EFFECT OF REFINING PROCESS ON POROSITY AND MECHANICAL PROPERTIES OF HIGH PRESSURE AL-SI ALLOY DIE CASTINGS

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Abstract: *This study presents the research results of effect that refining process has on porosity and mechanical properties of high pressure die castings made of AlSi12S alloy. The operation of refining was carried out in a melting furnace with the use of an FDU Mini Degasser. Mechanical properties (UTS, YS, Elongation, Brinell Hardness) were assessed on samples taken from high pressure die castings. The effect of molten metal transfer operation and the time elapsing from completion of the refining process on the alloy mechanical properties was determined.*

Keywords: *Al-Si alloy, refining, high pressure die castings, porosity content, mechanical properties.*

1. INTRODUCTION

In Al-Si high pressure die castings, gas porosity, shrinkage porosity or a combination of both are present. Pure gas porosity may occur in castings with properly developed feeding system but made of gassed alloys [1]. Gas pores represent isolated areas, while shrinkage pores occur in groups and are of irregular shapes [1].

Formation of gas porosity in castings is a result of gas solubility decrease in the course of alloy solidification. The main source of gas porosity is hydrogen which contributes to 90% of the total gas volume in the alloy. Gas cavities occur before the crystallization front, between branches of growing dendrites.

The gas porosity occurring in castings as a result of liquid alloy degassing reduces crystal cohesion and, consequently, impairs the alloy's mechanical properties. The porosity reduces pressure tightness of castings. Oxide inclusions, hard and brittle by their nature, result in casting brittleness and impair casting workability [2, 3].

Refining of aluminum-silicon alloys is aimed at removing hydrogen, oxides, borides, nitrides and spinels.

Problems related to refining aluminum-silicon alloys (devices, gases used for refining, effectiveness of the refining process, decay of the refining effect) are discussed in numerous studies [4-8].

To manufacture good quality high pressure alloy Al-Si die castings, it is necessary to determine the possibilities that refining creates for the improvement of mechanical properties. The aim of this work was to establish the influence of refining, molten metal transferring and the time elapsing from completion of the refining process on porosity content and mechanical properties (UTS, YS, Elongation, Brinell Hardness) of high pressure die castings.

2. EXPERIMENTAL PROCEDURE

The material used in this research was AlSi12S alloy prepared from ingot pigs, process scraps and swarfs. Chemical composition of AlSi12S alloy used for the experiment is presented in Table 1.

The metal charge melting process was conducted in electric induction furnace at average frequency (250 Hz) with maximum melt capacity of 1,200 kg. The furnace burden was calculated as 1,000 kg.

In the case of melts #1 and #3, process scraps (20%) and pigs (20%) were introduced to the furnace. Upon melting, swarfs (20%) were introduced, and then the remaining pigs added. Before introduction to the furnace, swarfs were centrifuged in order to remove coolant.

In the case of melts #2 and #4, process scraps (40%) were first introduced to the furnace, and then pigs (60%).

At the first stage of examination, the porosity content and mechanical properties of non-refined

Table 1. Chemical analysis of AlSi12S alloy

Melt	Element content, % by weight						
	Si	Cu	Fe	Mn	Zn	Ti	Al
#1	11.83	0.111	0.49	0.064	0.103	0.015	rest
#2	11.88	0.112	0.53	0.074	0.109	0.011	rest
#3	11.86	0.110	0.51	0.061	0.098	0.014	rest
#4	11.90	0.113	0.52	0.072	0.108	0.012	rest

Melt number and charge material:

#1 – pigs (60%) + process scraps (20%) + swarfs (20%), non-refined;

#2 – pigs (60%) + process scraps (40%), non-refined;

#3 – pigs (60%) + process scraps (20%) + swarfs (20%), refined;

#4 – pigs (60%) + process scraps (40%), refined.

alloy were evaluated, as well as the porosity content of high pressure die castings made of this alloy.

Alloy density was measured with the use of density estimation kit (AS 160/X) and software program accounting for distilled water density as a function of temperature. The scale's measurement range was 0.01–160 g and sample mass (in air and in water) as determined with 0.001 g accuracy. Density measurements were carried out using samples with dimensions 20 mm x 10 mm x 5 mm. Porosity content P was calculated using the following formula:

$$P = \frac{\rho_t - \rho}{\rho_t} \cdot 100\% \quad (1)$$

where: ρ_t - theoretical density, ρ - material density [5].

