

Strjevalno zaporedje v zlitini AlSi11

Solidification Sequence of AlSi11 alloy

Povzetek

Avtomobilska industrija je zaradi medsebojne konkurence in okoljskih predpisov za zmanjšanje emisij in porabe goriva prisiljena uporabljati napredne materiale in tehnologije. Ta cilj se lahko doseže predvsem z zmanjševanjem mase in zmanjševanjem velikosti sestavnih delov, kar omogočajo napredni materiali in tehnologije.

Najbolj uporabljan avtomobilski aluminijast del so kolesa, ki so tlačno ulita. Za zapleteno geometrijo tankostenskega ulitka se uporablja zlitina AlSi11 (EN AC 44000). Ta zlitina spada v skupino »evtektičnih zlitin«, zanjo pa sta značilna sorazmerno nizko tališče ter ozek interval strjevanja, kar oboje pri enakomerno porazdeljeni evtektični mikrostrukturi daje odlične mehanske in tehnološke lastnosti. Zato se ta zlitina široko uporablja pri visokotlačnem in nizkotlačnem ulivanju. Silicij je eden od najpomembnejših zlitinskih elementov, ki omogoča dobro livnost aluminijevih zlitin. Dodatek silicija izboljša odpornost proti pokanju v vročem in sposobnost napajanja ulitkov. Sinergija med vplivi zlitinskih elementov in oligoelementov pojasnjuje nastanek različnih intermetalnih faz.

Delež stranskih zlitinskih elementov (Mg, Cu) in oligoelementov (Fe, Mn, Cr, Zn) je bil v preiskovani zlitini AlSi11 majhen. Tankostenska geometrija ulitka zagotavlja pri nizkotlačnem ulivanju in hitrem ohlajevanju (v čim krajšem času) nastajanje številnih pomembnih intermetalnih faz.

Metalografska analiza je pokazala prisotnost naslednjih mikrostrukturnih sestavin: primarni aluminij α_{Al} , glavni evtektik $\alpha_{Al} + \beta_{Si}$, visokotemperaturna železova faza Al₅FeSi, intermetalni fazi Mg₂Si in Al₈FeMg₃Si₆ v sekundarnem evtektiku.

Korelacija med ugotovljenimi mikrostrukturnimi sestavinami, termodinamičnim modeliranjem in diferencialno vrstično kalorimetrijo je pokazala natančno strjevalno zaporedje za zlitino s preiskovano kemično sestavo.

Ključne besede: AlSi11, avtomobilska industrija, termodinamično modeliranje, mikrostruktura, strjevanje

Abstract

The automotive industry is forced to apply advanced materials and technologies in order to overcome the mutual competition, but also for compliance with environmental regulations requiring reduction of emissions, and fuel consumption. One of main component for achieving this goal is weight saving by downsizing of components using advanced materials and production technologies.

The widest production of automotive aluminium component refers to wheels produced by low pressure die casting. Complex geometry of thin wall wheel casting indicates application of AlSi11 alloy (EN AC 44000). An AlSi11 alloy (EN AC 44000) belongs to the group of "eutectic alloys" and is characterized with relatively low melting point and narrow

solidification interval which both brought to the uniformly distributed eutectic microstructure indicating superior mechanical and technological properties. This is the reason for this alloy to be widely used for high and low pressure die casting production. Silicon is one of the most important alloying elements which comprehend to good castability of aluminium alloys. Addition of silicon improves resistance to hot cracks and feeding capability. Synergy of influenced alloying and trace elements effect comprehend to different intermetallic phase evolution.

The content of secondary alloying elements (Mg, Cu) and trace elements (Fe, Mn, Cr, Zn) was minor in investigated AlSi11 alloy. Also thin wall casting geometry using low pressure die casting technology ensures rapid cooling with minimal available time for significant number of intermetallic phases development.

Metallographic analysis resulted in following microstructural constituents: primary aluminium α_{Al} , main eutectic $\alpha_{Al} + \beta_{Si}$, high temperature iron phase Al_5FeSi , intermetallic phases in form of secondary eutectic Mg_2Si and $Al_8FeMg_3Si_6$.

Correlation of established microstructural constituents with thermodynamic modelling and differential scanning calorimetry indicates exact solidification sequence for this particular chemical composition.

Key words: AlSi11, automotive industry, thermodynamic modelling, microstructure, solidification

1. Uvod

Avtomobilskaindustrija je zaradi medsebojne konkurence in okoljskih predpisov za zmanjšanje emisij in porabe goriva prisiljena uporabljati napredne materiale in tehnologije. Odnos med zmanjšanjem mase in zmanjšanjem CO_2 emisij izpušnih plinov je precej zapleten. V odvisnosti od načina računanja so dobljene vrednosti zmanjšanja CO_2 med 3 g/km in 13 g/km pri zmanjšanju mase vozila za 100 kg. Vsi ti različni rezultati so pravilni, ker so odvisni od definicije, do kakšne mere se upošteva zmanjšanje mase. Zato je pomembno razlikovati med dvema vrstama zmanjšanja mase in dvema vrstama prihranka goriva [1]:

- neposredno zmanjšanje mase: masa enega ali več sestavnih delov se zmanjša zaradi zamenjave težjega materiala z lažjim;
- posredno zmanjšanje mase: dodatno zmanjšanje se doseže z zmanjšanjem velikosti določenih sestavnih delov (tj.

1. Introduction

The automotive industry is forced to apply advanced materials and technologies in order to overcome the mutual competition, but also for compliance with environmental regulations requiring reduction of emissions, and fuel consumption. The relation between light weighting and the reduction of tailpipe CO_2 emissions is quite complex. Depending on how the calculation is made, various CO_2 reduction values ranging from 3 g/km up to 13 g/km for a weight saving of 100 kg are reported. These different outcomes are all correct, as they depend on definitions and to what extent the light weighting is exploited. It is therefore important to distinguish between two kinds of weight savings and two kinds of fuel savings [1].

- Direct weight saving: the weight reduction due to exchanging a heavier material for a lighter material in one or several components.
- Indirect weight saving: additional weight reduction obtained by downsizing

zavor, obes, motorja itn.) s tem, da ostanejo zmogljivosti vozila enake kot prej. Posredno zmanjšanje mase se prišteva k posrednemu zmanjšanju in lahko predstavlja do 50 % dodatnih prihrankov pri masi celotnega avtomobila;

- primarni prihranek goriva: gorivo se prihrani zaradi manjše potrebne energije za gibanje manjše mase;
- sekundarni prihranek goriva: dodatni prihranek goriva se doseže z optimizacijo pogona (tj. prestavnega razmerja, elektronike pri motorju, gibne prostornine itn.) s tem, da se ohranjajo zmogljivosti vozila na enaki ravni.

