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Vpliv livarskih napak na električne lastnosti ulitka iz aluminija

Influence of Foundry Defects on the Electrical Properties of Al-Castings

Povzetek

Dosedanja tehnologija visokotlačnega litja aluminijastih kratkostičnih kletk rotorja indukcijskega elektromotorja je zadovoljila zahteve po visoki produktivnosti, ne pa tudi po največji možni končni učinkovitosti elektromotorjev. S tem namenom je bil v tem delu raziskan vpliv livarskih napak, kot so nečistoče in poroznost na električne lastnosti ulitka iz aluminija. Preizkušanci so bili uliti iz zlitin Al99,99, Al99,7 in Al99,5 pri različnih pogojih litja, in sicer v vakuumu ter na zraku. Med strjevanjem sta bili merjeni temperatura ter električna prevodnost ulitka. Vzorci so bili analizirani z optičnim mikroskopom z namenom analize deleža poroznosti v ulitku ter z vrstičnim elektronskim mikroskopom z namenom analize faz in nečistoč v ulitku. Na podlagi omenjenih analiz je bil pojasnjen vpliv deleža nečistoč in poroznosti na električne lastnosti aluminija.

Ključne besede: električne lastnosti, čistost Al-zlitin, poroznost

Abstract

The current aluminium high-pressure die casting technology for casting rotor squirrel cages of induction motor has to satisfy the requirements of high productivity, but does not satisfy the largest possible total efficiency of electric motors. With this aim the influence of casting defects, such as impurities and porosity, on the electrical properties of the cast aluminium was investigated. The specimens were cast from the Al-alloys Al99.99, Al99.7, Al99.5 and under various casting conditions, such as in the vacuum and in air. During the solidification, temperature and electrical conductivity of the castings were measured. Samples were analysed using an optical microscope to determine the proportion of the porosity in the castings, and using scanning electron microscope (SEM) to examine the phases and impurities in the castings. Based on these results the influence of impurities and porosity of the electrical properties of aluminium was explained.

Key words: electrical properties, purity of the Al-alloy, porosity

1 Uvod

Avtomobilska industrija za elektrifikacijo vozil trenutno pozna dva glavna tipa

1 Introduction

The automotive industry for the electrification of vehicles currently has two main types elektromotorjev: motorje s permanentnimi magneti (IPM – internal permanent magnet motors) ter indukcijske motorje (IM – induction motors). Indukcijski elektromotor (asinhronski motor na izmenični tok) je preprost, robat, toplotno neobčutljiv ter poceni za izdelavo. Izdelava takega elektromotorja je še posebej gospodarna, če je kratkostična kletka rotorja narejena s postopkom visokotlačnega litja aluminija. [1,2]

Pri visokotlačnem litju kratkostičnih kletk rotorja se uporablja tehnično čist aluminij z različnimi stopnjami čistosti: 99,0; 99,5 ali 99,7 mas.% (1xx.x družina zlitin). Izbira je odvisna od specifičnih delovnih karakteristik stroja in zahtevnosti izdelka. Tipična električna prevodnost aluminija 99,7 je 60% IACS (International Annealed Copper Standard). Za indukcijski elektromotor je električna prevodnost aluminija ključna za zmanjšanje tokovnih izgub v kratkostični kletki rotorja in je ena izmed postavk, ki definirajo celotne izgube. [3,4]

Posamezni koraki proizvodnega procesa litja kratkostične kletke lahko negativno vplivajo na električno prevodnost aluminija. Primarni aluminij vsebuje od 0,3 do 1,0 mas.% nečistoč, med glavnimi sta železo in silicij. Tipična vrednost železa v primarnem aluminiju znaša 0,03 – 0,15 mas.% s srednjo vrednostjo ~ 0,07 – 0,10 mas.%. Tekoči aluminij je sposoben raztapljati železo, ko pride v stik z nezaščitenimi površinami talilne opreme in visokotlačnih orodij. Ravnotežna koncentracija železa, raztopljenega v tekoči fazi aluminija, znaša 2,5 mas.% pri 700 °C ter naraste do 5 mas.% pri temperaturi 800 °C. Z dodajanjem sekundarnega materiala pri taljenju primarnega aluminija še dodatno vnesemo nečistoče, bogate z železom. Železo ima veliko topnost v tekočem aluminiju, medtem ko se ta močno zmanjša v trdnem (največja je 0,05 mas.%

