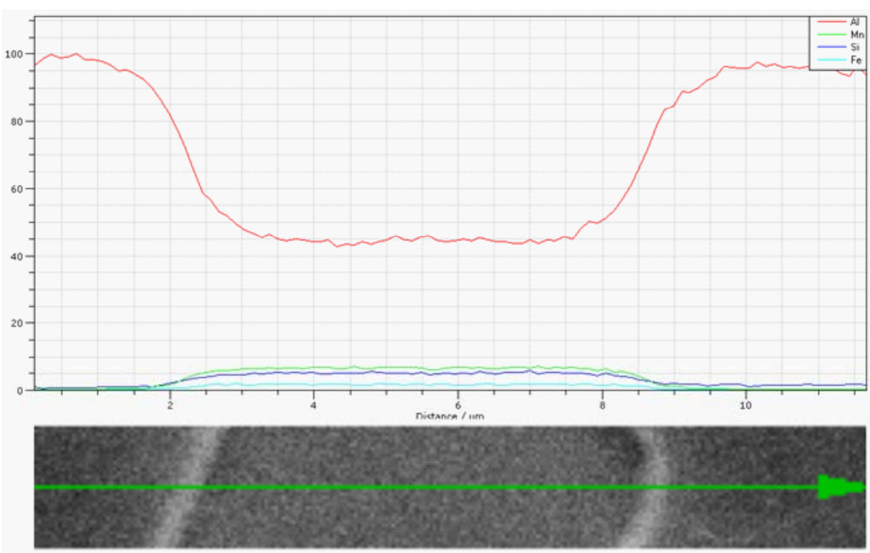
Figure 5. EDS investigation of particular intermetallic constituents; A) $Al_xMn_yFe_zSi_u$, B) Line analysis

A



Element	mas.%/ % mass fraction	at.%
aluminij / Aluminum	61,36	72,71
silicij / Silicon	8,71	9,91
železo / Iron	4,45	2,55
mangan / Manganese	25,48	14,83

B



Ker je bila mikrostruktura preskušancev pri tlačnem litju zelo drobnozrnata zaradi velike ohlajevalne hitrosti, nekaterih pričakovanih sestavin nismo zaznali pri svetlobni mikroskopiji. O neugodnih grobih zrnih faze Al5FeSi, o fazi Al8Mg3FeSi6, ki se je na koncu izločila na iglicah Al5FeSi in o sekundarni evtektični fazi Mg_2Si z razvejano morfologijo in porazdeljeni po kristalnih mejah, ki nastajajo pri majhnih ohlajevalnih hitrostih, smo že poročali [16].

Natančno smo identificirali posamezne mikrostrukturne komponente z vrstično elektronsko mikroskopijo in energijsko-disperzijsko spektrometrijo (slika 5).

Preiskava posameznih faz z EDS je odkrila prisotnost primarnega aluminija αAl, intermetalne faze $Al_xMn_yFe_zSi_u$ (A) in glavnega evtektika αAl+βSi. Linijska analiza je omogočila vpogled v koncentracije elementov zunaj in znotraj faze $Al_xMn_yFe_zSi_u$ (B). Koncentracija aluminija se je v fazi $Al_xMn_yFe_zSi_u$ zmanjšala, medtem ko so se koncentracije Mn, Si in Fe povečale. Največje povečanje smo opazili pri Mn, od ~0,25 na ~7,00 %, medtem ko se je koncentracija Fe povečala od ~0,25 na ~1,50 %. Razmerje koncentracij prehodnih elementov Mn: Fe je bilo v fazi $Al_xMn_yFe_zSi_u$ 4,5–5,5.

Intermetalna faza $Al_xMn_yFe_zSi_u$, ki je nastala pri velikih hitrostih ohlajanja, je imela kroglasto-poliedrično morfologijo, kar kaže na neodvisno nastajanje v zgodnjih fazah strjevanja. Preračun razmerja elementov na število dobljenih sestav te faze (Fe+Mn) kaže konstantno vsoto okoli 30 mas. % pri manjšem spreminjanju razmerja elementov med nastajanjem faze.