Najmanjše zmanjšanje emisije CO₂ se doseže pri kombinaciji neposrednega zmanjšanja mase in primarnega prihranka goriva. Največje zmanjšanje emisije CO₂ se doseže, če se prištejeta še posredno zmanjšanje mase in sekundarni prihranek goriva.

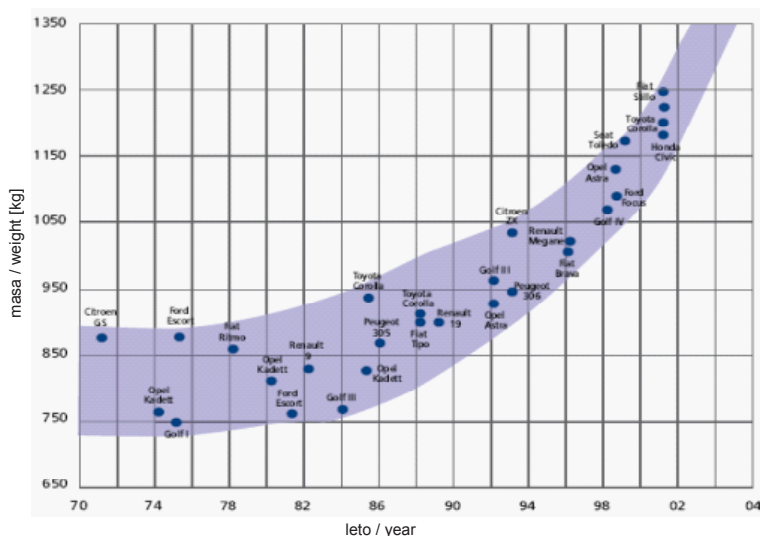
V zadnjih 40 letih je bilo opaziti dramatično povečanje mase avtomobilov za 300-400 kg v istem avtomobilskem razredu

certain components (i.e. brakes, suspension, engine, etc.) to keep vehicle performances at the same level as before. Indirect weight savings come on top of direct weight savings, and can represent up to 50% additional savings on the weight of the complete car.

- Primary fuel saving: fuel saved thanks to the lower energy demand related to moving a lighter mass.
- Secondary fuel saving: additional fuel saving obtained by optimizing the drive train (i.e. gear ratio, engine electronics, displacement, etc.) to keep performances at the same level as before.

The lowest CO₂ emissions savings will be achieved by combining direct weight savings and primary fuel savings exclusively. The largest CO₂ reductions are achieved when both indirect weight-saving and secondary fuel saving are added together.

A dramatic increase in car mass by 300-400 kg for the same class of cars has been noticed in last 40 years, despite the



Slika 1. Spirala mase pri proizvodnji avtomobilov [1]

Figure 1. Spiral of weight for cars production [1]

potrojila v letih 1990–2012, kar pomeni povečanje s 50 kg na 140 kg [2].

Z rastočim deležem vgrajenih aluminijevih sestavnih delov in sestavov (tudi iz drugih lahkih kovin in materialov) se je zmogljivost, varnost in ekološka prijaznost avtomobilov večala. Široka uporaba aluminijevih zlitin v avtomobilih je predstavljena na sliki 3.

Slika 4 kaže statistično porazdelitev aluminijevih delov za določen namen.

Glavni vzrok za tako široko uporabo je ekonomski. Povprečni evropski avtomobil, ki vsebuje 140 kg aluminija, prevozi več kot 200 000 km (15 000 na leto). Aluminijevski sestavni deli so v povprečju 40 % lažji kot deli, ki so bili z njimi nadomeščeni (neposredno zmanjšanje mase), 25 %-no zmanjšanje mase pa se doseže še z zmanjšanjem velikosti delov (posredno zmanjšanje mase). Na osnovi začetnih predpostavk se lahko izračuna [2]:

- vsak kg aluminija prispeva v povprečju 1 kg zmanjšanja mase,
- 1 kg aluminija v avtomobilu zmanjša emisijo CO₂ za 18 % v času uporabe

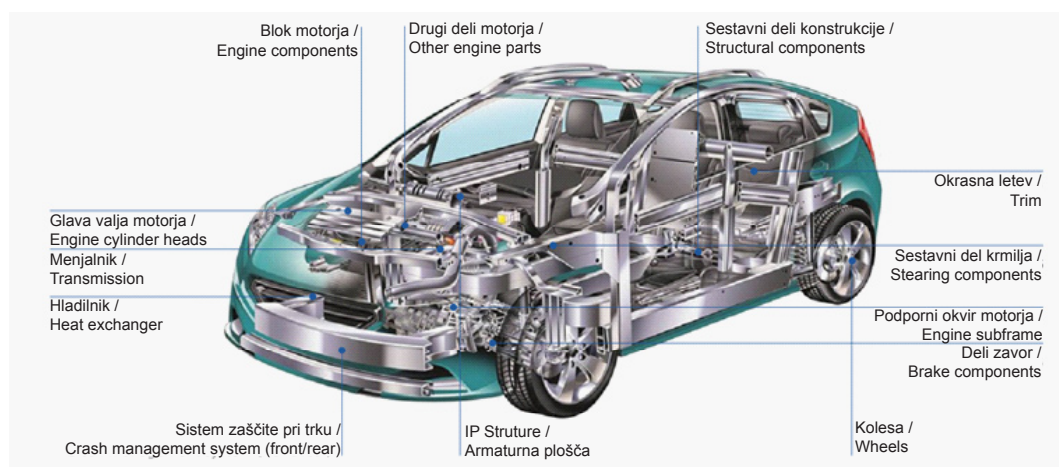
Europe almost tripled between 1990 and 2012, increasing from 50 kg to 140 kg [2].

With a growing share of built-in components and assemblies made of aluminium alloy (and other light metals and materials) performances, safety and eco-friendliness of cars is growing. Wide application of aluminium alloys in cars is shown in Figure 3.

Statistical distribution of aluminium components used for particular purpose is shown in Figure 4.

