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THE STUDY OF POROSITY IN A356 SECONDARY ALUMINIUM ALLOYS WITH HIGHER IRON CONTENT

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Abstract: The production of secondary (recycled) aluminium has gained significant importance in recent years, driven by the need to reduce electricity consumption and waste associated with primary aluminium production. Secondary aluminium alloys thus play a vital role in sustainable industrial practices, particularly within sectors such as automotive, aerospace and marine. Recently, these alloys have gained traction in electric vehicle components manufacturing, where lightweight and sustainable materials are critical to enhancing energy efficiency and extending vehicle range. However, secondary aluminium alloys are prone to impurities and casting defects, notably porosity, which presents challenges in achieving optimal mechanical properties and surface quality. Porosity reduces corrosion resistance, fatigue, and tensile strength, thus impacting overall material performance. This porosity can be categorised by size (microporosity and macroporosity) and origin, with gas and shrinkage porosity being the primary types. This study examined experimental A356 secondary aluminium alloys with varying iron contents in as-cast and T6 heat-treated conditions. The analysis focused on the quantitative assessment of casting defects within the microstructure, specifically, the types of pores present, the area percentage of pores, and average pore size. These insights contribute to a deeper understanding of how casting defects impact the performance of recycled aluminium alloys in sustainable applications, particularly in the context of next-generation electric vehicles.
Keywords: secondary aluminium, intermetallic phases, porosity, heat treatment

1. INTRODUCTION

Cast aluminium alloys are extensively utilised across various industries, including aerospace and automotive, because of their superior mechanical properties and excellent casting characteristics. However, aluminium production faces economic and environmental challenges, with primary production contributing about 3% of global greenhouse gas emissions (GHG). Around 65% of these emissions stem from fossil fuel-based electricity used during the electrolysis process in aluminium production. These environmental concerns underscore the importance of transitioning to more sustainable manufacturing practices, such as increasing the use of secondary (recycled) aluminium, significantly reducing energy consumption and mitigating the environmental impact of aluminium production (Raabe, 2022; Brough, 2020).

Aluminium can be classified into two types based on its production method. Primary aluminium is produced from bauxite ore, offering consistent quality and precise composition. In contrast, secondary aluminium is produced from recycled aluminium products, reducing the need for new raw materials, energy consumption, and GHG emissions. Secondary aluminium alloys might contain impurities (Fe, Cu, Be) from the recycling process that impact their mechanical properties (Raabe, 2022).

Despite its advantages, secondary aluminium cannot entirely replace primary aluminium, which remains essential for diluting recycled materials and adjusting alloy compositions even within closed-loop scrap streams. With aluminium demand surpassing the supply of recycled materials, improving the environmental footprint of primary production is imperative, especially as electrolysis dominates its energy use and emissions. This underscores the importance of assessing how enhancements in primary aluminium production might reduce the environmental impact (Raabe, 2022; Cullen and Allwood, 2013; Paraskevas et al., 2013).

Aluminium-silicon (Al-Si) alloys are commonly used due to their exceptional properties, including good thermal conductivity, corrosion resistance, high strength-to-weight ratio, and hot tearing resistance. These properties are heavily influenced by microstructural characteristics and casting defects such as bifilms, cavities, cracks (such as fatigue cracks or internal cracks), and pores (Nicoletto et al., 2012; Kuchariková et al., 2018).

Porosity, a common defect, can negatively impact surface quality and mechanical properties, and be classified based on the pore size: microporosity (a pore smaller than 300 μm in diameter) and macroporosity (>300 μm in diameter). Although some researchers (Cáceres (1996) and Akhtar (2010)) define microporosity as pores smaller than 100 μm, anything larger is considered macroporosity (Irfan et al., 2012; Fan et al., 2019; Lee et al., 2001).

Another classification of porosity depends on its origin, distinguishing between gas porosity and shrinkage porosity (Fig. 1). Gas porosity (often referred to as hydrogen porosity) typically manifests as isolated, rounded, and well-distributed pores. Aluminium absorbs hydrogen when in a liquid state, particularly under humid conditions. During solidification, the hydrogen is rejected from the solid phase into an adjoining liquid, forming bubbles when the hydrogen concentration exceeds the local solubility limit. In contrast, the shrinkage porosity appears interconnected or grouped, displaying an irregular shape akin to the interdendritic regions. This porosity occurs when the casting process cannot supply sufficient liquid metal during the transition from liquid to solid leading to contraction.