Metalografske značilnosti mikrostrukturnih sestavin imajo pomemben vpliv na mehanske lastnosti. Od mehanskih lastnosti smo ugotavljali natezno trdnost, napetost tečenja, raztezek in trdoto po Brinellu (razpredelnica 4).

as fibrous morphology of eutectic, all due to high cooling / solidification rate.

Complex intermetallic phase $Al_xMn_yFe_zSi_u$ forms by the reactions 1 and/or 2 (Table 2) due to both local undercooling and liquid composition which allow direct nucleation of the equilibrium $Al_xMn_yFe_zSi_u$ phase in the liquid; all the components Fe, Mn and Si for building the new particles of the $Al_xMn_yFe_zSi_u$ phase either by individual nucleation and growth or by increase in thickness of that originated previously, that have been transported mainly by diffusion in the liquid.

Since the samples microstructure was very fine, due to high cooling rate performed by applied high pressure die casting technology, some of expected constituent have not been established by optical microscopy analysis. Unfavorable blocky Al5FeSi, final precipitated phases on the magnesium base Al8Mg3FeSi6 evoluted on Al5FeSi needles and secondary eutecic phase Mg_2Si in characteristic ramified morphology distributed on the grain boundaries were established elsewhere at low cooling rates [16].

Exact identification of particular microstructural components was performed by scanning electron microscopy using energy dispersive spectrometer (Figure 5).

Investigation of particular phases by EDS reveals presence of primary aluminium αAl, intermetallic $Al_xMn_yFe_zSi_u$ phase (A), and main eutectic $\alpha_{Al}+\beta_{Si}$. Line analysis enables insight in elements ratio change outside and inside the $Al_xMn_yFe_zSi_u$ phase (B). Aluminum ratio decreases inside the $Al_xMn_yFe_zSi_u$ phase, while Mn, Si and Fe ratio increase. The most significant increase has been noticed for Mn ratio from ~0,25 to ~7,00%, while Fe ratio increase from ~0,25 to ~1,50%. The ratio of transition elements Mn:Fe inside the $Al_xMn_yFe_zSi_u$ phase is in range 4,5-5,5.

Razpredelnica 4. Mehanske lastnosti ulitkov iz zlitine AlSi9MgMn v odvisnosti od premera preskušanca, tj. hitrosti ohlajevanja/strjevanja

Table 4. Mechanical properties values for AlSi9MgMn alloy castings related to test sample diameter i.e. cooling / solidification rate.

Premer preskušanca / Test sample diameter, Φ mm	$Rp_{0,2}$ (N/mm^2)	R_m (N/mm^2)	Δl (%)	HB
6,4	153	306	5,8	85,2
9,0	154	274	3,8	79,61
11,0	125	242	3,3	89

Dobljene mehanske lastnosti so zelo visoke v primerjavi z navadnimi aluminijevimi avtomobilskimi zlitinami. Občutne razlike smo ugotovili pri povečanju ohlajevalne/strjevalne hitrosti. Pri preskušancu z manjšim premerom, tj. tanjšo steno, sta bili napetost tečenja in natezna trdnost višji zaradi drobnejše, v glavnem kroglasto-poliedrične morfologije primarnega aluminija, intermetalne faze $Al_xMn_yFe_zSi_u$ in popolnoma modificiranega vlaknatega evtektika. Trdota po Brinellu ni pokazala neke pravilne odvisnosti, čeprav so bile njene vrednosti mnogo večje, kot jih zahteva standard.

4 Sklepi

Prispevek poroča o preiskavi nove večkomponentne tehnične zlitine AlSi9MgMn z velikim deležem Mn, namenjene običajno za tlačno litje, ki je bila med litjem hitro ohlajena.

- Svetlobna in vrstična mikroskopija sta omogočili identificirati značilne mikrostrukturne sestavine na osnovi njihove morfologije in kemične sestave: primarni aluminij z mešano kroglasto-

Intermetallic phase $Al_xMn_yFe_zSi_u$ evaluated at high cooling rate reveals globular / polyedric morphology, which indicates independently evolution in early stages of solidification. Recalculation of the element ratios on the number of obtained chemical composition of this phase (Fe+Mn) indicates constant sum around 30 % (mass fraction) with minor replacement in elements ratio occurred during formation.