of electric motors, motors with permanent magnets (IPM - internal permanent magnet motors) and induction motors (IM - induction motors). The induction motor (asynchronous AC motor) is simple, rugged, thermally insensitive and inexpensive to manufacture. The manufactory of such an electric motor is especially economical if the short-circuit cage rotor is produced by a high-pressure die casting of aluminum. [1,2]

In the high-pressure die casting of short-cage rotor technically pure aluminium with varying degrees of purity: 99.0; 99.5 or 99.7 wt.% (1xx.x series of alloys) is used. The choice depends on the specific performance characteristics of the machinery and complexity of the product. A typical electrical conductivity of aluminium 99.7 is 60 % IACS (International Annealed Copper Standard). For the induction motor the electrical conductivity of aluminium is crucial to reduce the current losses in the short-cage rotor and is one of the factors that define a total loss. [3,4]

The individual steps of the manufacturing process of casting short-circuit cage may negatively affect the electrical conductivity of aluminium. Primary aluminium contains from 0.3 to 1.0 wt.% of impurities, mostly iron and silicon. The typical amount of iron in the primary aluminium is 0.03 to 0.15 wt.%. Liquid aluminium is able to dissolve the iron when it comes into contact with unprotected surfaces of the melting equipment and high-pressure tools. The equilibrium concentration of iron dissolved in the liquid phase of the aluminium is up to 2.5 wt.% at 700 °C and increases up to 5 wt.% at a temperature of 800 °C. By adding a secondary material in the smelting of primary aluminium additionally impurities rich in iron are entered. Iron has a high solubility in liquid aluminium, while it is greatly reduced in the solid (the highest is 0.05 wt.% at the solidus temperature). At pri solidus temperaturi). Pri strjevanju se izloča evtektik (α-Al + $Al_{13}Fe_4$). [5]

Poleg vseh zgoraj naštetih vplivov, ki slabšajo električne in mehanske lastnosti aluminija v rotorju elektromotorja, je poroznost aluminija med najvplivnejšimi. Poroznost se pojavi kot posledica krčenja pri strjevanju in ohlajanju aluminija (krčilna poroznost) in kot posledica raztopljenih plinov v talini, ki se sproščajo zaradi zmanjšane topnosti (plinska poroznost).

Po Blochovem teoremu napake v kristalni mreži (praznine, tuji atomi in termično nihanje) predstavljajo sipanje elektronov. Sipanje elektronov povzroča specifično upornost (ρ) kovine, ki je obratna vrednost specifične električne prevodnosti (σ). [6]

Večina dosegljivih raziskav specifične električne upornosti bazira na aluminijevih zlitinah s silicijem [7–9], ki so široko uporabne v industriji visokotlačnega litja, medtem ko so zlitine iz skupine 1xx.x zelo redko vključene v raziskave.

2 Eksperimentalno delo

V raziskovalnem delu bomo uporabili aluminij 99,7 (kot v procesu visokotlačnega litja rotorjev) ter primerjalno naredili analize tudi na elektrolizno čistem aluminiju 99,999 ter zlitini z dodatkom železa - torej z zmanjšano čistostjo aluminija na 99,5. Izvedli bomo analizo strjevanja in ohlajanja vseh treh zgoraj omenjenih zlitin ter pridobili tudi podatke električne upornosti ulitka, tako v tekočem kot tudi v trdnem stanju. Merilni inštrument poleg preproste termične analize omogoča še meritve napetosti pri prehodu znane količine toka skozi znan presek ulitka (slika 1). Analiza bo izvedena v laboratoriju, kjer bomo pridobili vzorce s kontrolirano naplinjenostjo z različnimi tehnikami: uporaba vakuuma (_Ar) ter litje

the solidification eutectic (α-Al + $Al_{13}Fe_4$) is formed. [5]