Insufficient mobility of liquid metal during solidification can also contribute to shrinkage porosity (Fan et al., 2019; Khalajzadeh and Beckermann, 2020; Kuchariková et al., 2018).

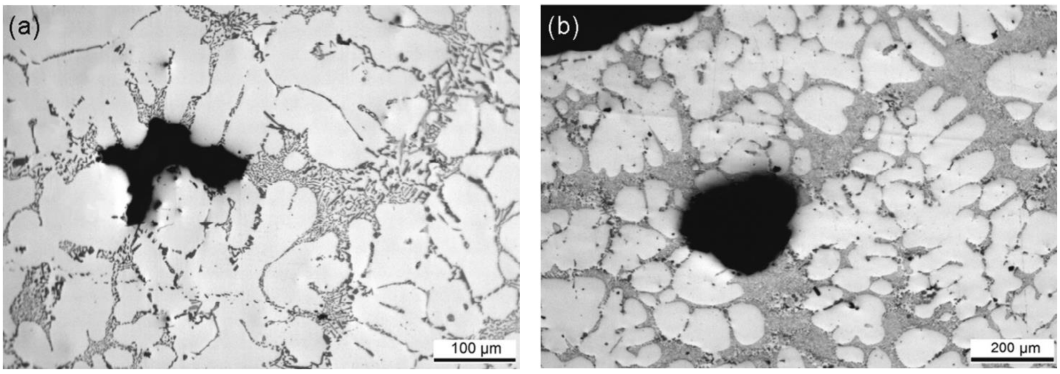


Fig. 1. The difference between a) shrinkage and b) gas porosity (Timelli et al., 2016)

In addition to porosity, other casting defects in these alloys are cracks and hot tearing. Hot tearing occurs during the semisolid casting, where an irreversible crack (failure) forms (Li and Appelian, 2011; Phillion et al., 2011).
This study investigates the effects of increased Fe content on porosity in secondary aluminium alloys, specifically A356 (AlSi7Mg0,3). Furthermore, the research evaluates heat treatment as a potential porosity mitigation strategy. The goal is to enable the use of secondary alloys with higher Fe content (>0.45%) while maintaining the mechanical properties required for electromobility applications, including battery housings, wheel discs, and motor controllers.

2. METHODOLOGY OF RESEARCH

The analysed specimens of the A356 secondary aluminium cast alloys were manufactured in the foundry UNEKO, Zátor, Czech Republic and provided for testing in the form of rods measuring 20 mm in diameter and 300 mm in length (Fig. 2). They were produced by gravity casting using sand moulds. Before casting, these sand moulds were treated with a protective spray to prevent the liquid metal from seeping into the sand, thereby ensuring a higher-quality surface finish.

Fig. 2. Supplied rods used for experimental samples without (top) and after (bottom) heat treatment

To evaluate the effect of higher Fe content on the presence of casting defects (porosity), 4 melts were cast. The iron content increased (alloy A 0.123 wt. %; B 0.454 wt. %; alloy C 0.679 wt. % and D 1.209 wt. %), but to assess, whether the negative effect of Fe on the presence of casting defects can be reduced, the experimental bars were subjected to heat treatment T6. The chemical composition of investigated secondary aluminium alloys is shown in Tab. 1.

Table 1
Chemical composition of experimental samples from A356 alloys (wt.%)

Alloy	Si	Fe	Mg	Mn	Cu	Ti	Zn	Cr	Al
A	7.028	**0.123**	0.355	0.009	0.013	0.123	0.036	0.002	ball.
B	7.340	**0.454**	0.302	0.009	0.021	0.118	0.020	0.002	ball.
C	7.346	**0.679**	0.398	0.006	0.0096	0.106	0.029	0.002	ball.
D	7.340	**1.209**	0.311	0.006	0.100	0.118	0.006	0.002	ball.

