ARCHIVES
of
FOUNDRY ENGINEERING

ISSN (2299-2944)
Volume 2024
Issue 3/2024

81 – 87

10.24425/afe.2024.151295

12/3

Published quarterly as the organ of the Foundry Commission of the Polish Academy of Sciences

Effect of Core Temperature at HPDC on the Internal Quality of the Casting

M. Matejka [a, *], D. Bolibruchová [a], R. Podprocká [b], P. Oslanec [c]
[a] University of Zilina, Faculty of Mechanical Engineering, Department of Technological Engineering, Slovakia
[b] Rosenberg-Slovakia s.r.o., Slovakia
[c] Slovak Academy of Sciences, Institute of Materials and Machine Mechanics, Slovakia
* Correspondence contact: e-mail: marek.matejka@fstroj.uniza.sk

Received 22.04.2024; accepted in revised form 28.08.2024; available online 11.10.2024

Abstract

High pressure die casting (HPDC) is one of the most productive casting methods to produce a wide range of aluminum components with high dimensional accuracy and complex geometries. The process parameters of high-pressure casting generally directly affect the resulting quality of the castings, such as the presence of pores in the casting or the microstructure. In addition to air entrapment, porosity can also be caused by the dissolution of hydrogen. Hydrogen is released by the reaction of water vapor and melt at high temperatures and is released during solidification. These defects can lead to a significant reduction in mechanical properties such as strength and ductility and especially fatigue properties. The aim of the presented article is to describe the effect of the temperature of the core of the high-pressure mold on the presence and distribution of porosity and the microstructure of the aluminum casting in two geometric variants. The temperature of the core was changed due to the use of two flowing media in the thermoregulation circuit of the core, i.e. demineralized water and heat transfer oil and worked with a core temperature of 130 ± 5 and 165 ± 5 °C. With both geometric variants, a higher porosity was achieved when using water (core temperature 130 ± 5 °C) than when using oil (core temperature 165 ± 5 °C). The opposite results were observed for microporosity, where higher microporosity was observed for tempering oil. The microstructure of the casting with water-cooled cores was more characterized by finer grains of phase α (Al) and eutectic Si. In tempering oil, the microstructure was characterized by coarse grains of the α phase (Al) and the Si lamellae were in the form of sharp-edged formations.

Keywords: HPDC, Al-Si-Cu alloy, Porosity, Microstructure

1. Introduction

High-pressure die casting is a complex process that takes into account a number of factors that significantly affect the final quality of the cast part. The basic parameters of the high-pressure die casting process are mainly the maintenance temperature, casting and molds temperature, hydrostatic pressure, or pressing pressure, and alloy flow rate in the inlet channel. The mechanical properties of a high-pressure die-cast product are primarily related to the temperature of the mold, the speed of the metal at the inlet and the applied casting pressure [1-3].

The combination of mold temperature, the fluidity of the molten metal, the complexity of the part geometry, and the cooling rate during high-pressure die casting all affect the integrity of the cast component. If these factors are not properly controlled, we can expect the appearance of various defects in the final casting. The thermal profile of the tool during operation is another important aspect of producing high quality components. Mold temperature is a key factor affecting heat removal from the molten metal, as well as for filling the mold and for correct setting of the casting properties [4-6]. A common source of defects in die casting is that the mold is not at the optimum temperature. This problem can be avoided by using a thermoregulating device [7,8].

In the production of high-pressure die-cast parts, the ability to control thermal processes in the tool plays a key role. Each mold should therefore be heated to the required temperature before production begins. This generally results in increased mold life. Casting with a cold or insufficiently preheated die can lead to high stress on the tool surface as well as low quality castings [9,10].

The key factors for effective temperature control of the die are the temperature control unit, suitable heat transfer medium and tempering circuits in the mold die. The tempering channels must be large enough to ensure rapid circulation and minimal pressure loss. Choosing the right temperature control unit depends on the design of the channels in the matrix. The temperature control unit must be powerful enough to regulate the temperature of the die and dissipate the heat. The heat-carrying medium plays an important role in ensuring optimal temperature regulation. The better the heat transfer properties of the used medium, the more efficiently it is possible to transfer a large amount of heat. Because of the high temperatures, die casting often uses oil-based heat transfer media [11].

The aim of the presented article is to assess the influence of the medium flowing in the thermoregulation circuit of the high-pressure die mold core on the change of the internal quality of castings in two geometric variants of the height of the casting tube. In the experimental part of the paper, we worked with demineralized water and heat transfer oil used as a medium for core temperature regulation. The internal quality of high-pressure die castings was evaluated by a combination of porosity analysis and structural analysis of selected critical locations on the casting. This evaluation should help us better understand how changing the thermoregulating medium affects the internal quality of castings.