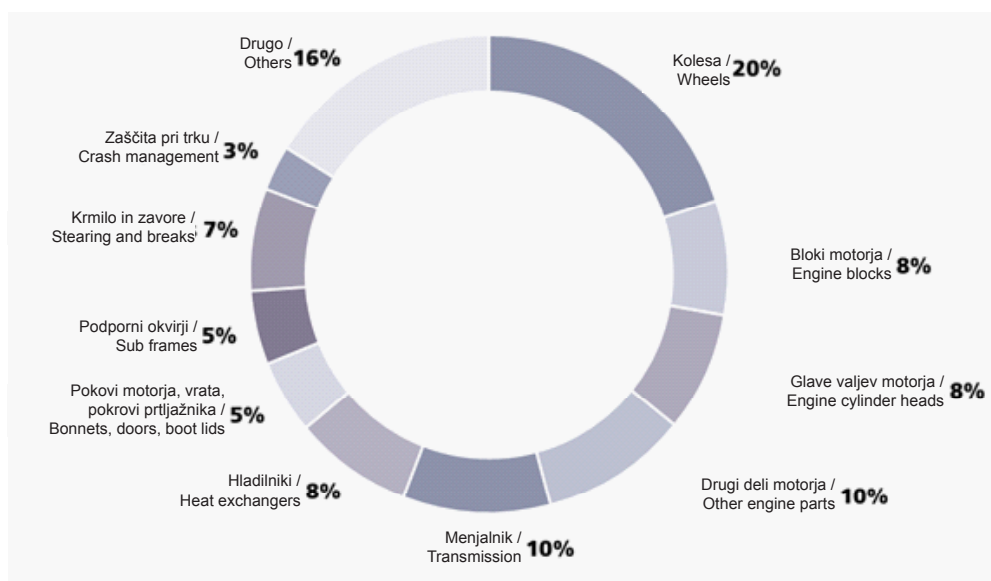
The main reason of such wide application lays down in economic approach. Average European car containing 140 kg of aluminium exceeds a driving distance of 200.000 km (15.000 km / year). Aluminium component is on average 40% lighter than the replaced component (direct weight saving) and that 25% additional weight reduction is obtained by downsizing other components (indirect weight savings). On the base of this initial assumption following calculation has been made [2]:

- each kg of aluminium provides an average light-weighting of 1 kg



Slika 3 Potencialna uporaba aluminija [2]

Figure 3. Potential of aluminium application [2]



Slika 4 Porazdelitev aluminija v EU-avtomobilih [2]

Figure 4. Distribution of aluminium in EU cars [2]

avtomobila,

- 1 kg aluminija v avtomobilu zmanjša emisijo CO₂ za 17 % med celotno življenjsko dobo avtomobila,
- ker je evropska proizvodnja 16 000 000 avtomobilov na leto, pomeni to okoli 40 000 000 ton emisij CO₂ v življenjski dobi avtomobila,
- 140 kg aluminija v povprečnem avtomobilu pomeni 65 litrov letnega prihranka goriva.

Najširše uporabljan aluminijski del so kolesa. Zapleteni geometriji tankostenskih ulitkov najbolj ustreza zlitina AlSi11 (EN AC 44000). Za kolesa se največ uporablja nizkotlačno litje. Cilj naše raziskave je bil ugotoviti strjevalno zaporedje v zlitini z analizo vzorcev, vzetih iz obroča kolesa. Primer ulitka kolesa prikazuje slika 5.

Zlitina AlSi11 (EN AC 40000) spada v skupino »evtektičnih zlitin«, zanjo pa je značilno sorazmerno nizko tališče

- 1 kg of aluminium in a car reduces CO₂ emissions by 18 kg during its use phase
- 1 kg of aluminium in a car reduces CO₂ emissions by 17 kg during its whole life-cycle
- based on a yearly European production of 16 million cars, this corresponds to roughly 40 million tons of avoided CO₂ emissions during their lifespan.
- 140 kg of aluminium in an average car result in an annual average fuel saving of 65 litres.

The widest production of aluminium component refers to wheels. Complex geometry of thin wall wheel casting indicates application of AlSi11 alloy (EN AC 44000). Wheels are mostly produced by low pressure die cast technology. The aim of this investigation was to establish the solidification sequence of an alloy by analysis of the sample taken from the



Slika 5. Ulitek kolesa

Figure 5. Wheel casting

in ozek interval strjevanja, kar oboje prispeva k enakomerni porazdelitvi evtektične mikrostrukture in s tem odličnim mehanskim ter tehnološkim lastnostim [3-5]. Zato se ta zlitina široko uporablja za visoko- in nizkotlačno litje. Silicij je eden najpomembnejših zlitinskih elementov, ki prispevajo k dobri livnosti aluminijevih zlitin. Dodatek silicija izboljša odpornost proti pokanju v vročem in sposobnost napajanja ulitkov [6]. Sinergija učinkov vplivnih elementov in oligoelementov nam omogoča

wheel ribbon. An example of wheel casting is shown in Figure 5.

An AlSi11 alloy (EN AC 44000) belongs to the group of "eutectic alloys" and it is characterized with relatively low melting point and narrow solidification interval which both brought to the uniformly distributed eutectic microstructure indicating superior mechanical and technological properties [3-5]. This is the reason for this alloy to be widely used for high and low pressure die casting production. Silicon is one of the most important alloying elements which comprehend to good castability of aluminium alloys. Addition of silicon improves resistance to hot cracks and feeding capability [6]. Synergy of influenced alloying and trace elements effect comprehend to different intermetallic phase evolution [7].

Predicted solidification sequence of an AlSi11 alloy and development of possible microstructural constituents is shown in Table 1.

2. Experimental

Experimental was related to AlSi11 alloy (EN AC-44000) [8]. Investigation methodology

Razpredelnica 1. Reakcije, ki potekajo med strjevanjem zlitine AlSi11 [7]

Table 1. Reaction occurring during solidification of AlSi11 alloy [7].

Opisi reakcije / Reaction description	Reakcija / Reaction
Nastanek dendritne mreže / Dendrite network development	$L \rightarrow \alpha_{Al}$
Izločanje faz AlMnFe in AlFeSi / Precipitation of AlMnFe and AlFeSi phases	$L \rightarrow \alpha_{Al} + Al_{15}(FeMn)_3Si_2$
	$L \rightarrow \alpha_{Al} + Al_{15}(FeMn)_3Si_2 + Al_5FeSi$
Glavna evtektična reakcija in izločanje Si in MnFe / Main eutectic reaction and precipitation of Si and MnFe phases	$L \rightarrow \alpha_{Al} + \beta_{Si} + Al_{15}(FeMn)_3Si_2 + Al_5FeSi$
Izločanje sekundarnih evtektikov Mg_2Si in Al_2Cu / Precipitation of secondary eutectic Mg_2Si and Al_2Cu phases	$L \rightarrow \alpha_{Al} + Mg_2Si + Al_2Cu + Al_5FeSi + \beta_{Si}$
Izločanje ternarnih evtektikov AlFeMgSi in AlCuMg / Precipitation of ternary eutectic AlFeMgSi and AlCuMg phases	$L \rightarrow \alpha_{Al} + \beta_{Si} + Mg_2Si + Al_8FeMg_3Si_6 + Al_5Mg_8Cu_2Si_6$

razumeti nastanek različnih intermetalnih faz [7].