The casting process was carried out at a temperature of 750 °C, and the refining process was carried out within the temperature range of 740 to 745 °C. Twenty-four bars were cast from each melt, and half were subjected to heat treatment. The heat treatment process chosen was T6 because of its suitability for Al-Si alloys.
The heat treatment T6 consisted of solution treatment at 530 ± 5 °C for 7 hours. The next step was rapid cooling into the water at 50 °C. The last step of T6 was artificial ageing. The alloys were reheated to 160 ± 5 °C for 6 hours. The samples were compared to determine whether the heat treatment, minimizes the presence of casting defects – pores.
The experimental samples were prepared using a metallographic procedure suitable for Al-Si alloys. Firstly, the samples were ground using 500 (coarse grinding) and 1 200 (fine grinding) - grit Strues SiC grinding paper. Secondly, the samples were polished using 3 μm and 1 μm diamond paste with the appropriate polishing cloth. The last step was oxide polishing using MD-Chem polishing disc with OP-S suspension. All the samples were etched with 0.5 % HF to highlight the pores and phases in the microstructure.
The microstructure analysis of experimental samples and quantitative analysis of casting defects in secondary A356 aluminium alloys was performed using an optical microscope NEOPHOT 32 with NIS Elements 5.2 software. The analysis was done to evaluate the average pore size and area per cent porosity in all experimental samples. The aim was to evaluate whether the increasing Fe content leads to an increase in the amount and size of pores in the microstructure and if the heat treatment mitigates this phenomenon.

3. RESULTS AND DISCUSSION

The characteristics microstructure features of experimental alloys are in Fig. 3. The main feature is α-phase, followed by eutectic and intermetallic phases. The α-phase is observed in the form of dendrites, crystallizing from the liquid as the primary phase. Eutectic is seen as dark grey crystals of Si in α-phase.

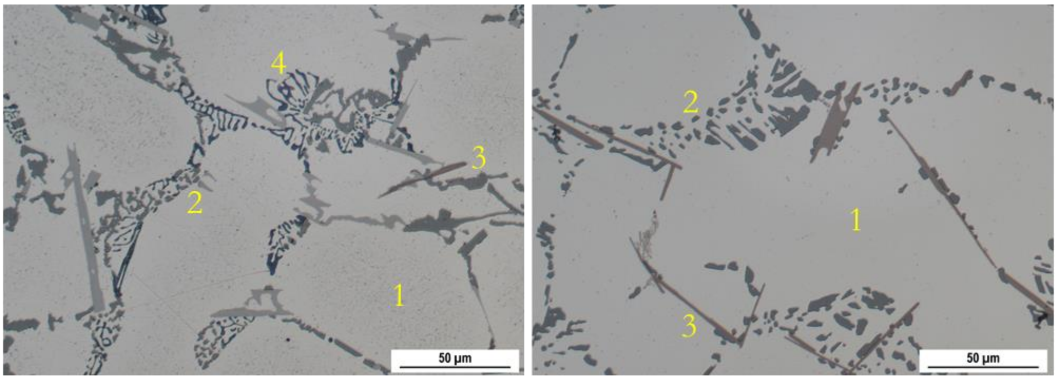


Fig. 3. Microstructure of experimental samples: α-phase (1); silicon grains (2); Fe-rich intermetallic phases Al_5FeSi (3); Mg_2Si phase (4), etch. 0.5% HF

In the as-cast state, silicon is observed in the shape of angular grains, but after heat treatment, the form changes into fine round particles. The intermetallic phases observed in A356 alloys are the Al_5FeSi phase in the form of needles (Fe-rich phase) and the Mg_2Si phase as very fine particles (Šurdová et al., 2022).

The quantitative analysis showed that casting defects in the microstructure were gas and shrinkage pores. Examples of gas and shrinkage pores are in Fig. 4. The shrinkage pores made up a majority of the pores present in the investigated samples in the alloys in both an as-cast state and after heat treatment.