2. Experimental process

In the experimental part, an aluminum alloy AlSi12Cu1(Fe) was used. It is a frequently used alloy for high pressure die casting process. This material is characterized by good mechanical properties and is used to produce thin-walled castings with complex shapes, which are intended for various industries such as the automotive or electrical engineering industries. The alloy has good electrical and thermal conductivity, excellent corrosion resistance and good heat-insulating ability. Chemical composition of the AlSi12Cu1(Fe) alloy used in the experiments is shown in Table 1.

Table 1
Chemical composition of the AlSi12Cu1(Fe) alloys [wt.%]

Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn
11.	0.69	0.89	0.31	0.06	0.01	0.06	0.34
4	6	1	8	7	4	8	3

For experimental purposes, a casting marked Statorbuchse EC 75 and Statorbuchse EC 55 was used (Fig. 1). Castings EC 75 and EC 55 are distinguished from each other by the different height of the tube part. Experimental castings were cast by Rosenberg-Slovakia s.r.o. in Medzev. The EC 75 and EC 55 castings are part of the EC (electronically commutated) motor. It is a synchronous motor with permanent magnets and an external impeller, which is powered by an inverter. EC motors are used to drive fans.

Both variants of castings were cast with a change of the medium flowing in the thermoregulating circuit of the mold in the core part. By changing the medium, core temperatures at the beginning of the cycle were reached for water of 130 ± 5 °C and for heat transfer oil of 165 ± 5 °C. Other machine parameters, such as piston speed in the filling chamber, mold treatment, mold temperature, casting temperature, and piston stroke, did not change during the casting process and are listed in Table 2.

Table 2
HPDC process parameters

Process parameters		EC 75	EC55
Temperature in the holding furnace		705 ± 10 °C	
Casting (tapping) temperature		705 ± 10 °C	
Temperature of mold	Stationary part	190 ± 5 °C	
	Moveable part	190 ± 5 °C	
Weight of casting		1 kg	0.9 kg
Maximum pressure in the chamber		95 MPa	
Filling chamber diameter		80 mm	
Active chamber length		470 mm	
Pressing time		5 s	
Degassing temperature		720 ± 5 °C	
Rotary degassed with nitrogen		120 s	

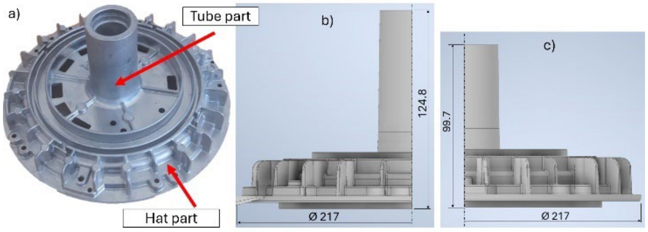

Fig. 1. Statorbuchse EC, a) Geometry, b) EC 75, c) EC 55

A STRIKO WESTOFEN MHS 750/350 melting furnace with a holding space capacity of 750 kg was used. The molten material was then poured from the furnace into the transport ladle. To prevent the formation of microbubbles in the aluminum, which are caused by the release of hydrogen during solidification, it was necessary to degas the melt with nitrogen for 120 seconds. After degassing, the oxide layers were mechanically removed from the surface of the melt and it was transported to the furnace, which serves to maintain the temperature of the melt and also to dose it. A pressure casting machine with a horizontal cold chamber CLH 400.02P was used for casting. An automated Gerlieva mold treatment system was also available during the casting process.

As part of the experimental work, two types of cooling media were used in the core part, namely water and heat transfer oil - ITERM 6MB. The water used to regulate the temperature of the mold was chemically treated - demineralized to prevent corrosion on flat channels or clogging of thermoregulation circuits with calcium deposits. The main difference between water and heat transfer oil is the several times higher heat transfer coefficient of water (≈ 800 W/(m^2.C) compared to ITERM 6MB oil (≈ 175 W/(m^2.C). The core is regulated by the so-called bulkhead, which is used for return channels (Fig. 2).