Napoved strjevalnega zaporedja v zlitini AlSi11 in nastanek možnih mikrostrukturnih sestavin daje razpredelnica 1.

2. Poskusi

Poskusi so bili narejeni z zlitino AlSi11 (EN AC-44000) [8]. Raziskovalna metodologija je zajemala taljenje in pripravo taline s kemično sestavo, zahtevano po predpisih. Uliivanje je potekalo na stroju za nizkotlačno ulivanje. Kemična sestava se je ugotavljala na licu mesta z analizo napravo ARL 3460 Advantage OES Metals Analyzer.

Kemična sestava taline se je najprej uporabila za izračun ravnotežnega faznega diagrama s programom ThermoCalc (TCW 5.0). Program omogoča izračun termodinamične stabilnosti posameznih faz. Za ugotavljanje temperatur izločanja posameznih mikrostrukturnih sestavin zlitine AlSi11 smo na napravi Netzch STA 409 C/CD napravili simultano termično analizo. Za analizo se je vzel preskušaneec z obroča dejanskega ulitka kolesa.

Metalografsko analizo smo napravili s svetlobnim mikroskopom Olympus GX51, da bi vizualno ugotovili posamezne mikrostrukturne sestavine. Vzorce smo fotografirali z digitalno kamero Olympus DP70 in jih pri različnih povečavah mikroskopa analizirali s programsko opremo Analysis@MaterialsResearchLab. Določene faze smo prepoznavali z vrstičnim mikroskopom Tescan Vega z EDS. Vzorca za metalografsko analizo so bili tudi vzeti iz ulitka dejanskega kolesa.

comprehends melting and preparation of requested chemical composition according requisition. Casting was performed on low pressure die casting machine. Chemical composition was determined "in situ" on ARL 3460 Advantage OES Metals Analyzer.

Chemical composition of melt was initial precondition for calculation of equilibrium phase diagram by ThermoCalc (TCW 5.0) programme. Programme enables calculation of thermodynamical stability of particular phases. In order to establish precipitation temperatures of particular microstructural constituents of AlSi11 alloy, simultaneous thermal analysis was performed on Netzch STA 409 C/CD. The analysis was performed on the test sample taken from the ribbon of actual wheel casting.

Metallographic analysis was performed on optical microscope Olympus GX51 in order to visually identification of particular microstructural constituents. Samples were recorded by digital camera Olympus DP70, while the analysis was performed by Analysis@MaterialsResearchLab software at different microscope magnifications. Particular phases were recognized on scanning electron microscope Tescan Vega by EDS investigation (energy dispersive spectrometry). Samples for metallographic analysis were also taken from the actual wheel casting.

3. Results and Discussion

3.1 Chemical investigation

Comparison of required chemical composition (EN 1706:1998, [8]) and actual sample shown in Table 2.

3. Rezultati in razprava

3.1 Kemična preiskava

Primerjavo med zahtevano kemično sestavo (EN 1706:1998 [8]) in sestavo vzorca daje razpredelnica 2.

3.2 Ravnotežno strjevanje – ThermoCalc (TCW)

Iz termodinamičnih izračunov stabilnosti posameznih faz pri začetni temperaturi 743 °C, tlaku 10⁵ MPa in ugotovljeni kemični sestavi preiskovane zlitine je bil sestavljen ravnotežni fazni diagram, ki ga kaže slika 6.

Politermni prerez faznega diagrama zlitine AlSi11 kaže naslednje izračunano strjevalno zaporedje: izračun dendritne faze α_{Al} poleg izločanja visokotemperaturne intermetalne faze na osnovi železa, izračun primarnega in evtektičnega Si, izločanje kompleksnih faz $Al_8FeMg_3Si_6$ in Mg_2Si sekundarnega evtektika. Ker je talina stabilna do 566 °C in izračun sekundarnih evtektičnih faz poteka pod to temperaturo, kaže to na omejene možnosti izločanja. Ravnotežno termodinamično modeliranje tudi kaže na izločanje drugih intermetalnih faz, kot so $Al_{13}Cr_4Si_4$, $Al_5Cu_2Mg_8Si_6$ in Al_3Ni . Vse poteka pod 400 °C kot rezultat reakcij v trdnem stanju.

Chemical composition of an actual sample indicates minor quantities of trace elements. Iron and manganese was much below the requested values. Ratio Fe/Mn~53,23 was very high which indicates possible needle-like Al_5FeSi evolution. Low contents of magnesium and copper also limitate significant amount of secondary eutectic phase Mg_2Si and Al_2Cu .

3.2 Equilibrium Solidification – ThermoCalc (TCW)

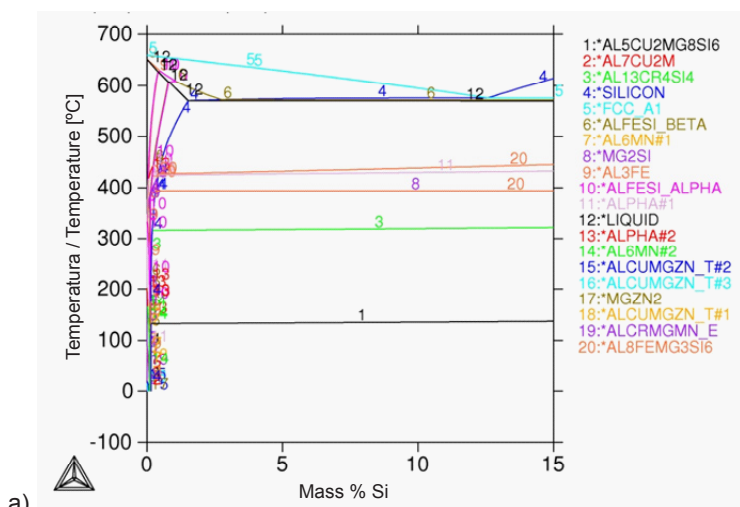
Thermodynamic calculation of particular phases stability at initial conditions of temperature 743 °C, pressure 10⁵ MPa and obtained chemical composition of investigated alloy resulted in equilibrium phase diagram, shown in Figure 6.