Melts #1 and #2 (non-refined)

As the alloy was prepared in the melting furnace, it was heated up to 720°C and the surface of the molten metal was then skimmed to take samples for porosity content evaluation and metallographic tests. The samples were cast in a steel die (Fig. 1).

Subsequently, the alloy was transferred to a transport ladle with 200 kg capacity. The surface of the molten metal in the ladle was cleaned and samples were taken from the ladle to evaluate the porosity content and perform metallographic tests. The ladle was transported to the HPDC machine stand. The injection (pouring) temperature was 690°C. Ten castings were made of melts #1 and #2. Samples for porosity content evaluation and samples for mechanical properties examination were taken from the castings (Fig. 2).

Melts #3 and #4 (refined)

At the second stage of examination, the porosity content of refined alloy was evaluated, as well as the porosity content and mechanical properties of high pressure die castings made of the refined alloy.

As the alloy was prepared in the melting furnace, it was heated up to 720 °C and the

Fig. 1. Samples for testing the alloy porosity content

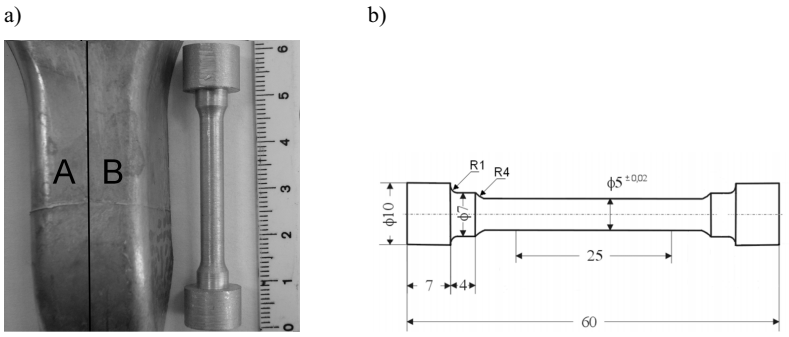

Fig. 2. (a) Location of casting samples, (A) location from which samples were taken to evaluate the porosity content and (B) location from which samples were taken to examine the mechanical properties. (b) dimensions of samples for testing mechanical properties (in mm)

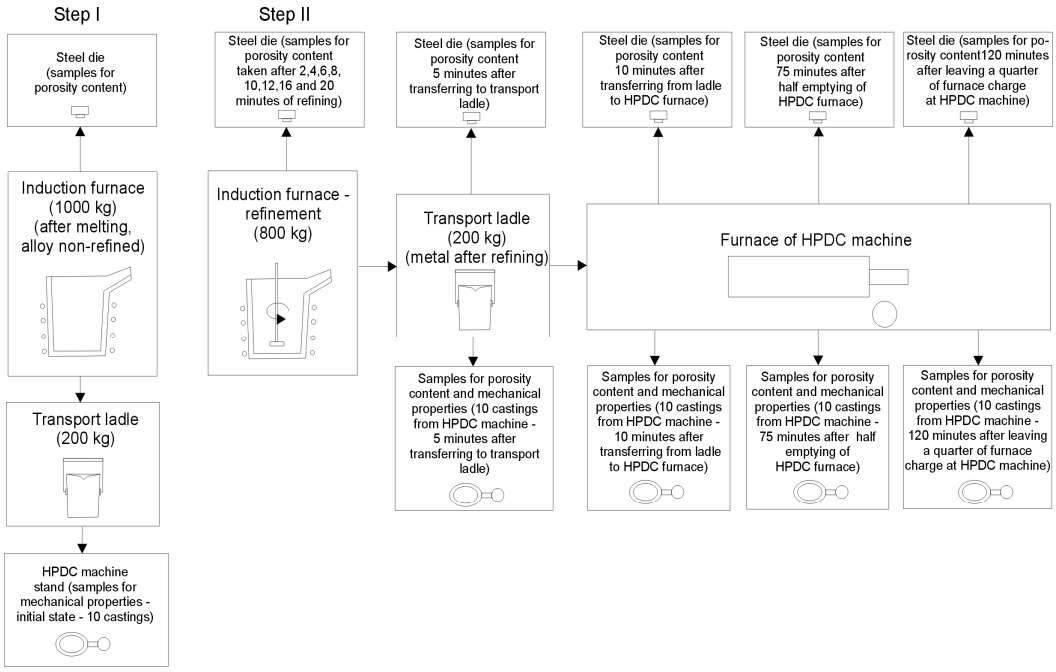

Fig. 3. Flow diagram of sampling (melts #3 and #4)

surface of the molten metal was then skimmed to take samples for porosity content evaluation. The samples were cast in a steel die.