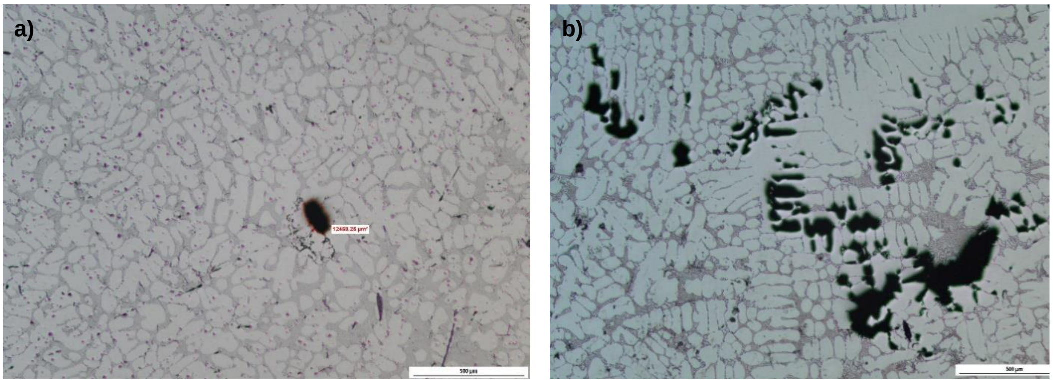


Fig. 4. a) Gas and b) shrinkage porosity in A356 investigated alloys

The results of the pore size assessment in experimental samples are in Fig. 5. The highest area per cent porosity is in alloy D (1.209% Fe) without the heat treatment T6 (Fig. 5d). As can be seen in Fig. 6 the defects in this alloy also have the largest size (56 155 μm2). The smallest casting defects were observed in alloy A (0.123% Fe) after the heat treatment. The area per cent porosity (1.00%) supports this claim (Fig. 6).

The area per cent porosity in alloys without heat treatment increases with increasing Fe content. This supports the results of Taylors' (2004) and Tuncay's (2017) research that increasing iron content in A356 alloys, and thus Fe-rich intermetallic phases cause higher porosity in aluminium alloys. Two mechanisms (Mahta et al., 2008) can cause this phenomenon.

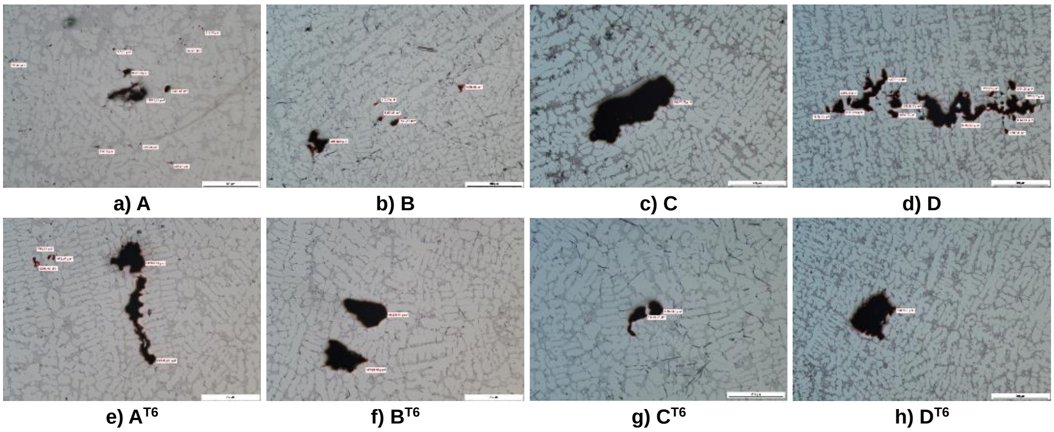


Fig. 5. Average size of pores – as cast state: a) 0.123% Fe; b) 0.454% Fe, c) 0.679% Fe and d) 1.209% Fe; after T6 - e) 0.123% Fe; f) 0.454% Fe, g) 0.679% Fe and h) 1.209% Fe; etch. H_2SO_4

According to Roy's (1996) research increased Fe content can result in more β-phase (Al_5FeSi) particles that then act as the nucleation sites for porosity. The other theory is that the β-phase in the form of platelets hinders the movement of interdendritic liquid during feeding which causes shrinkage porosity formation. This theory seems to be correct, but according to Taylor (2012), there are other mechanisms present as well. In alloy B (0.454% Fe), there is a slight decrease in area per cent porosity. This might be caused by the place where the sample for the quantitative analysis was cut from the rods provided for the analysis (a difference in porosity was observed at the beginning and middle of the test bars).