Polythermal section of phase diagram of AlSi11 alloy indicates solidification sequence as follows: dendrite evaluation α_{Al} beside precipitation of high temperature intermetallic phases on iron base, silicon (primary and eutectic) evaluation, and precipitation of complex secondary eutectic intermetallic phases $Al_8FeMg_3Si_6$ and Mg_2Si . Since liquid is stable till 566 °C, secondary eutectic phases evaluation is occurring below this temperature which indicate limited sources and positions for its precipitation. Equilibrium thermodynamic modelling also indicates precipitation of other intermetallic phases such as $Al_{13}Cr_4Si_4$, $Al_5Cu_2Mg_8Si_6$ and Al_3Ni , all below 400 °C as a result of solid state reactions.

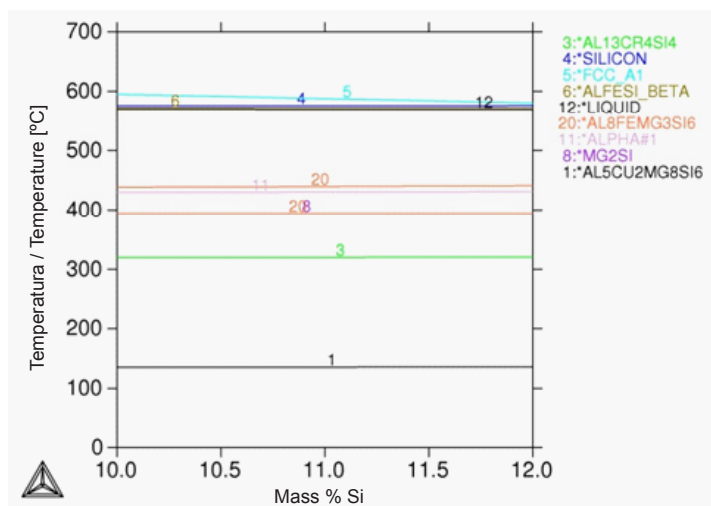
Razpredelnica 2. Primerjava med zahtevano kemično sestavo (EN 1706:1998 [8]) in sestavo vzorca

Table 2. Comparison of required chemical composition (EN 1706:1998, [8]) and actual sample

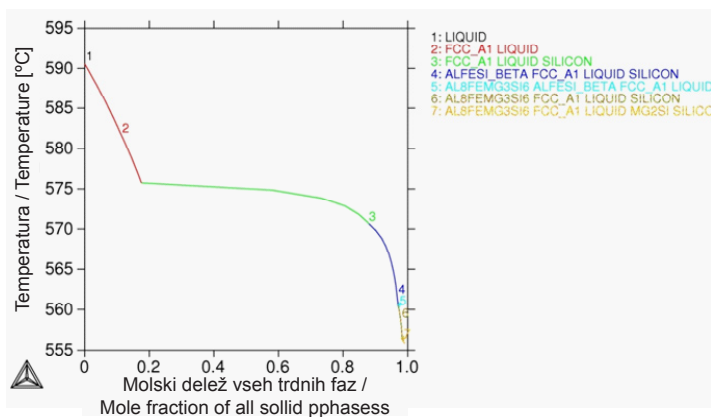
Element, m.f. %	Si	Fe	Cu	Mn	Mg	Zn	Ti	Cr	Ni	Sr
EN AC 44000	10,0-11,8	0,19	0,05	0,10	0,20-0,45	0,07	0,15	-	-	-
Dejanski vzorec / Actual sample	10,6276	0,0905	0,001	0,0017	0,1808	0,004	0,0909	0,0007	0,0046	0,0319



a)



b)



c)

Slika 6. Termodinamični izračun ravnotežnega faznega diagrama zlitine AlSi11

a) delni ravnotežni fazni diagram zlitine AlSi11 za 0–15 mas. % Si

b) delni ravnotežni fazni diagram zlitine AlSi11 za 12–15 mas. % Si

c) ravnotežno zaporedje strjevanja v zlitini AlSi11

Figure 6.

Thermodynamical calculation of equilibrium phase diagram of AlSi11 alloy

a) Partial equilibrium phase diagram of AlSi11 alloy from 0-15 % Si

b) Partial equilibrium phase diagram of AlSi11 alloy from 10-12 % Si

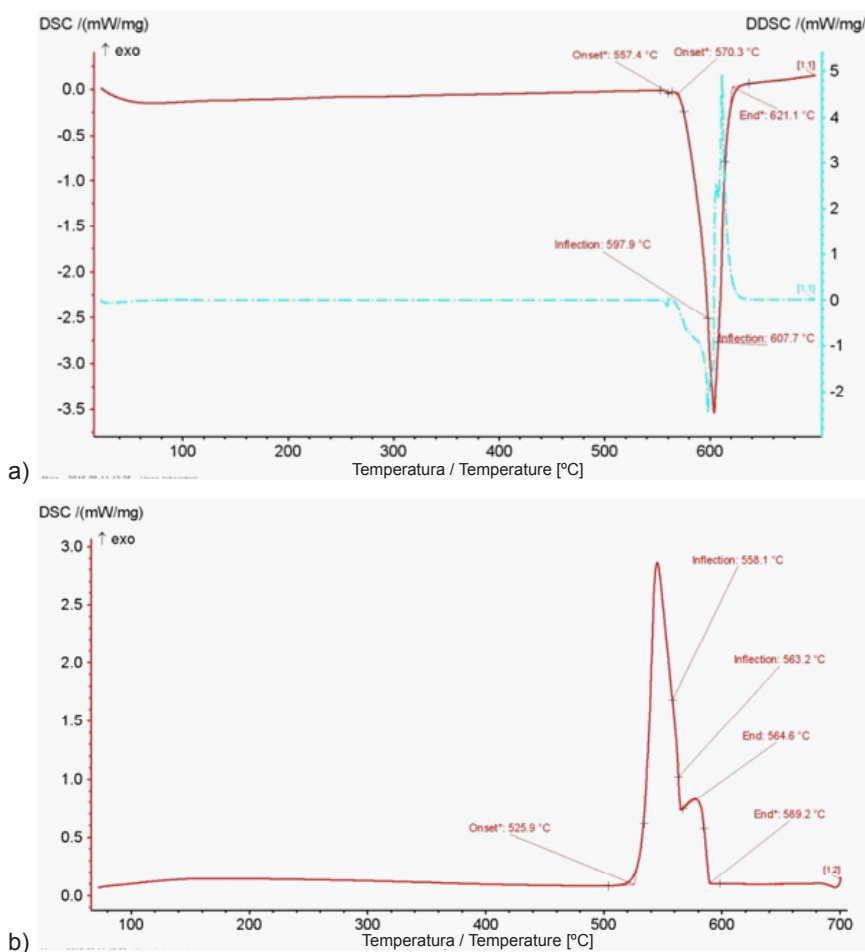
c) Equilibrium solidification sequence of AlSi11 alloy

3.3 Simultana termična analiza - diferencialna vrstična kalorimetrija (DSC)

Simultana termična analiza je bila narejena z napravo za diferencialno vrstično kalorimetrijo in prikazana kot diagram s segrevalnimi in ohlajevalnimi krivuljami, dobljenimi pri hitrosti 0,17 K/s, kot kažeta sliki 7a in 7b.