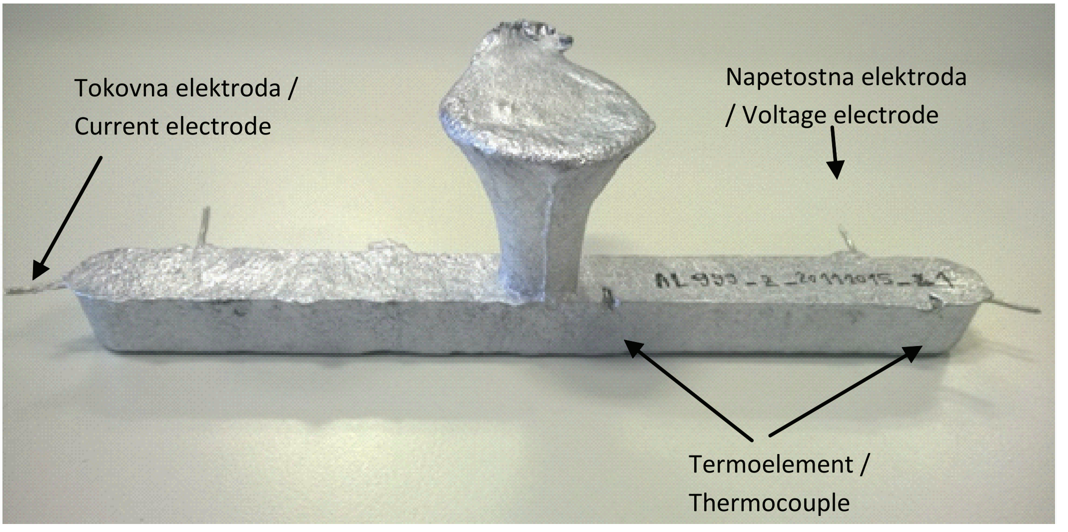
In addition to all the above influences that deteriorate the electrical and mechanical properties of aluminium in the rotor of the electric motor, the porosity of the aluminium is the most influential. The porosity occurs as a result of shrinkage during the solidification and cooling of the aluminium (shrink porosity) and as a consequence of the dissolved gases in the melt, which is emitted due to reduced solubility (gas porosity).

According to Bloch theorem, defects in the crystal lattice (vacancies, foreign atoms and thermal fluctuation) represent the scattering of electrons. Scattering of electrons causes a specific resistance (ρ) of the metal, which is the inverse of the specific electrical conductivity (σ). [6]

Most available researches of electrical resistivity are based on aluminium alloys using silicon [7-9], which are widely applied in the industry of high-pressure die casting, while the alloys from the group 1xx.x are very rarely involved in the research.

2 Experimental Work

In the research work aluminium 99.7 (as in the process of high-pressure die casting rotor) and as a comparative pure electrolytic aluminium 99.999 and alloy with the addition of iron - 99.5 were used. Analysis of solidification and cooling of the three above mentioned alloys were made, and the information of the electrical resistance of the cast part, in liquid as well as in solid state, was obtained. Measuring instruments in addition to the simple thermal analysis allows measurements of voltages when crossing a known quantity of flow through the known cross-section of the casting (Figure 1).



