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Effect of the refining process on porosity and selected mechanical properties of AlSi7Mg alloy pressure castings

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ABSTRACT

Based on research it has been found that the refining parameter that has a significant influence on the density of the alloy, as a controllable factor and also responsible for porosity, is the content of the introduced mixture of NH_2. For this reason, the article shows the effect of the content of the refining mixture (90%N + 10%H_2) on porosity (qualitative and quantitative) and selected mechanical properties (R_m; $R_{0.2}$, A) of AlSi7Mg alloy, used for die-cast automotive rims. It was found that the use of this mixture during the refining of AlSi7Mg alloy in a ladle with a capacity of about 2.000 kg provides the best results in terms of reducing porosity and improving mechanical properties when its content does not exceed 19.25 $l \cdot min^{-1}$. (approximately 55 s. of introduction into the alloy). Exceeding these values causes both deterioration of porosity (qualitatively and quantitatively) and hardness, as well as selected mechanical properties. The research was conducted at Superior Industries Production Poland Stalowa Wola under industrial production conditions.

Keywords: pressure die-cast Al-Si alloys, refining, porosity, mechanical properties.

INTRODUCTION

Due to their comparatively good strength combined with low density and high conductivity, cast aluminum alloys are widely used in various industrial areas, including but not limited to automotive applications. The strength of aluminum alloys is highly dependent on various types of microstructure inhomogeneities resulting from the manufacturing process. According to technology and heat treatment, the microstructure can be significantly altered, mainly in terms of the morphology and size of the components, i.e.: dendrites of the solid solution α (Al), silicon crystals in the eutectic α(Al) + β(Si) and the form of intermetallic phases [1]. Technology also affects casting defects, mainly shrinkage and gas porosity [2; 3] – Figure 1. However, despite the presence of

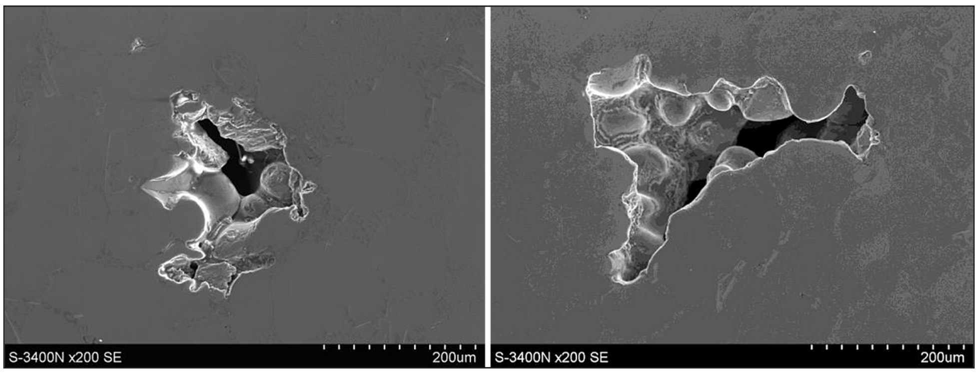

Figure 1. SEM microstructure of AlSi7Mg alloy showing shrinkage porosity

these defects, casting manufacturers must ensure the required quality level of their products. In the case of porosity, foundries establish control procedures through, for example, microstructure tests to detect defects and reject those products that contain pores, as a criterion for evaluating their quality and marketability.

This is because porosity negatively affects many performance properties, mainly mechanical strength and yield point of aluminum alloy castings [4]. An increase in porosity of about 1% results in a decrease in strength of R_m by approximately 40% [5]. It also negatively affects the castability of aluminum alloys [6; 7]. Porosity in castings is the result of two, coexisting processes i.e. [8; 9]:

- shrinkage during crystallization, which induces a vacuum of the liquid phase in the dendrite growth zone of the solid solution of α(Al) - Darcy's law) [10],
- segregation of gases in the liquid alloy, which occurs with varying intensity. Trace gaseous elements are less soluble in the solid phase, causing their microsegregation into the liquid phase. If the gas concentration reaches the solubility limit, which decreases with pressure and temperature, then micropores nucleate [11].