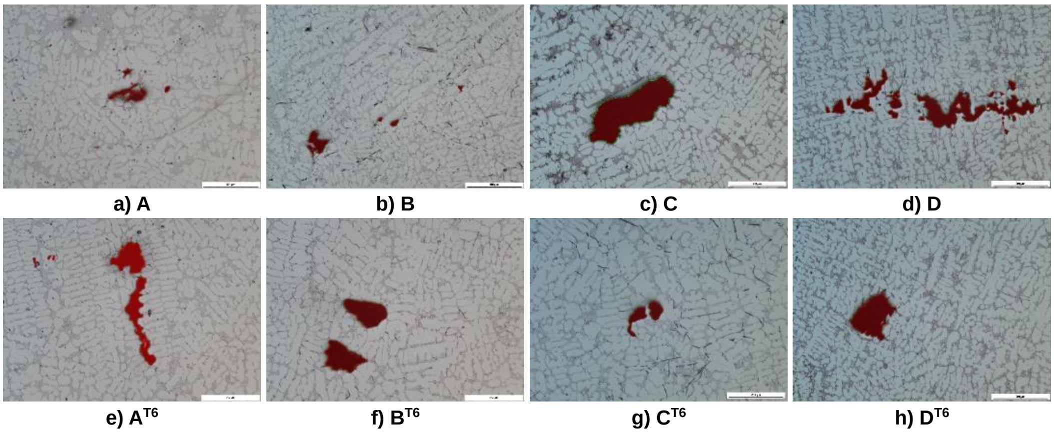


Fig. 6. Pore shape and area per cent – as cast state: a) 0.123% Fe; b) 0.454% Fe, c) 0.679% Fe and d) 1.209% Fe; after T6 - e) 0.123% Fe; f) 0.454% Fe, g) 0.679% Fe and h) 1.209% Fe; etch. H_2SO_4

Shrinkage porosity is seen in Fig. 6d) and Fig. 6e). In the samples after the heat treatment, the number of pores and their size decreased. For better visualisation of the results of quantitative analysis diagrams were constructed (Fig. 7).

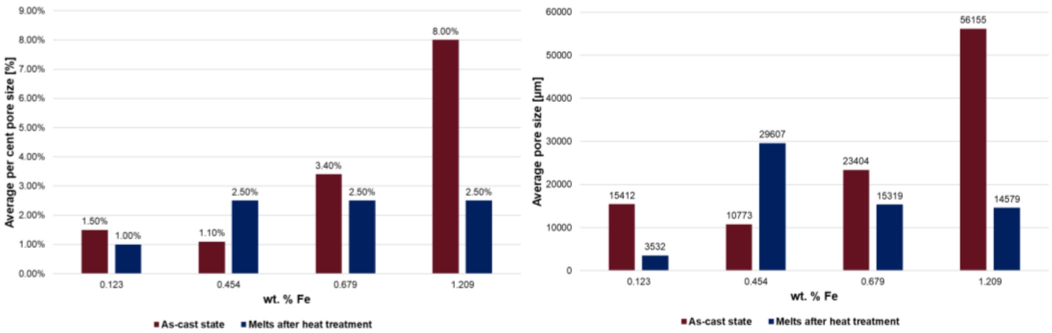
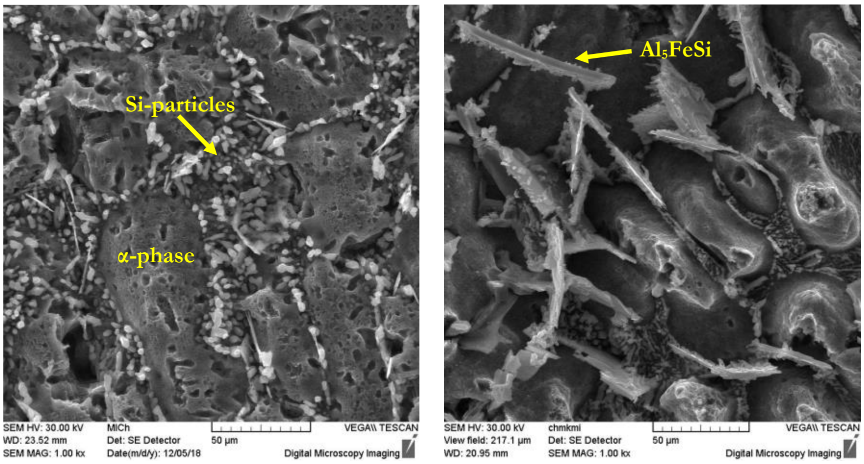