Slika 1: Ulitek iz merilne celice, kjer so vidna mesta meritve temperature, pozicije napetostnih elektrod ter pozicije tokovnih elektrod

Figure 1: Casting from the measuring cell, where the place of temperature measurement, the position of voltage electrode and the current positions of the electrodes are visible.

na zraku (_z). Iz kemične sestave aluminija in aluminijevih zlitin bomo s programom ThermoCalc izračunali termodinamično ravnotežje ter predvideli nastanek faz, ki slabšalno vplivajo na električno prevodnost ulitka. Pridobljene vzorce bomo preiskali z rentgenom, s katerim bomo analizirali delež poroznosti v ulitkih, ter tudi z optičnim in elektronskim mikroskopom in tako analizirali mikrostrukturne sestavine aluminija 99,7, tehnično čistega aluminija 99,999 ter aluminijeve zlitine 99,5 %.

3 Rezultati in diskusija

V raziskavi so bile uporabljene Al-zlitine, katerih kemijska sestava je podana v tabeli 1. Na podlagi kemijske sestave je bil izračunan ravnotežni fazni diagram ter predviden ravnotežni delež faz, ki jih lahko najdemo v preiskovanih zlitinah pri sobni

The analysis was carried out in a laboratory where samples were obtained with controlled gassing using different techniques: the use of a protective gas Ar (_Ar) and casting in air (_z). From the chemical composition of aluminium and aluminium alloys ThermoCalc program was used to calculate the thermodynamic equilibrium and to predict the phase formation which negatively affects the electrical conductivity of the casting. Furthermore, samples were examined by X-ray to analyse the proportion of porosity in castings, as well as optical and electron microscope to analyse the microstructure phases of aluminium 99.7, technically pure aluminium 99.999 and aluminium alloy 99.5%.

3 Results and Discussion

In this study the Al-alloy, which chemical composition is given in Table 1, were used.

temperaturi. Potek strjevanja je naslednji (slika 2): najprej se strdijo primarni zmesni kristali α-Al pri temp. 659,6 °C, nato poteka strjevanje evtektika (α-Al + $Al_{13}Fe_4$) pri 653,2 °C, solidus temperatura znaša 652,8 °C. Pri temperaturi 284,9 °C se iz trdnega izloči še faza $Al_9Fe_2Si_2$, katere delež je zelo majhen glede na našo sestavo. Delež evtektske faze $Al_{13}Fe_4$ se glede na delež Fe v Al-zlitini ustrezno spreminja: pri Al99,5 ta znaša 1,13 mas. %, pri Al99,7 0,32 mas. %, pri Al99,9 pa strjevanje Fe-faze ni predvideno.

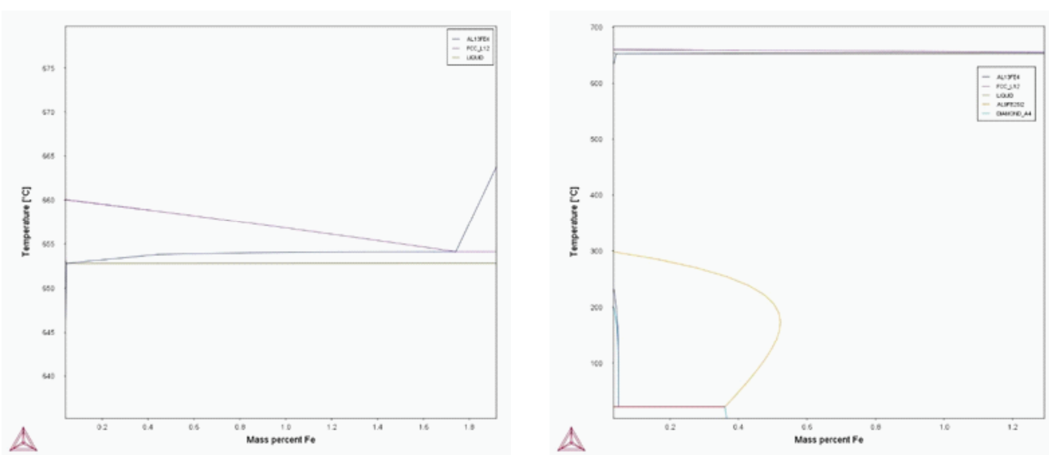
Meritve specifične električne upornosti preiskovanih zlitin prikazujeta sliki 3 in