The same procedure done for melts #1 and #2 was carried out to assess mechanical properties.

The rest of the liquid alloy was used to make pig castings. The molten metal that remained in the furnace was subject to refining.

The refining was performed using rotary degasser. Argon output was controlled at level of 22 l/min. The rotor rate was 500 rpm.

To determine the influence of molten metal refining time on the porosity content, alloy samples were taken. The total time of refining was 20 min.

After completion of the refining process (melts #3 and #4), granular flux (Ecremal) was sprinkled over the molten metal surface to bind non-metallic inclusions.

When temperature of liquid metal in transport ladle reached 690°C, samples for porosity assessment were taken. Then, 10 pressure castings were poured of metal taken from the transport ladle. Next, the metal from transport ladle was transferred to the pressure machine's

heating furnace. The furnace capacity was 250 kg. After oxides were removed from the molten metal surface, samples were taken for porosity content evaluation and 10 castings were made. Samples for porosity content evaluation and mechanical properties examination were taken from the castings.

To establish the influence of period for which the molten metal was detained in the furnace at the pouring stand (75 minutes and 120 minutes after completion of refining) on the porosity content and mechanical properties, test samples were cast and 10 high pressure die castings were made. Flow diagram of sampling from melts #3 and #4 is presented in Fig. 3.

Table 2. The porosity content of the AlSi12S alloy evaluated for die-cast samples and for samples taken from high pressure die castings. Melts #1 and #2. Non-refined alloy

Melt	Sampling location	Porosity content *P*, %	
		die-castings	high pressure die castings
#1	induction furnace	2.8	–
	transport ladle	3.3	5.6
#2	induction furnace	2.6	–
	transport ladle	3.1	5.5

Table 3. Mechanical properties of AlSi12S alloy assessed for samples taken from high pressure die castings obtained from melts #1 and #2 (non-refined). Castings were made of the alloy taken from the transport ladle

Melt	Mechanical properties			HB
	UTS, MPa	YS, MPa	Elongation, %	
#1	150	140	0.7	61
#2	152	142	0.8	63

3. RESULTS AND ANALYSIS

Results of the porosity content evaluation of non-refined AlSi12S alloy (melts #1 and #2) samples taken from melting furnace, transport ladle and high pressure die castings are presented in Table 2.

The results obtained indicate that non-refined alloy had a high value of porosity content, i.e. 2.8% (melt #1) and 2.6% (melt #2). Transfer of the alloy from melting furnace to transport ladle resulted in the porosity content increase by 0.5% (melts #1 and #2) . The porosity content of high pressure die casting material made of the alloy taken from the ladle amounted to 5.6% (melt #1) and 5.5% (melt #2) and was approximately by 70% higher than the porosity content of the material of sample poured into the die. The increase of porosity content to 5.6 or 5.5% is related to air gas entrapment in high pressure die-casting.

Example microstructures of AlSi12S alloy samples (melt #1) cast in a die are presented in Fig. 4. Metallographic sections confirm existence

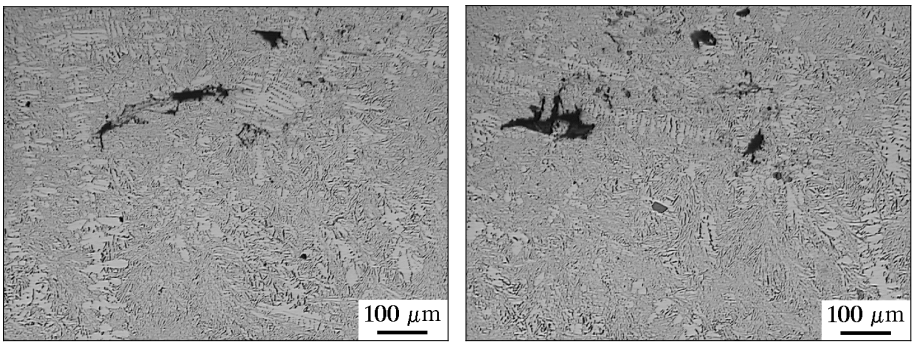

Fig. 4. Example microstructure of AlSi12S from melt #1 (non-refined alloy). (a) Sample taken from the furnace and (b) sample taken from the ladle