Fig. 7. The effect of increasing iron content and heat treatment on the area per cent porosity and average pore size in secondary A356 alloy

The results of the quantitative analysis of Fe-phases were evaluated in the work of Šurdová (2022). In order to support the results obtained by the theory of Roy (1996) and Taylor (2012) that a larger amount of Al5FeSi needle/platelet-like phases may hinder the Al-matrix from flowing and cause the higher porosity, deep etched samples were observed on SEM. Results can be seen in Fig. 8.



a) 0.123% Fe b) 1.209% Fe

Fig. 8. Morphology and phase distribution after deep etching, SEM, etch. HCl

The Al_5FeSi phase creates barriers and obstructs the movement of the liquid metal. We suggest that the mechanism by which the Al5FeSi phase causes porosity is related to the solidification of the Al alloy. Based on the Al-Si and Al-Si-Fe phase diagrams, at a critical Fe content (approximately 0.45% Fe), the Al_5FeSi plates solidify as the initial component of the ternary eutectic. At higher Fe levels, this Al_5FeSi phase is already well developed when solidification of the ternary eutectic begins, whereas at lower Fe content it is formed as a component of the ternary eutectic only after the formation of the Al-Si binary eutectic. Each of these solidification paths leads to different variations in microstructural permeability, i.e. interdendritic feedability, and hence porosity formation. At the critical Fe level, the smaller ternary Al_5FeSi phases do not block the interdendritic liquid flow, whereas below and above this level the larger binary Al_5FeSi phases block the interdendritic regions, causing higher levels of porosity. Taylor (2012) and Samuel (2017) also suggested a correlation of porosity with the fluid flow through the interdendritic regions during solidification or with the ease of fluid flow through the interdendritic regions, respectively.

4. CONCLUSION

The study of casting defects and the influence of increasing iron content on their presence in investigated secondary A356 aluminium alloys was carried out. The experimental samples were observed in the as-cast state and the state after heat treatment T6. As a result, the conclusions are as follows:

- The microstructure of experimental alloys includes microstructural features: α-phase, eutectic, and intermetallic phases as needle-like Al_5FeSi Fe-phase, and Mg_2Si.
- The casting defects present in the investigated alloys were gas and shrinkage pores, shrinkage pores being the dominant defect.
- The smallest pores were observed in alloy A after the heat treatment. This was supported by the amount of area per cent porosity present in this alloy.
- The increasing Fe leads to an increase in the amount and size of the pores present in the microstructure in as-cast samples.
- The samples after heat treatment showed a decrease in the amount and size of pores, which is probably related to the segmentation and spheroidization of the needle-like Fe-phase Al_5FeSi and the spheroidization of eutectic silicon.

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REFERENCES

Akhtar, Sh., 2010. *Hydrogen Porosity in Al-Si Foundry Alloys. Department of Materials Science and Engineering*, Norwegian University of Science and Technology. Trondheim: PhD Thesis.

Brough, D., Jouhara, H., 2020. *The aluminium industry: A review on state-of-the-art technologies, environmental impacts and possibilities for waste heat recovery.* International Journal of Thermofluids, 1-2, 1 – 39, DOI: 10.1016/j.ijft.2019.100007.

Cáceres, C. H., Selling, B. I.,1996. *Casting defects and the tensile properties of an Al-Si-Mg alloy.* Materials Science and Engineering A, 220(1), 109 – 116, DOI: 10.1016/S0921-5093(96)10433-0.

Cullen, J. M., Allwood, J. M., 2013. *Mapping the Global Flow of Aluminum: From Liquid Aluminum to End-Use Goods*. Environmental Science & Technology, 47(7), 1 – 17, DOI: 10.1021/es304256s.

Fan, P., Cockcroft, S. L., Maijer, D. M., Yao, L., Reilly, C., Phillion, A. B., 2019. *Porosity Prediction in A356 Wheel Casting*. Metallurgical and Materials Transactions. B, Process Metallurgy and Materials Processing Science, 50(5), 1 – 15, DOI: 10.1007/s11663-019-01642-9.

Irfan, M. A., Schwam, D., Karve, A., Ryder, R., 2012. *Porosity reduction and mechanical properties improvement in die cast engine blocks*. Materials Science and Engineering A, 535(15), 108 – 114, DOI: 10.1016/j.msea.2011.12.049.