3.3 Simultaneous Thermal Analysis - Differential Scanning Calorimetry (DSC)

Simultaneous thermal analysis has been performed using differential scanning calorimetry (DSC) resulted in heating and cooling curves diagram with the rate of 0,17 K/s, shown in Figures 7a and b, respectively.



Slika 7 Simultana termična analiza zlitine AlSi11, narejena z napravo za diferencialno vrstično kalorimetrijo; a) segrevalna krivulja; b) ohlajevalna krivulja

Figure 7. Simultaneous thermal analysis of AlSi11 alloy samples by DSC method; a) heating and b) cooling curve

Razpredelnica 3 Primerjava temperatur faznih premen po DSC in TCW**Table 3.** Comparison of TCW and DSC phase transformation temperatures

Reakcija št. / Reaction No.	Temperatura / Temperature [°C]		Napovedana reakcija / Predicted reaction
	TCW	DSC	
1	590	589,2	Nastanek dendritne mreže / Dendrite network development
2	575	-	Izločanje primarnega silicija / Primary silicon evolution
3	572	564,6	Izločanje faze Al_5FeSi / Precipitation of Al_5FeSi phase
4	502	563,2	Eutektična reakcija / Eutectic reaction
5	439	558,1	Izločanje faze $\text{Al}_8\text{FeMg}_3\text{Si}_6$ / Precipitation of $\text{Al}_8\text{FeMg}_3\text{Si}_6$ phase
6	394	525,9	Izločanje faze Mg_2Si / Precipitation of Mg_2Si phase

Simultana termična analiza je pokazala na številne fazne premene pri strjevanju zlitine AlSi11. Primerjavo med temperaturami, dobljenimi z DSC, in z termodinamičnim modeliranjem (TCW) daje razpredelnica 3.

Pomik pomembnih faznih premen, ugotovljenih z diferencialno vrstično kalometrijo, k nižjim temperaturam je bil pričakovan zaradi neravnotežnih razmer. Eutektična reakcija poteka pri občutno višji temperaturi (563,2 °C) v primerjavi z ravnotežnimi razmerami. Strjevanje dejanskega vzorca se konča s kompleksnimi fazama $\text{Al}_8\text{FeMg}_3\text{Si}_6$ in Mg_2Si .

3.4 Metalografska analiza

Zlitino AlSi11 smo metalografsko analizirali s svetlobnim in vrstičnim elektronskim mikroskopom. S svetlobnim mikroskopom so se vizualno ugotavljale mikrostrukturne sestavine na osnovi njihovih morfoloških značilnosti. Določene značilne faze smo prepoznavali z vrstičnim elektronskim mikroskopom (SEM) z energijsko disperzijsko sprektrometrijo (EDS).

3.5 Svetlobna mikroskopija

Z mikrostrukturno preiskavo smo ugotavljali mikrostrukturne sestavine vzorcev osnovne

Simultaneous thermal analysis indicates a number of phase transformations during solidification of AlSi11 alloy. Comparison of DSC obtained temperatures with those obtained by thermodynamic modelling – TCW is shown in Table 3.

The shift of significant DSC phase transformations temperatures toward lower values was expected due to non-equilibrium conditions. Eutectic reaction occurs at significantly higher values (563,2 °C) when compared to equilibrium one. Solidification of actual sample ends with complex intermetallic phases $\text{Al}_8\text{FeMg}_3\text{Si}_6$ and Mg_2Si .

3.4 Metallographic Analysis

Metallographic analysis of AlSi11 alloy was performed by optical and scanning electron microscopy. Optical microscopy was used for visual identification of microstructural constituents on the base of their morphology characteristics. Noticed characteristic phases were identified by scanning electron microscope (SEM) using energy dispersive spectrometry (EDS).

3.5 Light Microscopy

Microstructural investigations comprehend visual identification of microstructural

in modificirane zlitine AlSi11, vzetih iz taline, in jih primerjali z mikrostrukturnim atlasom [7].

Različne povečave so odkrile številne mikrostrukturne sestavine in njihove morfologije, kot prikazuje slika 8.

V splošnem je bila mikrostruktura vzorca zlitine AlSi11 sestavljena iz naslednjih sestavin: primarni dendriti aluminija (α_{Al}), eutektični silicij, intermetalne faze na osnovi železa, predvsem igličasta faza Al_5FeSi , in še drobne faze na osnovi magnezija (Mg_2Si , $Al_8FeMg_3Si_6$).