Table 4. Results of porosity content evaluation for samples of AlSi12S alloy (refined)

Time elapsed	Porosity content *P*, %			
	Samples cast in dies		Samples taken from castings	
	Melt #3	Melt #4	Melt #3	Melt #4
Initial state	2.5	2.4	–	–
2 minutes of refining	2.2	2.1	–	–
4 minutes of refining	2.0	1.8	–	–
6 minutes of refining	1.9	1.7	–	–
8 minutes of refining	1.8	1.7	–	–
10 minutes of refining	1.6	1.6	–	–
12 minutes of refining	1.5	1.4	–	–
16 minutes of refining	1.5	1.4	–	–
20 minutes of refining	1.5	1.4	–	–
5 minutes after refining (after transferring to transport ladle)	1.7	1.5	4.3	4.2
10 minutes after refining (after transferring from ladle to pressure machine furnace)	1.9	1.7	4.8	4.7
75 minutes after refining (after half emptying of pressure machine furnace)	2.0	1.9	5.0	4.8
120 minutes after refining (after leaving a quarter of furnace charge at pressure machine)	2.1	2.0	5.1	5.0

of discontinuities in the sample material.

Results of measurements performed to determine mechanical properties of samples taken from high pressure die castings made of non-refined alloy (melts #1 and #2) poured from the transport ladle are presented in Table 3.

The results obtained indicate that the use of swarfs in the charge material had no significant influence on mechanical properties of the high pressure die castings, because the results of mechanical properties are influenced by air gas entrapment in HPDC.

Values of the porosity content of AlSi12S alloy samples (melts #3 and #4) taken from the melting furnace in the course of refining, from the transport ladle, and from the pressure machine furnace, as well as of samples taken from high pressure die castings made of the alloy poured from transport ladle and the pressure machine furnace, are presented in Table 4.

An example microstructure of AlSi12S alloy samples (melt #3) taken from the furnace during refining is presented in Fig. 5.

Microstructure of refined alloy samples taken from the transport ladle and from the pressure machine furnace is presented in Fig. 6. Samples of the transport ladle were taken every 5 minutes starting from the end of refining. Samples of the transport ladle were taken after 10 and 75 minutes from the end of refining.

The obtained results indicate that the initial alloy used for the study had porosity content equaling 2.8% (melt #1, non-refined), 2.6% (melt #2, non-refined), 2.5% (melt #3, refined) and 2.4% (melt #4, refined).

Research on the effect of the alloy refining time from melts #3 and #4 on its quality revealed that after 12 minutes, the porosity content had

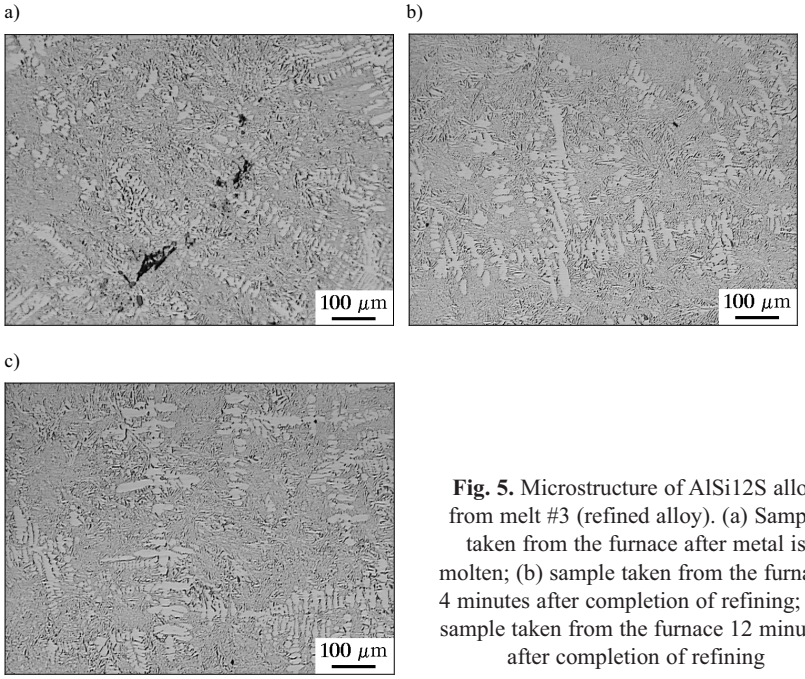

Fig. 5. Microstructure of AlSi12S alloy from melt #3 (refined alloy). (a) Sample taken from the furnace after metal is molten; (b) sample taken from the furnace 4 minutes after completion of refining; (c) sample taken from the furnace 12 minutes after completion of refining