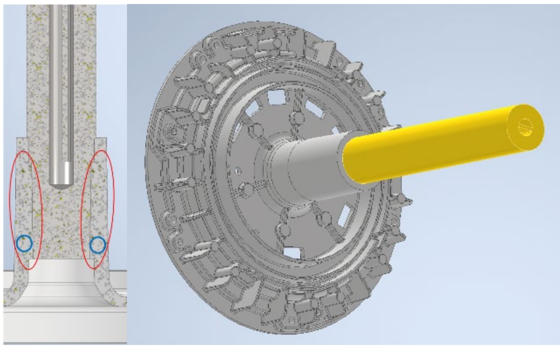

Fig. 2. Section through the core and location of the core in the cast and marking of critical places on the cast with a red ellipse and sampling locations for microstructural analysis with a red ellipse

Samples for microstructural analysis were taken from the critical part - the lower part of the tube (Fig. 2 blue circles). Sample preparation consisted of coarse and fine wet grinding, diamond emulsion polishing and finally etched in 0.5% HF solution. Observations using a NEOPHOT 32 optical microscope (OM), VEGA LMU II scanning electron microscopy (SEM) and EDX analysis were used to evaluate the samples.

The evaluation of porosity by means of a CT scan was carried out on a NIKON - XT H225 ST device.

3. Results

3.1. Porosity evaluation by computer tomography

For evaluation by CT scanning, the hat part of the casts was cut away and the evaluation was focused on the critical tube part of the cast (Fig. 3 and Fig. 4). The CT images were subsequently subjected to a quantitative evaluation of the area share of pores in the sections of each casting in the Quickphoto industrial 3.2 program. In addition to the area fraction, the average value of the maximum pore length was determined based on the Feret Diameter. Sections through the X, Y, Z planes were evaluated on each cast and 3 sections were selected on each plane. The results of the assessment are shown in Table 3. An example of the evaluation procedure is shown in Fig. 5.

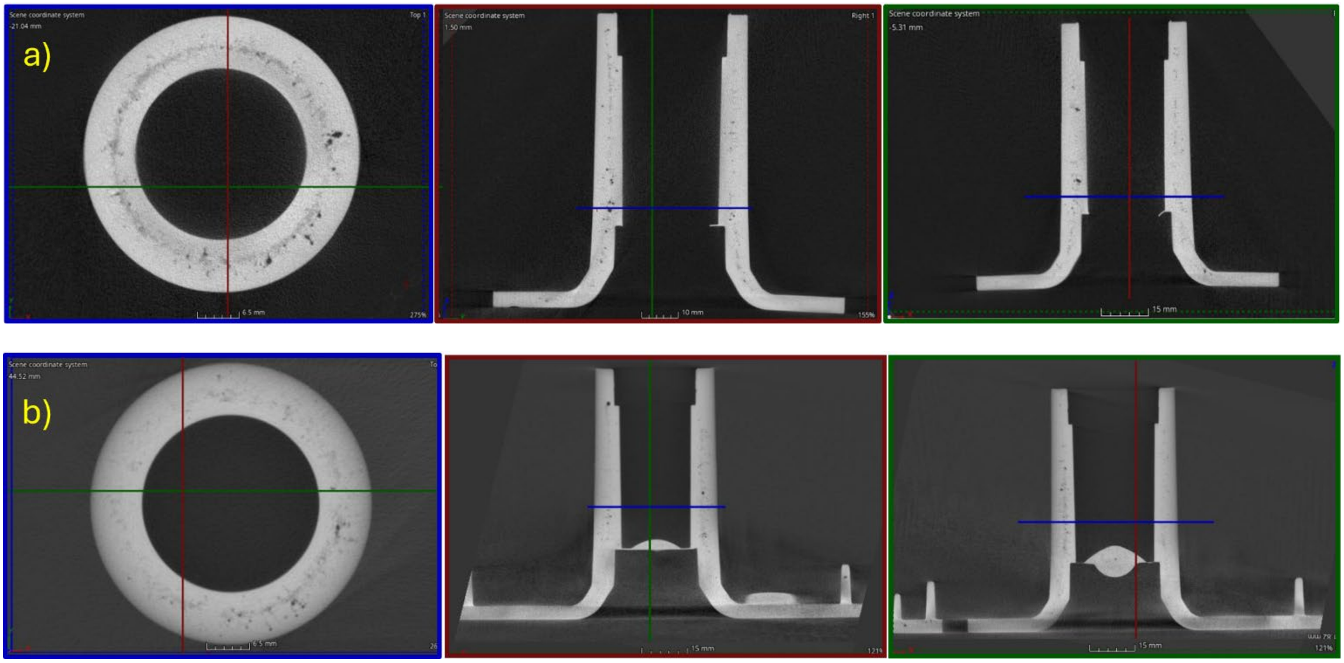

Fig. 3. CT image of EC 55 casting; a) water-cooled (core temperatures 130 ± 5 °C), b) oil-tempered (core temperatures 165 ± 5 °C)