Metallographic features of microstructural constituents have a significant impact on mechanical properties development.

Mechanical properties investigation resulted in yield and tensile strength, elongation and Brinell hardness determination (Table 4).

Obtained mechanical properties were very high when compared to common aluminium automotive alloys. A significant differentiation has been established due to increasing of cooling / solidification rate. Smaller test sample diameter i.e. thinner wall shows increase in yield and tensile strength and elongation due to finer microstructure, prominent globular / polyhedron microstructure of primary aluminium, intermetallic $Al_xMn_yFe_zSi_u$ phase and completely modified fibrous eutectic. Brinell hardness has not shown any regularity, although the values are much higher than those required by norm.

4 Conclusions

Novel multicomponent technical AlSi9MgMn alloy with high manganese content usually intended for high pressure die casting was investigated in this work at high cooling rate conditions.

- Optical and scanning electron microscopy enables identification of characteristic microstructural dendritno morfologijo, kompleksno intermetalno spojino $Al_xMn_yFe_zSi_u$ s kroglasto/poliedrično morfologijo, glavni evtektik (α_{Al} + β_{Si}) v meddendritnih prostorih

- Kompleksna intermetalna faza $Al_xMn_yFe_zSi_u$, ima kroglasto/poliedrično morfologijo zaradi neodvisne individualne nukleacije ravnotežne faze kot posledice lokalnih podhladitev in sestave taline pri velikih ohlajevalnih/strjevalnih hitrostih. Vsota Fe+Mn je konstantna pri okoli 30 mas. % ob manjšem odstopanju deleža obeh elementov v njunem razmerju med nastajanjem.
- Glavni evtektik (α_{Al} + β_{Si}) ima lamelasto-vlaknato morfologijo v odvisnosti od ohlajevalne/strjevalne hitrosti.
- Ugotovljene mehanske lastnosti so zelo visoke, a občutne razlike so nastale s povečanjem ohlajevalne/strjevalne hitrosti v vzorcih z različnimi premeri. Tanjši vzorci so imeli zaradi drobnejše mikrostrukture kot posledice tanjše debeline stene, dobro vidne kroglaste mikrostrukture primarnega aluminija, intermetalne faze $Al_xMn_yFe_zSi_u$ in popolnoma modificiranega vlaknatega evtektika večjo napetost tečenja, natezno trdnost in raztezek. Trdota po Brinellu ni pokazala neke pravilne odvisnosti, a vse njene vrednosti so bile mnogo višje od zahtevanih v standardu.

Karakterizacija nove večkomponentne zlitine AlSi9MgMn z dobrimi mehanskimi lastnostmi zaradi drobnih mikrostrukturnih sestavin in njihovih ugodnih morfologij kaže, da je ta material primeren za izdelavo varnih kritičnih sestavnih delov in sestavov v avtomobilski industriji.

constituents on the base of their morphology and chemical composition: primary aluminum (α_{Al}) with mixed dendrite and globular morphology, complex intermetallic phase $Al_xMn_yFe_zSi_u$ in globular / polyhedron morphology, main eutectic in interdendritic spaces (α_{Al} + β_{Si}).

- Complex intermetallic phase $Al_xMn_yFe_zSi_u$ reveals in globular / polyhedron morphology by independent individual nucleation of equilibrium phase due to both local undercooling and liquid composition at high cooling/solidification rates. Sum (Fe+Mn) has been constant at ~30 % mass fraction with minor replacement in elements ratio occurred during formation.
- Main eutectic (α_{Al} + β_{Si}) evaluate in mixed lamellar – fibrous morphology related to cooling/solidification rate.
- Obatined mechanical properties were very high, although significant differentiation has been established due to increasing of cooling/solidification rate obtained by several sample diameters. Smaller test sample diameter i.e. thinner wall shows increase in yield and tensile strength and elongation due to finer microstructure, prominent globular microstructure of primary aluminium, intermetallic $Al_xMn_yFe_zSi_u$ phase and completely modified fibrous eutectic. Brinell hardness has not show any regularity, although the values are much higher than those required by norm.