Khalajzadeh, V., Beckermann, Ch., 2020. *Simulation of Shrinkage Porosity Formation During Alloy Solidification.* Metallurgical and Materials Transactions A, 51, 2239 – 2254, DOI: 10.1007/s11661-020-05699-z.

Kuchariková, L., *Porosity in Aluminum Alloy Castings.* Encyclopedia of Aluminum and Its Alloys. CRC Press, Boca Raton.

Lee. P.D., Chirazi, A., See, D., 2001. *Modeling Microporosity in Aluminum-Silicon Alloys: A Review*. Journal of Light Metals, 1(1), 15 – 30, DOI:10.1016/S1471-5317(00)00003-1.

Li, S., Appelian, D., 2011. *Hot tearing of aluminium alloys a critical literature review.* International Journal of Mealcasting/Winter, 11, 23 – 40, DOI:10.1007/BF03355505.

Mahta, M., Emamy, M., Cao, X., Campbell, J., 2008. *Overview of B-Al_5FeSi phase in Al-Si alloys*. Nova Science Publishers, Inc. New York, USA.

Nicoletto, G., Konečná, R., Fintová, S., 2012. *Characterization of microshrinkage casting defects of Al–Si alloys by X-ray computed tomography and metallography*. International Journal of Fatigue, 41, 39 – 46, DOI: 10.1016/j.ijfatigue.2012.01.006.

Paraskevas, D., Kellens, K., Dewulf, W., Duflou., 2013. *Closed and Open Loop Recycling of Aluminium: A life Cycle Assessment perspective*. IProceedings of 11th Global Conference on Sustainable Manufacturing. Innovative Solutions, 305 – 310.

Phillion, A. B., Cockroft, S. L., Lee, P. D., 2008. *A new methodology for measurement of semi-solid constitutive behavior and its application to examination of as-cast porosity and hot tearing in aluminum alloys*. Materials Science and Engineering: A, 491(1-2), 237 – 247, DOI: 10.1016/j.msea.2008.01.078.

Raabe, D., et al., 2022. *Making sustainable aluminum by recycling scrap: The science of “dirty” alloys*. Progress in Materials Science, 128, 1 – 150. DOI: 10.1016/j.pmatsci. 2022.100947.

Roy, N., Samuel, A. M., Samuel, F. H., 1996. *Porosity formation in Al-9 Wt Pct Si-3 Wt Pct Cu alloy systems: Metallographic observations.* Metallurgical and Materials Transactions A, 27, 415 – 429, DOI: 10.1007/BF02648419.

Samuel, F. H., 2017. *On Porosity Formation in Al–Si–Cu Cast Alloys*. In: Ratvik, A. (eds) Light Metals 2017. The Minerals, Metals & Materials Series. Springer, Cham. DOI: 10.1007/978-3-319-51541-0_33.

Šurdová, Z., Kuchariková, L., Tillová, E., Pastierovičová, L., Chalupová, M., Uhríčik, M., Mikolajčík, M., 2022. *The Influence of Fe Content on Corrosion Resistance of Secondary AlSi7Mg0.3 Cast Alloy with Increased Fe-content.* In: Manufacturing technology: Engineering Science and Research Journal, 22(5), 598 – 604, DOI: 10.21062/mft.2022.073.

Taylor, J., A., 2004. *The effect of iron in Al-Si casting alloys*. Proceedings of 35th Australian Foundry Institute National Conference, 1 – 11, DOI: 10.1016/j.mspro.2012.06.004.

Taylor, J., A., 2012. *Iron-containing intermetallic phases in Al-Si based casting alloys.* Procedia Materials Science, 1, 19 – 33.

Timelli, G., Caliari, D., Rakhmonov, J., 2016. *Influence of Process Parameters and Sr Addition on the Microstructure and Casting Defects of LPDC A356 Alloy for Engine Blocks*. Journal of Material Science and Technology, 32(6), 515 – 523, DOI: 10.1016/j.jmst.2016.03.010.

Tuncay, T., Bayoğlu, S., 2017. *The Effect of Iron Content on Microstructure and Mechanical Properties of A356 Cast Alloy*. Metallurgical and Materials Transactions B, 48(2), 794 – 804, DOI: 10.1007/s11663-016-0909-1.