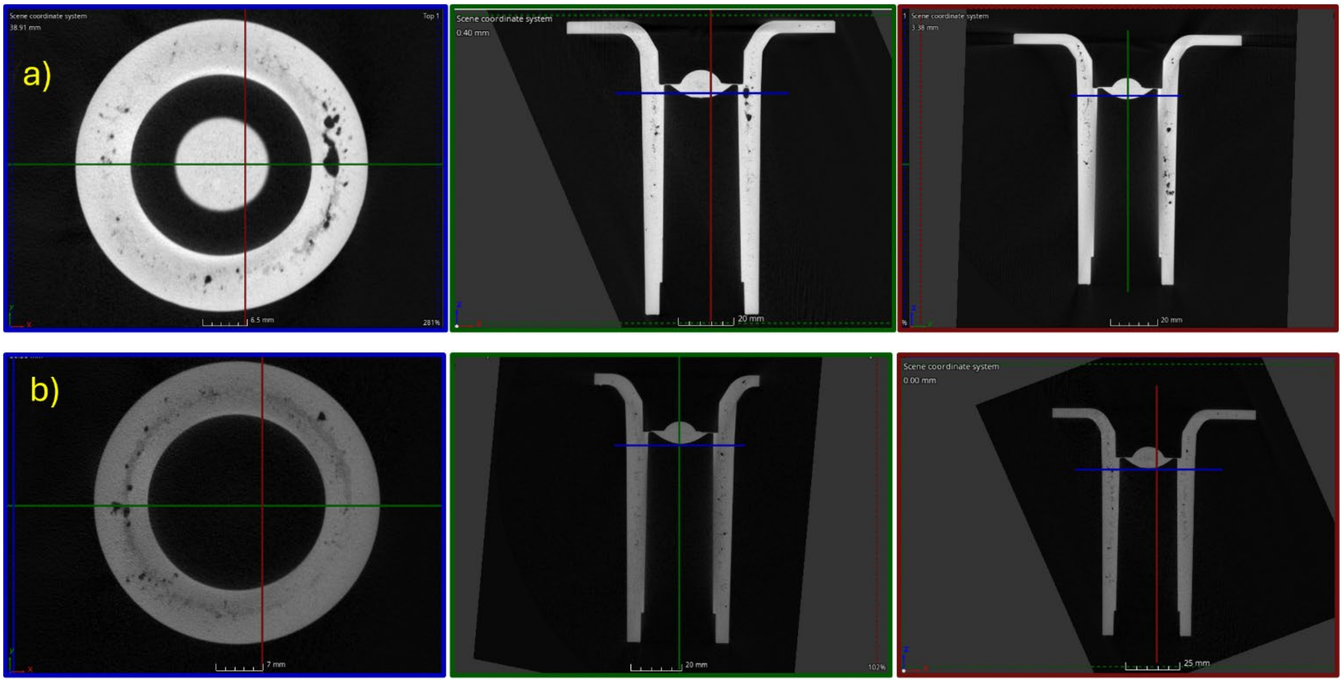

Fig. 4. CT image of EC 75 casting; a) water-cooled (core temperatures 130 ± 5 °C), b) oil-tempered (core temperatures 165 ± 5 °C)

Table 3
Pore area fraction and average maximum pore length

	EC 55 water	EC 55 oil	EC 75 water	EC75 oil
Pore area fraction [%]	0.48	0.38	0.93	0.44
Maximum pore length [mm]	0.85	0.62	1.19	0.70

When comparing CT images of EC 55 castings, we can see that the number of pores when tempering oil is used is smaller compared to water-cooled castings. The occurrence of pores is approximately up to 2/3 of the height of the tube when using oil, when using water there is already the presence of pores in the entire volume of the casting. Using water also increased the size of the pores (Fig. 3).

By observing EC 75 castings that were tempered with oil, we see that porosity is already present in the lower part of the tube. For castings that were cooled by water, the number and size of pores, especially in the critical part of the tube, increased significantly. The range of pores found in EC 75 castings is significantly larger than in EC 55 castings. In EC 75 castings that were water-cooled, the pore size also increased (Fig. 4).