On the basis of the chemical composition the equilibrium phase diagram and the expected equilibrium proportion of phases, which can be found in the investigated alloys at room temperature, were calculated. Solidification is as follows (Figure 2): as first primary crystals α-Al at the temp. 659.6 °C solidify, followed by the solidification of eutectic (α-Al + $Al_{13}Fe_4$) at 653.2 °C, the solidus temperature is at 652.8 °C. At a temperature of 284.9 °C, the precipitation of $Al_9Fe_2Si_2$ phase from the solid state occurs, whose proportion is very small relative to our composition. The proportion of eutectic

Tabela 1: Kemijska sestava preiskovanih vzorcev, v mas.%

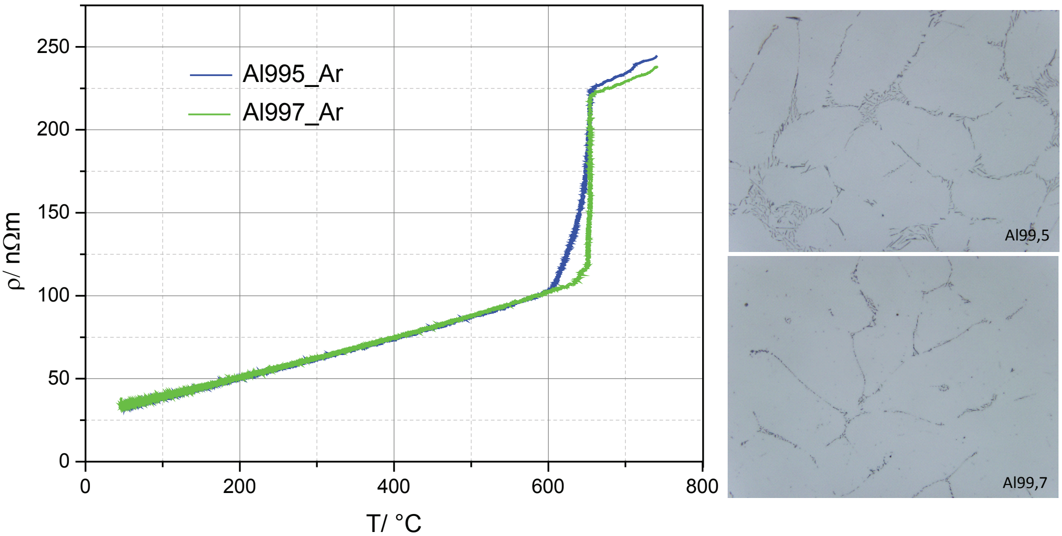
Table 1: Chemical composition of investigated samples, in wt.%.

Vzorec / Sample	Element								
	Al	Si	Fe	Cu	Mn	Mg	Cr	Ni	Ti
Al99.5_z	99,46867	0,03183	0,44166	0,00346	0,00131	0,00078	0,00139	0,02966	0,00199
Al99.5_Ar	99,54293	0,02699	0,38474	0,00307	0,00143	0,00083	0,00067	0,01531	0,00202
Al99.7_z	99,72397	0,02657	0,1609	0,00279	0,00141	0,00085	0,00321	0,05655	0,00212
Al99.7_Ar	99,75834	0,02517	0,15584	0,00265	0,0015	0,00024	0,00142	0,03712	0,00188
Al99.99_z	99,86324	0,00263	0,00114	0,00011	0,00061	0,0038	0,01194	0,11502	0,00019
Al99.99_Ar	99,99052	0,00191	0,00033	0,00023	0,00034	-0,00002	0,00034	0,00372	0,00035



Slika 2: Ravnotežni fazni diagram izračunan iz kemijske sestave za vzorec Al99.7_z