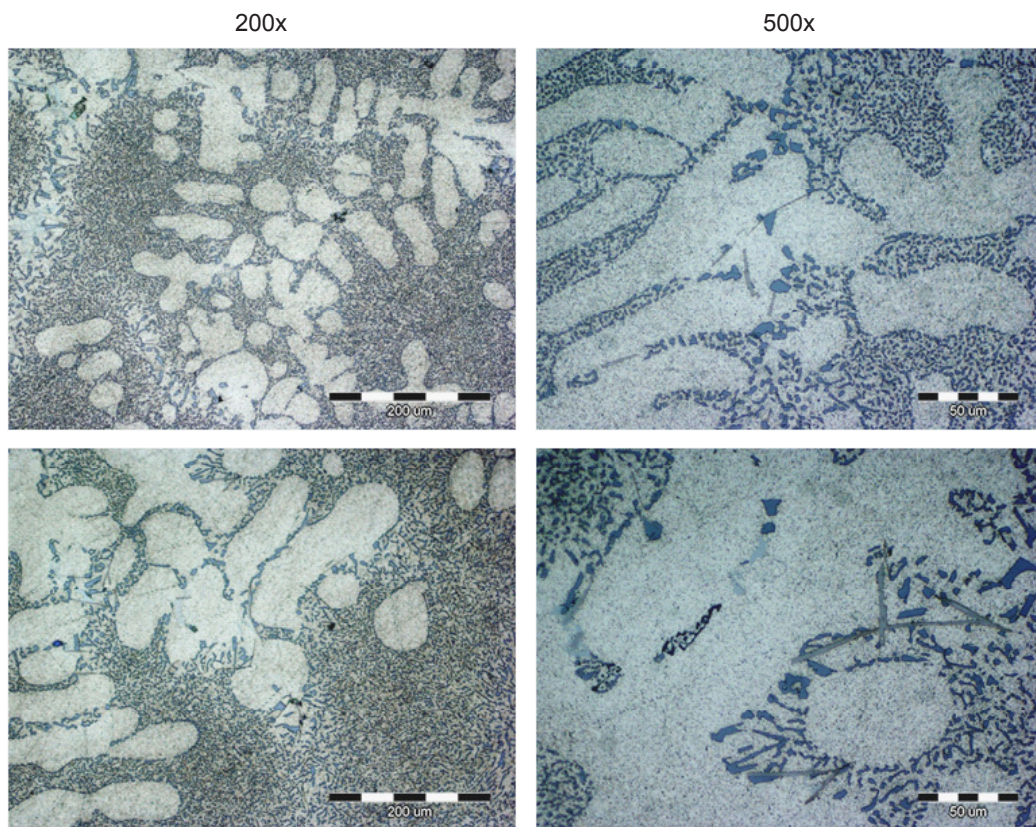
Mikrostruktura kaže na dobro razvito dendritno mrežo. Analiza razdalj med sekundarnimi dendritnimi vejami (SDAS) je

constituents of base and modified AlSi11 alloy melt samples by comparison with the microstructure atlas [7].

Different magnification reveals number of microstructural constituents and their morphologies, as shown in Figure 8.

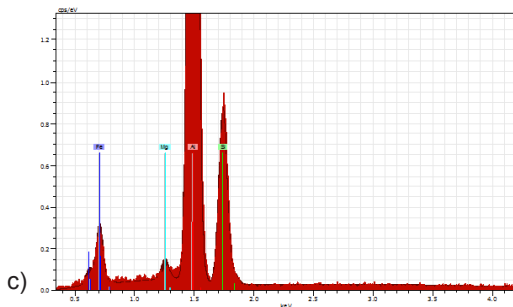
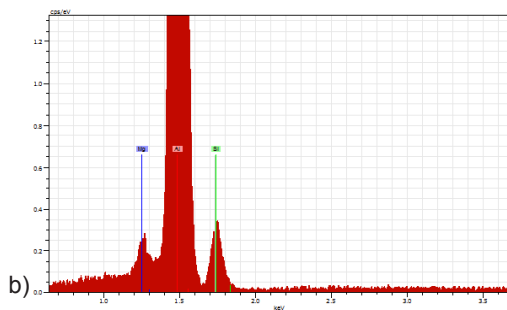
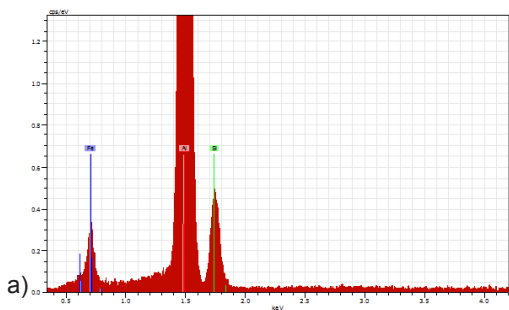
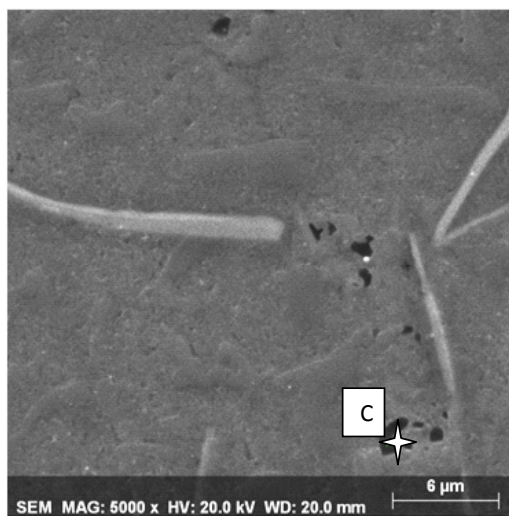
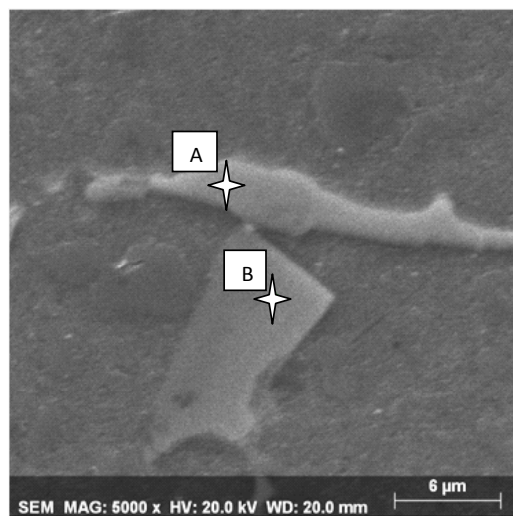
In general, in microstructure of AlSi11 alloy sample consist from following constituent: primary aluminum dendrites (α_{Al}), eutectic silicon, intermetallic phases on iron base mostly in needle-like morphology Al_5FeSi , as well as fine secondary intermetallic phases on the base of magnesium (Mg_2Si , $Al_8FeMg_3Si_6$).

Microstructure indicates highly developed dendrite network. An analysis of



Slika 8 Mikrostruktura zlitine AlSi11

Figure 8. Microstructure of AlSi11 alloy



Slika 9. Analiza mikrostrukturnih sestavin v zlitini AlSi11 s SEM/EDS

Figure 9. Analysis of microstructural constituents of AlSi11 alloy by SEM/EDS

dala naslednji rezultat SDAS = 30,39 μm , kar ustreza tehnologiji nizkotlačnega litja. Eutektični silicij je bil v celoti modificiran.

secondary dendrite arm spacing resulted in following value SDAS = 30,39 μm which corresponds to applied low pressure die casting technology. Eutectic silicon has been completely modified.