Gas porosity is the result of the solubility in the melt of gases, mainly hydrogen [12; 13] and oxygen [14], decreasing with decreasing temperature [15]. Once the solubility limit is exceeded, there is an intense release of gases, resulting in the formation of gas bubbles inside the casting. As the gas bubbles grow and flow to the surface of the melt, they increase the surface tension and develop the phase separation surface. In this way, some of the gas pores become trapped in the coagulated alloy[16]. This happens, for example, during die casting due to turbulent flow of the liquid alloy through the gating system and mold cavity, accompanied by turbulence and mixing of the liquid alloy streams [17; 18]. The main factors promoting the formation of porosity inaluminum alloys are [19]:

- the chemical composition of the alloy and the content of gaseous impurities, which are considered the substrate for the nucleation of gas bubbles. Literature data [20] shows that this process is similar to the nucleation of components of the structure of metal alloys,
- the rate of crystallization of the alloy [21],
- the production technology – gravity or pressure casting [22],
- temperature gradient [23].

Al-Si alloys with a sub-eutectic composition tend to be less porous (about 0.3 to 0.6% – measured by pore volume fraction) than those with a per-eutectic composition of about 2.5 to 4.8%. According to studies, this is related to the different range of crystallization ($T_{lik.} – T_{sol.}$) and chemical composition [1]. Frequently, however, this composition (type of alloy) is imposed by the customer so the contractor does not have the opportunity to change it. Then, there are other activities that have an impact on reducing the porosity of castings. The most important of these include:

- maintaining the correct values of the parameters for melting the charge or remelting the alloy,
- correct method of alloy modification and refining [24; 25],
- selection of casting parameters to reduce turbulent melt flow during filling of the casting mould cavity [26; 27].

The effect of modification on the porosity of Al-Si alloy castings varies and depends on many factors, such as: the technology used, the type and content of the modifier, the modification time, the temperature at which the modifier was introduced, etc [28]. In particular, care should be taken with the modifier content, as it was shown in a study [29] that increasing the modifier content increases porosity.

Refining is also crucial. Its effect on the porosity of Al-Si alloy castings is multifactorial and depends mainly on the type and content of the refiner, the time of refining, whether the refining is carried out in a furnace or in a ladle, the time from refining to casting, the refining method, etc. These procedures are individually applied by foundries and depend on production specifications and technical acceptance conditions that are approved by customers. Factors that also affect the porosity of castings are the process parameters of casting. However, they are determined by the given technology and adjusted by trial and error to the individual settings of the casting machine and the structural characteristics of the casting (wall thickness, dimensions, complexity of the product, its purpose, etc.). The general tendencies to reduce the porosity of pressure castings mainly concern such operations as:

- lower the pouring temperature and reduce the shrinkage,
- optimize the injection pressure and boost pressure to improve the compactness,
- modify the inner gate to make the pressure better, which is conducive to the feeding effect of liquid alloy,

- change the structure of the castings, eliminate the metal gathering parts, and make the wall thickness as uniform as possible,
- speed up the cooling of thick parts.

It follows from the above that, despite the numerous studies on ways to reduce porosity in Al-Si alloy castings (obtained by gravity and pressure), the development of casting design methods is still relevant, especially taking into account the main factors that affect the achievement of a structure free of casting defects.

PROBLEM STATEMENT

Inspection of the quality of aluminum alloys revealed an excessive proportion of defects, mainly porosity (gas and shrinkage porosity) in cast car rims (Fig. 2). For low-pressure cast products, porosity is the most common criterion for compliance with customer specifications, and therefore decisive for sales. The manufacturer, on the one hand, should minimize the defectiveness of the castings produced, (reduce the proportion of defective products), and on the other hand, due to corporate considerations, cannot directly interfere with the change of technology and type of casting alloy.

Such changes require each time the customer's approval and are associated with costly pre-production tests. This highlights those activities that improve the profitability of the manufacturer, are inexpensive, relatively easy to implement and do not require the consent of the customer. Such an activity is improving the parameters of the AlSi7Mg alloy refining process (for example mixture introduction time NH_2). These parameters can be easily changed by observing their effect on, among other things, the porosity and mechanical properties of automotive rim castings, the required values of which are presented in Table 1.