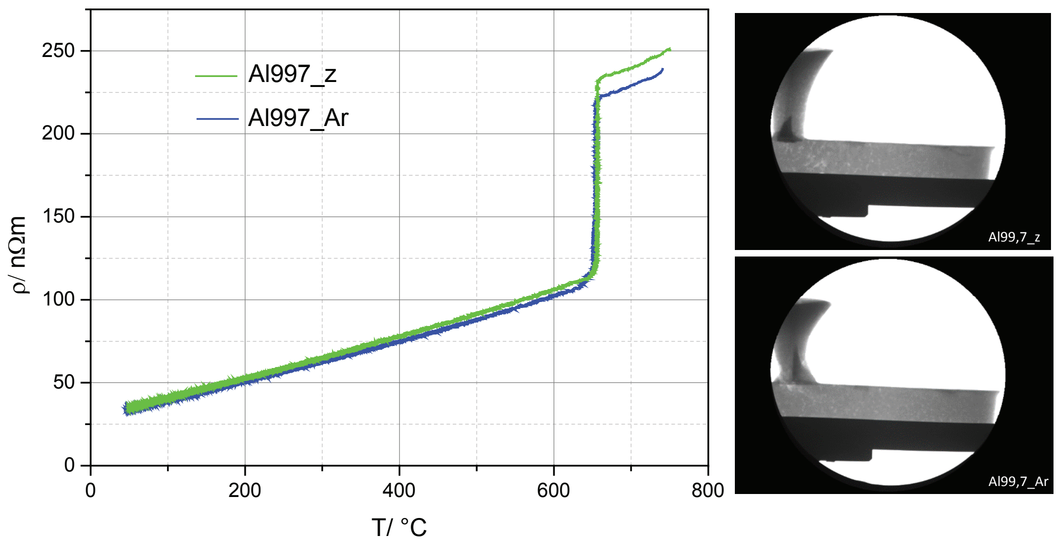
Figure 2: Isoplete equilibrium phase diagram calculated form the chemical composition of sample Al99.7_z



a) b)

Slika 3: Specifična električna upornost v odvisnosti od temperature za vzorce ulite na zraku a) ter ustrezni posnetki mikrostrukture b)

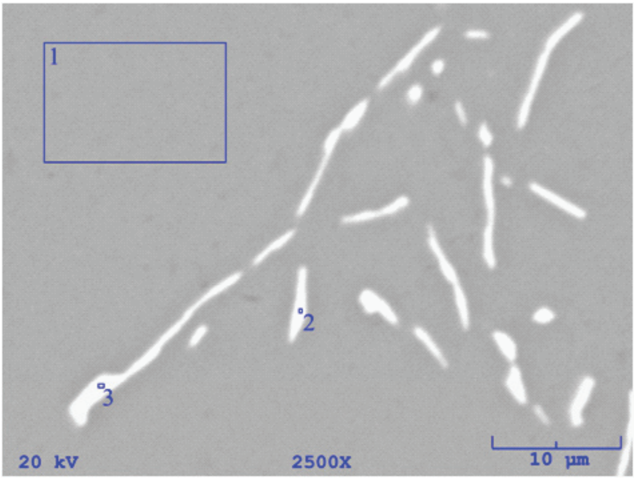
Figure 3: Specific electric resistivity regarding the temperature at various Fe contents a) and corresponding microstructure (b)



a) b)

Slika 4: Specifična električna upornost v odvisnosti od temperature za vzorce Al99,7, ulite na zraku in v Ar a) ter ustrezni rentgenski posnetki ulitkov b).

Figure 4: Specific electric resistivity regarding the temperature made for Al99.7 alloy in various atmospheres a) and corresponding X-ray b)



Spekter 1 / Spectrum 1	Wt. %	At. %
Al	100	100
Spekter 2 / Spectrum 2	Wt. %	At. %
Al	76.225	86.904
Fe	23.775	13.096
Spekter 3 / Spectrum 3	Wt. %	At. %
Al	72.133	84.270
Fe	27.867	15.730