The smaller number of pores in the tube section can be explained by the reduction in the cooling rate due to the heat transfer oil allowing more trapped air to escape from the observed area into the venting system. The second possibility is that the increased temperature of the mold surface, which evaporated the cooling and separation sprays more quickly and thus escaped in larger quantities into the atmosphere before the cavity was closed. The lower temperature of the core surface could have caused slower evaporation of the cooling and separation sprays, which subsequently remained closed inside the casting as excess water, which evaporates during the casting process and thus creates air bubbles.

In the volume of castings, it is possible to observe pores with a rounded shape, which are located more in the middle and upper part of the tube. In EC 75 castings, pores with irregular shapes prevail in the lower - critical part of the tube, which disrupts the homogeneity to a greater extent. Pores with irregular shapes are characteristic that the mechanism of formation is a combination of shrinkage and the presence of trapped air.

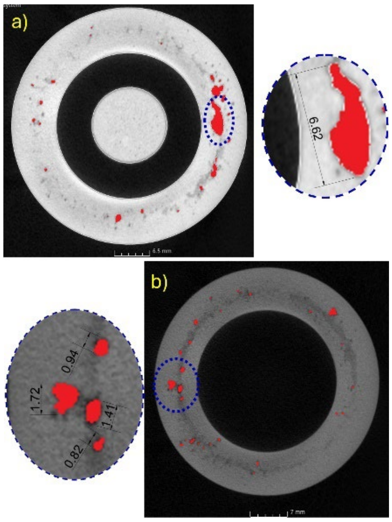

Fig. 5. CT image of EC 75 casting after evaluating pore area fraction and average maximum pore length; a) water-cooled (core temperatures 130 ± 5 °C), b) oil-tempered (core temperatures 165 ± 5 °C)

3.2. Microstructure analysis

The microstructure of the eutectic alloy AlSi12Cu1(Fe) of EC 55 and 75 castings can be seen in the optical microscope images (Figs. 6 and 7) at 200- and 500-times magnification. The microstructure is formed by the eutectic (dark gray color) distributed in the α (Al) phase (pale gray color) and intermetallic phases based on Fe and Cu.

The eutectic particles in the water-cooled EC 55 casting have the shape of compact plate-like silicon particles - lamellae, or grains (Fig. 6a). Fe-rich intermetallic phases are observed as Al5FeSi type phases (short needle morphology) or locally together with Mn form $Al_{15}(FeMn)_3Si_2$ type phases. $Al_{15}(FeMn)_3Si_2$ phases can be observed in the inter-dendritic regions and are predominantly in the shape of sharp-edged formations, or the so-called "Chinese script". However, the higher Mn, Cr and Fe content resulted in the formation of so-called sludge phases, which can be observed as gray irregular formations.

EC 55 castings that were tempered with oil have a thicker structure (Fig. 6b) compared to water-cooled castings, which was caused by slower cooling rate of the tube part. It can also be observed that in the oil-tempered alloy, the eutectic and Fe-rich phases (in needle morphology) crystallized to longer lengths, and sludge phases were locally observed up to approximately 20 μm in size (Fig. 6b).

On the microstructure of the water-cooled EC 75 casting (Fig. 7a), can see lamellae of eutectic Si in shorter and more rounded shapes (similar to the water-cooled EC 55 casting), which are dispersed throughout the entire volume of the matrix. Conversely, tempering with oil led to the crystallization of coarser grains of the primary α phase and longer Si lamellae with sharper terminations (Fig. 7b). Intermetallic phases based on Fe and Cu were not significantly affected by changing the geometry of the tube. Al_5FeSi phase needles are present in shorter lengths in water-cooled castings.