Characterization of novel multicomponent AlSi9MgMn alloy with high mechanical properties related to fine microstructure constituents and their favourable morphologies indicate applicability of this material for safety critical parts and sets in automotive industry.

Viri / References

[1] RHEINFELDEN, catalogue: SILAFONT 36- AlSi9MgMn
[2] G. Barlock, L. F. Mondolfo, Structure of some aluminium-iron-magnesium-manganese-silicon alloys, ZeitschriftfürMetallkunde /Materials Research and Advanced Techniques, 66 (10), 1995, 605-611
[3] J. E. Tibballs, J. A. Horst, C. J. Simensen, Precipitation of a-Al(Fe,Mn)Si from the melt, Journal of materials science 36 (2001), 937-941
[4] M. Warmuzek, K. Rabczak, J. Sieniawski, The course of the peritectic transformation in the Al-rich Al–Fe–Mn–Si alloys, Journal of Materials Processing Technology 162–163 (2005) 422–428
[5] M. Warmuzek, J. Sieniawski, K. Wicher, G. Mrówka, The study of the distribution of the transition metals and Si during primary precipitation of the intermetallic phases in Al–Mn–Si alloys, Journal of Materials Processing Technology 175 (2006) 421–426
[6] L. Backerund, G. Chai, J. Tamminen, Solidification Characteristics of Aluminium Alloys, Volume 2, Foundry Alloys, AFS/Skanaluminium, Stockhlom, 1999.
[7] M. V. Kral, A crystallographic identification of intermetallic phases in Al–Si alloys, Mater. Lett., 59 (2005), pp. 2271–2276
[8] M. Tash, F. H. Samuel, F. Mucciardi, Effect of metallurgical parameters on the hardness and microstructural characterization of as-cast and heat-treated 356 and 319 aluminum alloys Mater. Sci. Eng. A, 443 (2007), pp. 185–201
[9] S. Belmares-Perales, M. Castro-Román, M. Herrera-Trejo, L. E. Ramírez-Vidaurri, Effect of cooling rate and Fe/Mn weight ratio on volume fractions of α-AlFeSi and β-AlFeSi phases in Al−7.3Si−3.5Cu alloy, Metals and Materials International, (14) 2008, 3, 307-314
[10] A. Couture, Iron in aluminum casting alloys - a literature survey, International cast metals journal, 6 (1981), 4, 9-17
[11] P. N. Crepeau, Effect of Iron in Al-Si Casting Alloys: A Critical Review, AFS Transactions, 103 (1995), 361-366.
[12] C. M. Dinnis, J. A. Taylor, A. K. Dahle, As-cast morphology of iron-intermetallics in Al–Si foundry alloys, Scripta Mater., 53 (2005), pp. 955–958
[13] Z. ZovkoBrodarac, D. Stanić, F. Unkić, Investigation of AlSi9MgMn alloy solidification by thermal analysis, Conference Proceedings of 52nd International Foundry Conference Portorose 2012, Slovenia, 58-59
[14] D. Stanić, Influence of the solidification conditions and melt treatment on microstructural and mechanical properties of AlSi9MgMn alloy, PhD Thesis, University of Zagreb, Faculty of Metallurgy, Sisak, 2012
[15] Z. Zovko Brodarac, D. Stanić, Effect of the cooling rate on distribution of transition elements in the intermetallic Al-Mn-Fe-Si phase in AlSi9MgMn alloy, 71st World Foundry Congress, Advanced Sustainable Foundry, May, 19-21, 2014., Bilbao, Spain, World Foundry Organization, Non ferrous_10
[16] Z. Zovko Brodarac, D. Stanić, Characterization of novel multicomponent AlSi9MgMn alloy at low cooling rate, Proceeding book of MATRIB 2014, Croatian Society for Materials and Tribology, Zagreb, 2014., 637-646