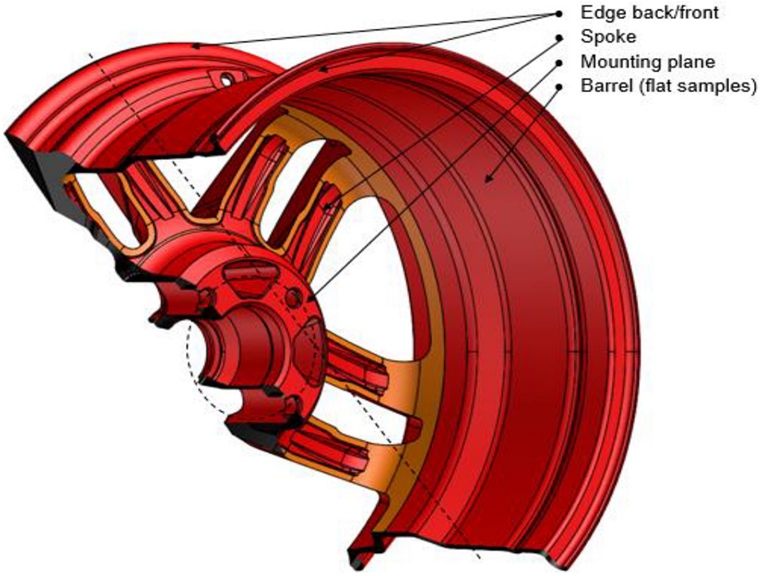

Figure 2. The most important parts of the rim

Table 1. Required mechanical properties of the various parts of the rim shown in Figure 2

Yield strength $R_{0.2}$, MPa	Tensile strength R_m, MPa	Elongation A, %	Brinell hardness HB
Spoke			
≥ 160	≥ 220	≥ 4	≥ 80
Mounting plane			
≥ 160	≥ 220	≥ 4	≥ 80
Edge back/front			
≥ 170	≥ 240	≥ 7	≥ 80
Barrel (flat samples)			
≥ 160	≥ 220	≥ 4	≥ 70

AlSi7Mg alloy is supplied in the form of metallurgical ingots. Deliveries are inspected for conformity of type and elemental content according to the supplier's certificate. At specified intervals, for a given type of alloy, a sample is taken for chemical composition analysis and verification with the supplier's certificate. If the chemical composition meets the requirements specified by the customer, the material is transferred to production, where it is melted in gas melting furnaces. After reaching a temperature of about740^{o}C, the alloy is transferred from the melting furnaces to a transport ladle (2.000 kg), where modification and refining are carried out. Refining is the disruption of the absorption equilibrium between the liquid metal and its impurities as a result of which they are separated from the metal. The refining of AlSi7Mg alloy was carried out using the barbotage method, which involves introducing an inert gas (nitrogen) into the liquid aluminum alloy using a lance (rotor). The first step in the refining process is to create a whirlpool to distribute the ecosaltevenly then we have a mixing process after which the rotating rotor introduces a stream of fine nitrogen bubbles into the metal bath, which absorb hydrogen throughout the metal. As a result, any impurities diffuse to the surface of the alloy in the form of dross, from where they are mechanically removed. The currently used AlSi7Mg alloy refining parameters and the process of removing melting dross from the transport ladle are shown in Figure 3.

It often happened that cast, with the refining parameters currently used (Fig.3a), car rims had porosity, mainly located at the ends of the spokes. Examples of such porosity in cast car rims are shown in Figure 4.

Pareto-Lorenz analysis shows that the number and size of casting defects detected during X-ray inspection of the rims is strongly influenced by the density of the AlSi7Mg alloy, which for the minimum proportion of casting defects ranges from 2.42 to 2.6 kg·dm^{-3}. It is a controlled parameter of the refining process (as opposed to, for example, air humidity)that determines the proportion of casting defects, including, in particular, the porosity of castings.

In connection with the above, it seems justified to conduct research on the AlSi7Mg alloy refining process in order to optimize those parameters that most significantly affect the share of gas porosity, defined as a criterion of the metallurgical quality of car wheel rim castings.