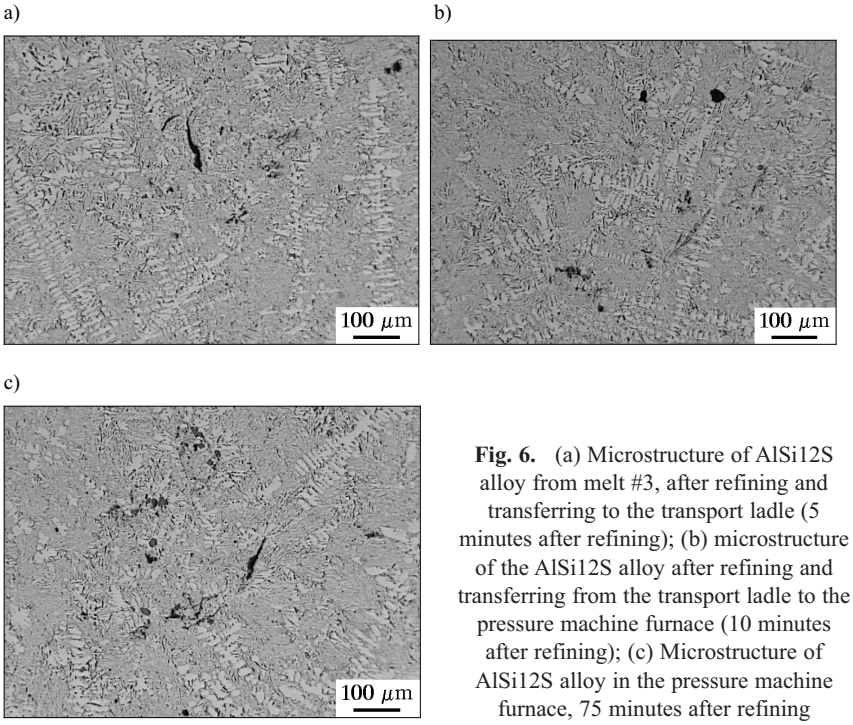

Fig. 6. (a) Microstructure of AlSi12S alloy from melt #3, after refining and transferring to the transport ladle (5 minutes after refining); (b) microstructure of the AlSi12S alloy after refining and transferring from the transport ladle to the pressure machine furnace (10 minutes after refining); (c) Microstructure of AlSi12S alloy in the pressure machine furnace, 75 minutes after refining

stabilized at levels of 1.5% (melt #3) and 1.4% (melt #4), respectively. Increase of the refining time up to 20 minutes did not affect these values. Transferring the alloy to the transport ladle and detaining it for 5 minutes after completion of the refining process resulted in increase in porosity content by 0.2% (melt #3) and 0.1% (melt #4). Pouring the alloy from the transport ladle to the