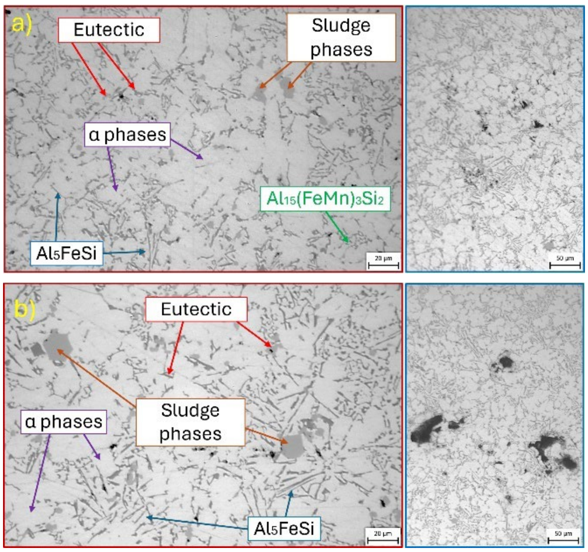

Fig. 6. EC 55 casting microstructure; a) cooled by water, b) tempered by oil

The change in the flowing medium was manifested by an increase in microporosity, which can be observed in the images at 200 times magnification (Fig. 6 and 7 - blue color). Microporosity was observed mainly with the mechanism of shrinkage and the places of its combination with a gas bubble. In his study [12], Wang describes in detail the mechanism of microporosity decrease with increasing cooling rate. The higher the cooling rate, the finer the grain of the primary phase. Since the rate of hydrogen diffusion in the solid phase is much lower than in the liquid phase, this refined microstructure will prevent hydrogen diffusion and reduce the concentration between the microporosity, leading to a decrease in the microporosity size. On the other hand, grain refinement leads to the reduction of inter-dendritic distances, which limit the growth space of microporosity. In addition, a slight increase in microporosity was observed due to the increase in tube height, thereby increasing the areas of hot spots that increase the risk of shrinkage.

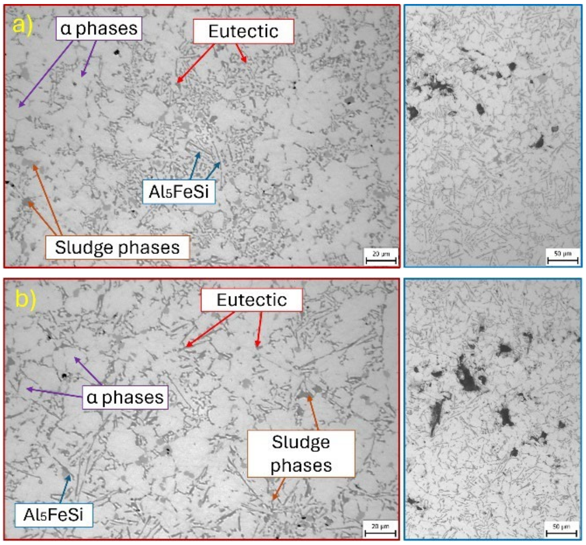

Fig. 7. EC 75 casting microstructure; a) cooled by water, b) tempered by oil

Images from a scanning electron microscope allow a more detailed view of individual structural components. When taking a closer look at the morphology of eutectic Si, a clearly visible change is the effect of the used medium in the thermoregulation system of the core (Fig. 8). The morphology of the eutectic in the water-cooled casting is observed in the cutting plane as various round grains and lamellae, which in the 3D morphology are observed as rods. The morphology of the eutectic in the tempered casting is in the form of sharp-edged lamellae (needles) with an uneven surface (protruding steps), which are related to the twinning of the basic Si crystal. In 3D morphologies observed as hexagonal plates. Similar results were also observed in works by authors Shen [13], Li [14] or Niklas [15]. In his research, Shen worked with an AlSi10 alloy with increased Fe content and a cylinder-shaped casting with dimensions of a cavity diameter of 20 mm and a height of 120 mm. By increasing the cooling rate, there was a transformation from coarse needle-like particles to fine particles of eutectic Si. Li s and the collective evaluated the cooling rate on AlSi7Mg0.3 alloy and casting with two different thicknesses (30 mm and 0.8 mm). The cooling rate for a wall thickness of 30 mm was 30 K/s and for a thin wall of 0.8 mm it was 130 K/s. At a cooling rate of 30 K/s, the eutectic Si showed a flake-like morphology, and by increasing the rate to 130 K/s, a slight morphology was already observed branching. Niklas also worked with the same alloy and a casting with a cylindrical shape with an oven thickness of 0.3 to 1.5 cm. The result was the transformation of Eutectic Si grains due to the increase in the cooling rate from thick plate-like formations to well-rounded particles.

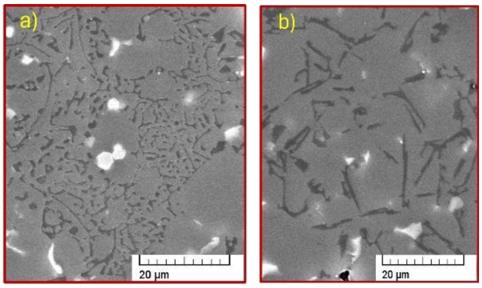

Fig. 8. Detail of eutectic Si in EC 55 casting; a) cooled by water, b) tempered by oil

SEM images and elements mapping applications confirmed the presence of sludge phases (Fig. 9). These are polyhedral compounds formed by a peritectic reaction, such as primary α – $Al_{15}(Fe,Mn,Cr)_3Si_2$. Copper-rich intermetallic phases in all castings are primarily nucleated near eutectic silicon grains or iron-rich phases. The Cu-rich phases crystallized as Al_2Cu phases or, in the presence of Fe, as Al_7FeCu.