PURPOSE AND SCOPE OF THE STUDY

The purpose of the study was to identify and select those AlSi7Mg alloy refining parameters that most significantly reduce porosity and improve

a)

Refiningstages, unit	Value
Swirlformation, 15 l·min^{-1} N_2	30 s
Introducing ecosal*, 15 l·min^{-1} N_2	2400 g
Mixing alloy, 15 l·min^{-1} N_2	20 s
Introducing nitrogen (N_2).	345 s
Mixture introduction time NH_2, s (90%N/10%H_2)	43 s
Alloy stabilization, 15 l·min^{-1} N_2	12 s

* - ECOSAl-145GT ®

b)

Figure 3. Refining of AlSi7Mg alloy: a) current process parameters; b) removal of melting dross from ladle

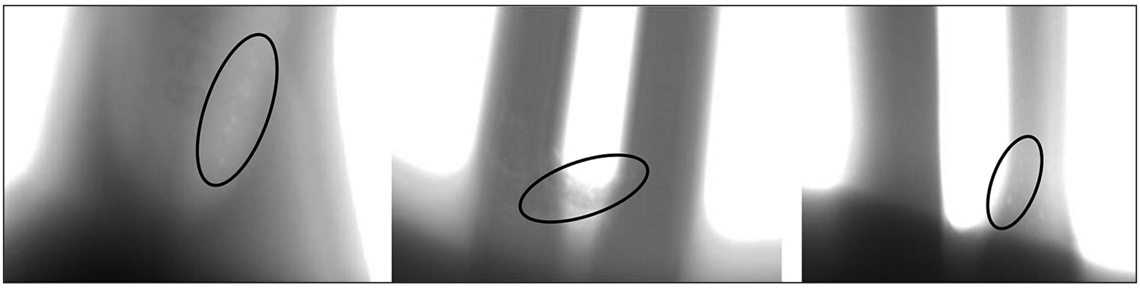

Figure 4. Porosity in car rim castings (x-ray image)

Brinell Hardness and the required mechanical properties (R_m; $R_{0.2}$; A). The results obtained were compared with those required (Table 1). It was characteristic that the study of the effect of changing the AlSi7Mg alloy refining parameters on selected resultant characteristics was carried out under industrial production conditions.The scope of the study included:

- making smelts of AlSi7Mg alloy at different refining parameters and casting samples,
- microstructure tests for the proportion of porosity in the castings,
- testing of hardness and required mechanical properties (R_m; $R_{0.2}$; A),
- analysis of results, summary and conclusion.

MATERIAL AND RESEARCH METHODOLOGY

The chemical composition of the AlSi7Mg alloy is shown in Table 2. It is a standard alloy for the manufacture of car rims.

Preliminary studies have shown that the refining parameter that most influences the change in density, and therefore microstructure, of the AlSi7Mg alloy is the amount of mixture NH_2(90%N + 10%H_2) introduced. Therefore, the study plan was to change the introduction time of the mixture NH_2 every 5 s – as presented in Table 3.

For the parameters specified in Table 3, samples were cast for metallographic, hardness and the required mechanical properties (R_m; $R_{0.2}$; A). Acquisition of images of the microstructure of the samples was performed on an Olympus GX-71 light microscope (Nanjing, China), in the bright field, at a total magnification of 50 times. The metallographic specimens, prepared based on the recommendations of the Büehler expert system, were polished, not etched. For quantitative evaluation of porosity, 15 images each were taken in random fields of view, giving a total analysis area of 70.5 mm^2. Porosity was measured using quantitative metallography methods with an ImageJ image analyzer [30].

HB hardness was measured in accordance with PN-EN ISO6506-1 on a Zwick ZHF hardness tester (Zwick Roell, Ulm, Austria)with a load of 187.5 kg with a 2.5 mm diameter steel ball and a measurement time of 35 s.

Mechanical properties (R_m; $R_{0.2}$; A) were read from a static tensile test at temperature of 20 °C according to DIN 50125:2022-08 Testing of metallic materials – Tensile test pieces (type H Tensile test pieces– Figure 5) on an Instron 3382 testing machine (University Ave, Norwood, Miami, USA) using a 20:1 ratio and a constant tensile speed of 4 $mm \cdot min^{-1}$. A total of 8 measurements each were taken, discarding the two outliers, and the arithmetic mean was calculated from the remaining measurements, rounding the result to the nearest whole number. The specimen was taken from the spoke from places precisely indicated on the mechanical drawing.