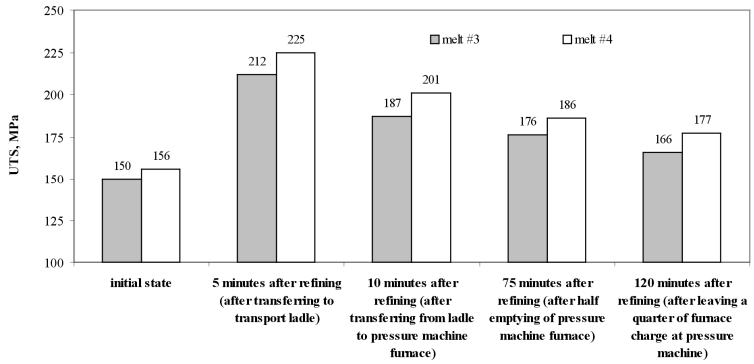

Fig. 7. UTS of AlSi12S alloy samples taken from high pressure die castings

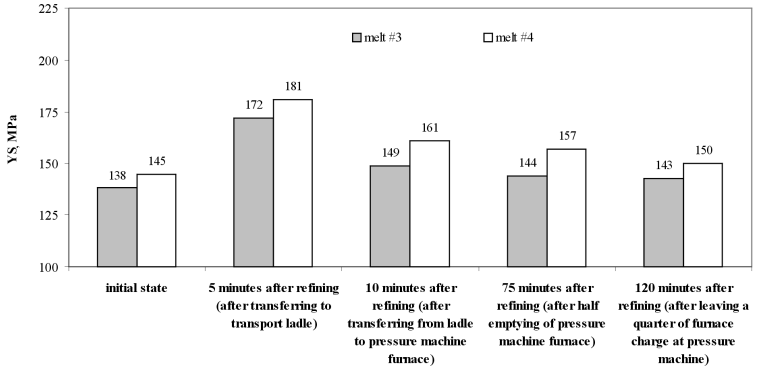

Fig. 8. YS of AlSi12S alloy samples taken from high pressure die castings

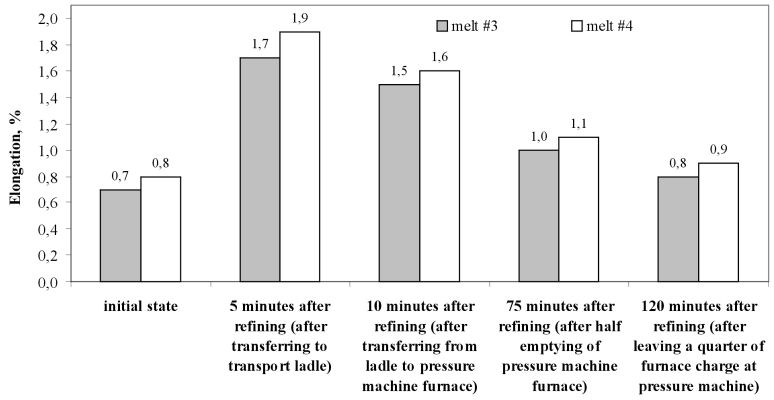

Fig. 9. Elongation of AlSi12S alloy samples taken from high pressure die castings

pressure machine furnace and detaining it for 10 minutes after the end of refining resulted in increase of porosity content by another 0.2% (melts #3 and #4). The alloy gassing increased with length of the period for which the liquid alloy was detained in the pressure machine's furnace. 75 minutes after completion of refining, the porosity content increased by 0.1% (melt #3) and 0.2% (melt #4).

After another 45 minutes, the value increased again by 0.1% (melts #3 and #4). The maximum period of detention of liquid alloy in the pressure machine furnace, assumed for the purpose of this study, allowed for complete removal of molten

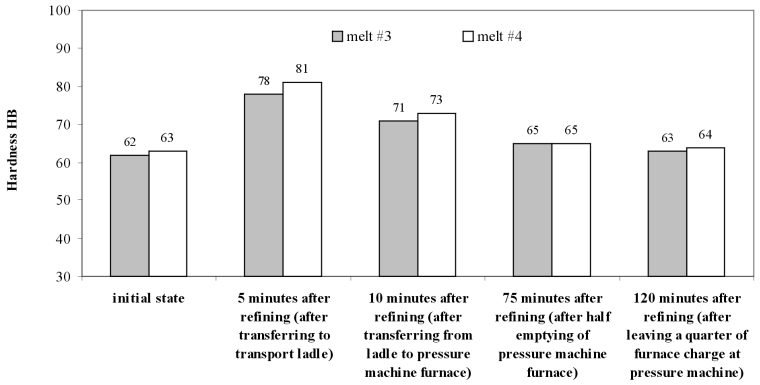

Fig. 10. Hardness HB of AlSi12S alloy samples taken from high pressure die castings

metal during the machine operation.

The analysis concerning porosity content in material of samples cast in the die as well as that of high pressure die castings indicate that in the case of non-refined castings, higher porosity appeared in the pressure cast material. This is an effect of additional gassing of metal occurring in the course of another transfer when the molten metal is poured to the loading chamber, interaction of piston lubricant and mould coating combustion products, and turbulent flow of metal at filling the pressure mould cavity.

Material porosity analysis of samples cast in the die of the refined alloy taken from the ladle shows that the porosity content decreases to 1.7% (melt #3) and 1.5% (melt #4), compared to 3.3% (melt #1) and 3.1% (melt #2) in the case of non-refined alloy being used.