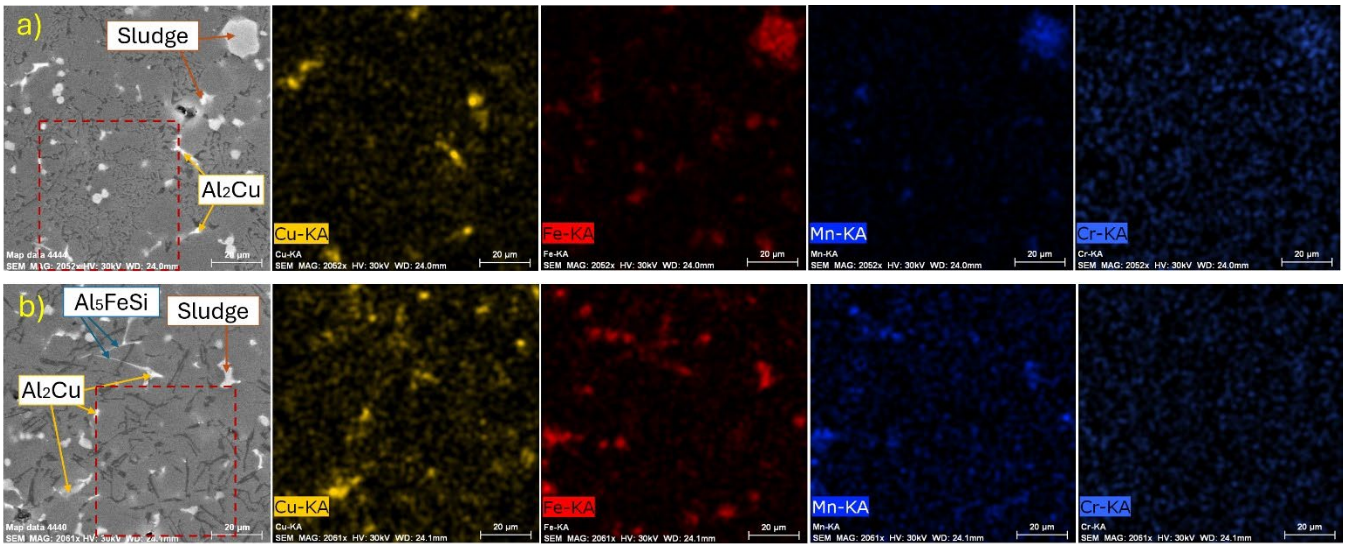

Fig. 9. EC 55 casting microstructure; a) cooled by water, b) tempered by oil

4. Conclusions

The aim of the presented article was to assess the effect of the temperature change due to the influence of the medium flowing in the thermoregulating circuit of the core of the high-pressure mold on the internal quality of the castings in two geometric variants of the height of the casting tube.

The use of heat transfer oil has shown itself favorably in the evaluation of the porosity of the tube, which is in direct contact with the core. By applying water to the thermoregulation circuit, the initial temperature of the core during the work cycle was reduced (130 ± 5 °C), which resulted in the appearance of a larger number of pores in the form of closed air in the entire volume of the tube. The effect of tube growth confirmed the trend of increasing the presence of pores in the evaluated area of the EC 75 casting.

On the contrary, the increased cooling rate due to water's influence in the thermoregulation circuit led to a decrease in microporosity with the mechanism of shrinkage in the critical area of the tube. A more favorable microstructure was also achieved due to the influence of water flow in the core. The microstructure of the water-cooled castings was more characterized by finer grains of the α phase (Al) and eutectic silicon in the form of round grains and lamellae. Coarse grains of the α phase (Al) and Si lamellae in the form of sharp-edged lamellae (needles) with an uneven surface were characteristic of the oil-tempered castings.

The results show that maintaining the correct temperature of the work surface is very important. In our case, it can be said that the use of heat transfer oil as a medium in the thermoregulation circuit of the core was more optimal because essentially lower gas porosity was achieved in the critical area (at the expense of the deterioration of the microstructure and the greater presence of contractions), which plays an essential role in the functions of the casting.