Slika 5: SEM posnetek in EDS analiza faz v vzorcu Al99,5_z

Figure 5: SEM micro-shot and EDS analysis pf phases in sample Al99.5_z

4. Na sliki 3.a je prikazana primerjava med meritvami upornosti glede na delež vsebnosti Fe. Vsi vzorci so bili v tem primeru uliti na zraku. Specifična upornost čistega aluminija Al99,9 je najnižja, kar je v skladu z literaturnimi viri [X, Y, Z]. Zlitini, ki vsebujeta večji delež Fe, pa kažeta večjo specifično električno upornost. Mikrostrukturni posnetki (narejeni na mestu termoelementa bližje roba ulitka) na sliki 3.b potrjujejo delež Fe in posledično Fe-evtektika (α-Al + $Al_{13}Fe_4$) v preiskovanih zlitinah.

Slika 4 prikazuje primerjavo električne upornosti za vzorec Al99,7, prvič ulit v zaščitni atmosferi argona ter drugič ulit na zraku, ter ustrezne rentgenske posnetke za ugotavljanje poroznosti v ulitku. Razvidno je, da je ρ večji v primeru ulitka ulitega na zraku, kar je posledica večje plinske poroznosti ulitka (0,51 % na zraku in 0,39 % v Ar). To je bilo tudi dokazano z rentgensko analizo vzorcev.

Slika 5 prikazuje SEM posnetek vzorca Al99,7, ulitega na zraku, ter ustrezne EDS

phase $Al_{13}Fe_4$ corresponds to the proportion of Fe in Al-alloys: in Al99.5 alloy it amounts 1.13 wt. %, in Al99.7 alloy is 0.32 wt. % and in Al99.9 alloy the solidification of Fe-phase is not foreseen.

Measurements of the specific electrical resistivity of the investigated alloys are shown in Figures 3 and 4. In Figure 3.a a comparison between the measured resistance of Al-alloys at various Fe content are presented. All samples were in this case cast in Ar. Alloy Al99.5, which contains a greater proportion of Fe (0.44) displaying a higher specific electrical resistance, which is in accordance with the literature [8, 9]. Micrographs (built on the site of the thermocouple closer to the end of the casting) in Figure 3.b confirm the proportion of Fe and the resulting Fe-eutectic (α-Al + $Al_{13}Fe_4$) in the investigated alloys.

Figure 4 shows a comparison of the electrical resistance of the sample Al99.7, firstly cast in a protective atmosphere of argon, and the second cast in the air with the relevant X-rays to determine the porosity analize posameznih faz. Potrjena je bila faza $Al_{13}Fe_4$, faze $Al_9Fe_2Si_2$ nismo zasledili.

4 Zaključki

Meritve električne upornosti so pokazale, da delež Fe ter delež poroznosti zvišujeta specifično električno upornost (ρ) aluminija. Fe v Al tvori evtektsko fazo (α-Al + $Al_{13}Fe_4$), katere večji delež povečuje ρ, tako ima zlitina Al99,5 večjo ρ kot zlitina Al99,9. Poroznost ter evtektska faza (α-Al + $Al_{13}Fe_4$) povzročata večje sipanje elektronov, posledica je večja ρ.

in the casting. It is evident that ρ is greater in the case of the cast part in air as a result of higher gas porosity of the cast part (0.51 % in air, and 0.39 % in Ar). This has been proved by X-ray analysis of the samples.

Figure 5 shows SEM images of a sample Al99.7, cast in the air and the corresponding EDS analysis of individual phases. The presence of $Al_{13}Fe_4$ It phase was confirmed. $Al_9Fe_2Si_2$ phase was not detected.

4 Conclusion

Measurements of the electrical resistance show that the proportion of Fe and share of the porosity greatly enhanced specific electrical resistivity (ρ) of aluminium. Fe in the Al form eutectic (α-Al + $Al_{13}Fe_4$) phase, which increased portion increases ρ. Porosity and eutectic (α-Al + $Al_{13}Fe_4$) phase are causing greater scattering of the electrons, resulting in a higher ρ.

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