Material porosity analysis of high pressure die castings made of the alloy taken from the ladle indicates that refining allowed to reduce the porosity content to 4.3% (melt #3) and 4.2% (melt #4), compared to 5.6% (melt #3) and 5.5% (melt #4) in the case of non-refined alloy being used.

With increasing residence time of liquid alloy in the pressure machine furnace, further gassing of the alloy occurred, which resulted in an increase in the casting porosity content. The casting porosity content was 4.8% (melt #3) and 4.7% (melt #4) 10 minutes after refining, 5.0% (melt #3) and 4.8% (melt #4) after 75 minutes and 5.1% (melt #3) and 5.0% (melt #4) after 120 minutes.

Results of measurements performed to determine mechanical properties of samples taken from high pressure die castings made of refined alloy (melts #3 and #4), are presented in Figs. 7–10.

4. DISCUSSION

The refining of AlSi12S alloy with the refining parameters used in this study (rotational speed 500 rpm, argon flow rate 22 l/min, refining time 12 minutes) allowed for effective reduction of alloy porosity by 1%.

It was found that the porosity content of high pressure die castings material is much higher than that observed in the liquid alloy taken from the pressure machine furnace. This is an effect of increased alloy gassing during transfer to the loading chamber, interaction between piston lubricant and mould coating combustion products, and turbulent flow of metal occurring when the pressure mould cavity is filled.

Transfer of liquid alloy and time elapsing from completion of refining resulted in an increase of its gassing and consequential increase of pressure casting porosity.

The liquid alloy refining process, despite multiple subsequent transfers (furnace/ladle/ pressure machine furnace/pressure mould pouring) and the time elapsing from the end of refining, allowed to obtain castings with less porosity compared to the use of a non-refined alloy.

Refining allowed for distinct growth of tensile strength, yield strength, elongation and hardness of high pressure die castings material, compared to the high pressure die castings material made of non-refined alloy. On the other hand, transferring the alloy from the transport ladle to the pressure

machine furnace resulted in deterioration of the high pressure die casting material mechanical properties. Further deterioration of the alloy properties occurred in the course of detention of the liquid metal detention in the pressure machine furnace.

Material of high pressure die castings made of alloys refined in a melting furnace, despite numerous transfers (from the furnace to the transport ladle, from the ladle to the pressure machine furnace, from the pressure machine furnace to the machine loading chamber) and despite the time of detention in the pressure machine furnace, which was approximately 2 hours, it was characterized by better mechanical properties than the material of high pressure die castings made of non-refined alloy.

A number of studies [2, 9-11] indicate that formation of porosity in aluminum-silicon alloys occurs in significant correlation with SDAS (secondary dendrite arm spacing) structural parameter. Its value is closely related to the alloy crystallization rate [12, 13]. On the other hand it can be concluded that liquid metal transferring and turbulent flow occurring in the course of filling a pressure mould cavity create favorable conditions for gassing of castings. In view of the fact that test samples were taken always from the same regions of castings, characterized with the same crystallization rate, it can be concluded that value of SDAS structural parameter as well as its effect on mechanical parameters was similar in case of each sample taken

It is the well-known fact that in the case of material with high compactness, microcracks originate on largest silicon precipitations secretions ($l_{max\ Si}$) or on boundaries of such precipitations with the matrix [14]. Development of cracks occurs then through the matrix to neighboring silicon precipitations. For that reason, susceptibility of aluminum-silicon alloys to cracking is usually characterized with parameter $l_{max\ Si}/\lambda_E$, where λ_E is the distance between silicon precipitations in the eutectic [15].

In the case of porous material, pore dimensions diameters are usually larger than values of the structural parameter $l_{max\ Si}$. For that reason, pores will be decisive for susceptibility of the material to cracking, and thus also for its mechanical properties.

Immediately after refining (at low porosity), mechanical properties of the alloy were better than those of non-refined alloy. Pore dimensions in non-refined alloy were larger than those observed in the refined and repeatedly transferred alloy.

The obtained results show that use of cleaned machining swarf in the metal charge did not result in any significant increase of pressure castings' porosity (an hence the mechanical properties) regardless of whether the alloy was refined or not.

The results indicate that refining in the pressure machine furnace would be an optimum solution of the problem of porosity in castings made by means of conventional pressure casting method.

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