3.6 Elektronska mikroskopija

Mikrostrukturne sestavine zlitine AlSi11 so bile preiskane z energijskodisperzijsko spektrometrijo. Primere ugotavljanja intermetalnih faz kaže slika 9.

Z EDS smo ugotovili naslednje mikrostrukturne sestavine v zlitini AlSi11: primarni aluminij (α_{Al}), glavni evtektik ($\alpha_{Al} + \beta_{Si}$), visokotemperaturno fazo Al_5FeSi na osnovi železa, in intermetalni fazi sekundarnega evtektika (Mg_2Si , $Al_8FeMg_3Si_6$).

4 Sklepi

Zlitina AlSi11 je navadno uporabljana zlitina v avtomobilski industriji, ker ima ozek interval strjevanja, kar omogoča dobro livnost in specifično strjevalno zaporedje zaradi večje količine sekundarnih zlitinskih elementov in oligoelementov. Delež sekundarnih zlitinskih elementov (Mg, Cu) in oligoelementov (Fe, Mn, Cr, Zn) je bil v preiskani zlitini AlSi11 majhen. Tankostenska geometrija ulitka zagotavlja hitro ohlajanje v zelo kratkem času, kar je pomembno za nastanek številnih intermetalnih faz. Modeliranje ravnotežnega faznega diagrama, simultana fazna analiza in mikrostrukturne preiskave so omogočile ugotoviti strjevalno zaporedje v zlitini AlSi11.

Metalografska analiza je pokazala prisotnost naslednjih faz: primarni aluminij (α_{Al}), glavni evtektik ($\alpha_{Al} + \beta_{Si}$), visokotemperaturna faza Al_5FeSi na osnovi železa, in intermetalni fazi sekundarnega evtektika (Mg_2Si , $Al_8FeMg_3Si_6$).

Primerjava dobljenih mikrostrukturnih sestavin, sestavin, napovedanih s termodinamičnim modeliranjem, in sestavin, ki jih je nakazala diferencialna vrstična kalorimetrija, je omogočila natančno ugotoviti strjevalno zaporedje zlitine z našo

3.6 Electron Microscopy

Microstructural constituent of AlSi11 alloys were examined by energy dispersive spectrometry. Examples of identification of intermetallic phases are shown in Figure 9.

Following microstructural constituents have been established by EDS analysis of AlSi11 alloy: primary aluminium α_{Al} , main eutectic $\alpha_{Al} + \beta_{Si}$, high temperature iron base phase Al_5FeSi , secondary eutectic intermetallic phases Mg_2Si and $Al_8FeMg_3Si_6$.

4 Conclusions

Although AlSi11 alloy represents a common alloy in automotive applications with narrow solidification interval characterized with high castability, it reveals specific solidification sequence due to amount of secondary alloying and trace elements. The content of secondary alloying elements (Mg, Cu) and trace elements (Fe, Mn, Cr, Zn) was minor in investigated AlSi11 alloy. Also thin wall casting geometry ensures rapid cooling with minimal available time for significant number of intermetallic phases development. Modelling of equilibrium phase diagram, simultaneous phase analysis and microstructural investigations resulted in determination of solidification sequence of AlSi11 alloy.

Metallographic analysis resulted in following microstructural constituents: primary aluminium α_{Al} , main eutectic $\alpha_{Al} + \beta_{Si}$, high temperature iron phase Al_5FeSi , intermetallic phases in form of secondary eutectic Mg_2Si and $Al_8FeMg_3Si_6$.

Correlation of established microstructural constituents with thermodynamic modelling and differential scanning calorimetry indicates exact solidification sequence for this particular

sestavo: nastanek dendritne mreže (589,2 °C), izločanje faze Al_5FeSi (564,6 °C), eutektična reakcija (563,2 °C), izločanje faze $\text{Al}_8\text{FeMg}_3\text{Si}_6$ (558,1 °C) ter izločanje Mg_2Si faze (525,9 °C).

chemical composition as follows: dendrite network development (589,2 °C), precipitation of Al_5FeSi phase (564,6 °C), eutectic reaction (563,2 °C), precipitation of $\text{Al}_8\text{FeMg}_3\text{Si}_6$ phase (558,1 °C), and precipitation of Mg_2Si phase (525,9 °C).

Viri / Literature

- [1] EAA - European Aluminium Association 4: Aluminium in cars, report "Sustainability of the European aluminium industry 2008", http://www.european-aluminium.eu/pdf/Aluminium_in_cars_Sept2008.pdf
- [2] EAA-Aluminium-in-Cars-Unlocking-the-light-weighting-potential, 2013, http://www.european-aluminium.eu/wp-content/uploads/2013/10/EAA-Aluminium-in-Cars-Unlocking-the-light-weighting-potential_September2013_03.pdf
- [3] J. R. Davis, Aluminium and Aluminum Alloys, ASM Specialty Handbook, ASM International, Materials Park, Ohio, USA, (2002).
- [4] J. Campbell, Metal quality studies in secondary remelting of aluminum, Technical Paper, 47 (2004), 78-81.
- [5] K. Krone, Aluminiumrecycling, Vom Vorstoff bis zur fertigen Legierung, Vereinigung Deutscher Schemlzhütten, Düsseldorf, 2000
- [6] BAKER, H.: Alloy Phase Diagrams. ASM Handbook – Volume 3. ASM International, Materials Park. Ohio, 1992., p. 253
- [7] L. Bäckerund, G. Chai, J. Tamminen: Solidification Characteristics of Aluminium Alloys, Foundry Alloys, AFS/Skanaluminium, Stockholom, 2, (1999).
- [8] EN 1706:1998 Aluminium and aluminium alloys – Castings – Chemical composition and mechanical properties

AKTUALNO / ACTUAL

Koledar livarskih prireditvev

Termin	Naziv dogodka	Kraj / država dogodka
14.-16.09.2016	56th International Foundry Conference Portoroz 2016	Portoroz/Slovenija
20.-22.09.2016	Metal 2016	Kielce/Poljska
21.-23.09.2016	Int. Zinc Diecasting Conference	Brescia/Italija
23.-24.09.2016	International Foundry Forum	Dresden/Nemčija
28.09.-01.10.2016	48. IOC 2016	Bor/Srbija
29.09.-01.10.2016	ANKIROS – ANNOFER - TURKCAST	Istanbul/Turčija
03.-07.10.2016	Fond-Ex	Brno/Češka
01.-02.02.2017	VDI-Tagung Giesstechnik im Motorenbau	Magdeburg/Nemčija
16.-17.03.2017	Aachener Giesserei-Kolloquium	Aachen/Nemčija