Acknowledgements

A The article was created as part of the **VEGA 1/0160/22** a **KEGA 022ŽU-4/2021**. The authors thank the agency for their support.

References

[1] Kalpakjian, S., Schmid, S.R. (2009). *Manufacturing Engineering and Technology*. (6th ed.). Pearson Ed Asia.

[2] Sadeghi, M. & Mahmoudi, J. (2012). Experimental and theoretical studies on the effect of die temperature on the quality of the products in high-pressure die-casting process. *Advances in Materials Science and Engineering*. 1, 1-9. https://doi.org/10.1155/2012/434605.

[3] Bruna, M., Bolibruchová, D., Pastircák, R. & Remisová, A. (2019). Gating system design optimization for investment casting process. *Journal of Materials Engineering and Performance*. 28(54), 3887-3893. DOI: 10.1007/s11665-019-03933-3.

[4] Tavakoli, S., Ranc-Darbord, I. & Wagner, D. (2014). Thermal behavior of the mold surface in HPDC process by infrared thermography and comparison with simulation. In Proceedings of the 12th International Conference on Quantitative Infrared Thermography, July 2014. France, Bordeaux. DOI: 10.21611/qirt.2014.054.

[5] Shin, S.-S. & Lee, S.-K., Kim, D. & Lee, B. (2021). Enhanced cooling channel efficiency of high-pressure die-casting molds with pure copper linings in cooling channels via explosive bonding. *Journal of Materials Processing Technology*. 297. 117235, 1-19. DOI: 10.1016/j.jmatprotec.2021.117235.

[6] Pastircák, R., Scury, J. & Moravec, J. (2017). The effects of pressure during the crystallization on properties of the AlSi12 alloy. *Archives of Foundry Engineering*. 17(3), 103-106. DOI: 10.1515/afe-2017-0099.

[7] Hu, H., Chen, F. Chen, X., Chu, Y. & Cheng, P. (2004). Effect of cooling water flow rates on local temperatures and heat transfer of casting dies. *Journal of Materials Processing Technology.* 148(1). 57-67. DOI: 10.1016/j.jmatprotec.2004.01.040.

[8] Jarfors, A., Sevastopol, R., Karamchedu, S., Zhang, Q., Steggo, J. & Stolt, R. (2021). On the use of conformal cooling in high-pressure die-casting and semisolid casting. *Technologies*. 9(2), 39. https://doi.org/10.3390/technologies9020039.

[9] Fiorentini, F., Curcio, P., Armentani, E., Rosso, C. & Baldissera, P. (2019). Study of two alternative cooling systems of a mold insert used in die casting process of light alloy components. *Procedia Structural Integrity*. 24, 569-582. DOI: 10.1016/j.prostr.2020.02.050.

[10] Kimura, T, Yamagata, H. & Tanikawa, S. (2015). FEM stress analysis of the cooling hole of an HPDC die. *IOP Conference Series: Materials Science and Engineering.* 84, 012052, 1-7. DOI: 10.1088/1757-899X/84/1/012052.

[11] Tool-Temp. (2023 April). *Die casting - we provide you with perfect tool tempering*. Retrieved April 08, 2024, form https://tool-temp.ch/en/industries-temperature-control-units/die-casting-industry-temperature-control-unit/.

[12] Wang, R., Zuo, Y., Zhu, Q., Liu, X. & Wang, J. (2022). Effect of temperature field on the porosity and mechanical properties of 2024 aluminum alloy prepared by direct chill casting with melt shearing. *Journal of Materials Processing Technology.* 307, 117687, 1-13. https://doi.org/10.1016/j.jmatprotec.2022.117687.

[13] Shen, X., Liu, S., Wang, X., Cui, C., Gong, P., Zhao, L., Han, X. & Li, Z. (2022). Effect of cooling rate on the microstructure evolution and mechanical properties of iron-rich Al-Si alloy. *Materials*. 15(2), 411, 1-10. DOI: 10.3390/ma15020411.

[14] Li, L., Li. D., Mao. F., Feng, J., Zhang, Y. & Kang, Y. (2020). Effect of cooling rate on eutectic Si in Al-7.0Si-0.3Mg alloys modified by La additions. *Journal of Alloys and Compounds*. 826, 154206, 1-10. https://doi.org/10.1016/j.jallcom.2020.154206.

[15] Niklas, A., Abaunza, U., Isabel, F. Lacaze, J. & Suarez, R. (2010). Thermal analysis as a microstructure prediction tool for A356 aluminium parts solidified under various cooling conditions. *China Foundry.* 59(11), 1167-1171.