Table 2. Chemical composition of AlSi7Mg* alloy, in %mas

Range	Si	Fe	Cu	Mn	Mg	Zn	Ti	Ca	Sr	Other	
										Individually	Total
Min.	6.80	0.00	0.00	0.00	0.26	0.00	0.10	0.00	0.02	Individually	Total
Max.	7.40	0.13	0.01	0.03	0.32	0.03	0.15	0.002	0.03	0.03	0.10

Note: * Rest of aluminum.

Table 3. The time and quantity of NH_2 mixture during refining of AlSi7Mg alloy

Sample No.	Mixture introduction time NH_2, s	NH_2 in alloy AlSi7Mg*, $l \cdot min^{-1}$
1	30	10.50
2	35	12.25
3	40	14.00
**	45	15.75
4	50	17.50
5	55	19.25
6	60	21.00

Note: * The flow of NH_2 mixture through the rotor during refining is approximately 21 $l \cdot min^{-1}$, ** currently used parameters for the introduction of NH_2 mixture.

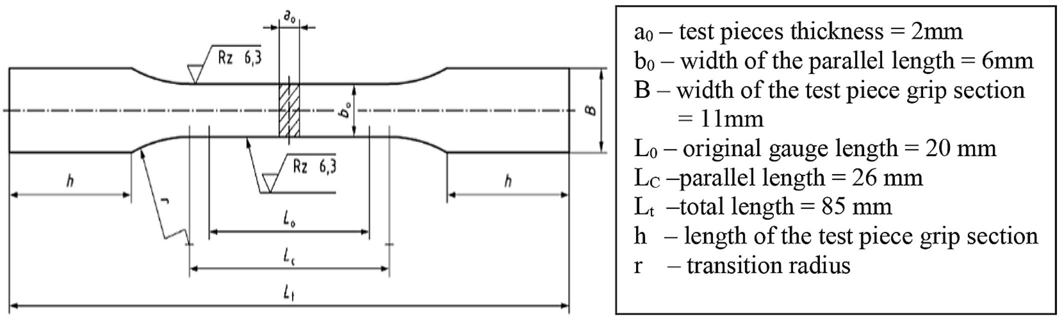

Figure 5. View of the sample for testing of mechanical properties and its dimensions

RESULTS AND ANALYSIS

The effect of different time and NH_2 mixture content (Table 4) on the microstructure in terms of porosity of AlSi7Mg alloy is shown in Figure 6.

From the analysis of the results of quantitative metallography parameters presented in Table 4, it can be seen that increasing the dosing time of the mixture NH_2 during the refining of AlSi7Mg alloy to about 50–55 s results in a reduction in the proportion of porosity. The number of pores, as measured by the volume proportion of pores for the samples tested, ranges from 0.002 to 0.132%. The number of pores per 1 mm^2 is from approximately 0.04 to 0.26 mm^{-2}, and the average diameter of the flat pore cross-section ranges from about 30 to 54 µm. After exceeding the value of about 55 s of mixture dosage of NH_2, the trend begins to reverse and the porosity (in terms of quantity and quality) increases. Taking into account the above, it should be concluded that during the refining of about 2000 kg of AlSi7Mg alloy, the dosing time of NH_2 should not be exceeded over 55s. Exceeding this value can increase porosity and thus the proportion of casting defects in finished products. This is likely due to the increasing proportion of hydrogen in the alloy (10%H_2), which causes a decrease in melt density [15]. This is consistent with studies [12; 13], but confirmation of this assumption requires further research.

In addition to porosity, as a key quality criterion for accepting a product for sale, another is hardness and mechanical properties (R_m; $R_{0.2}$; A). Therefore, further research was conducted on the effect of the content of the mixture NH_2 on these strength characteristics read from the static tensile test. Effect of different time and NH_2 mixture content (Table 3) on hardness and selected mechanical properties of AlSi7Mg alloy is shown in Figure 7. The tests shown in Figure 7 demonstrate that both the hardness and mechanical properties

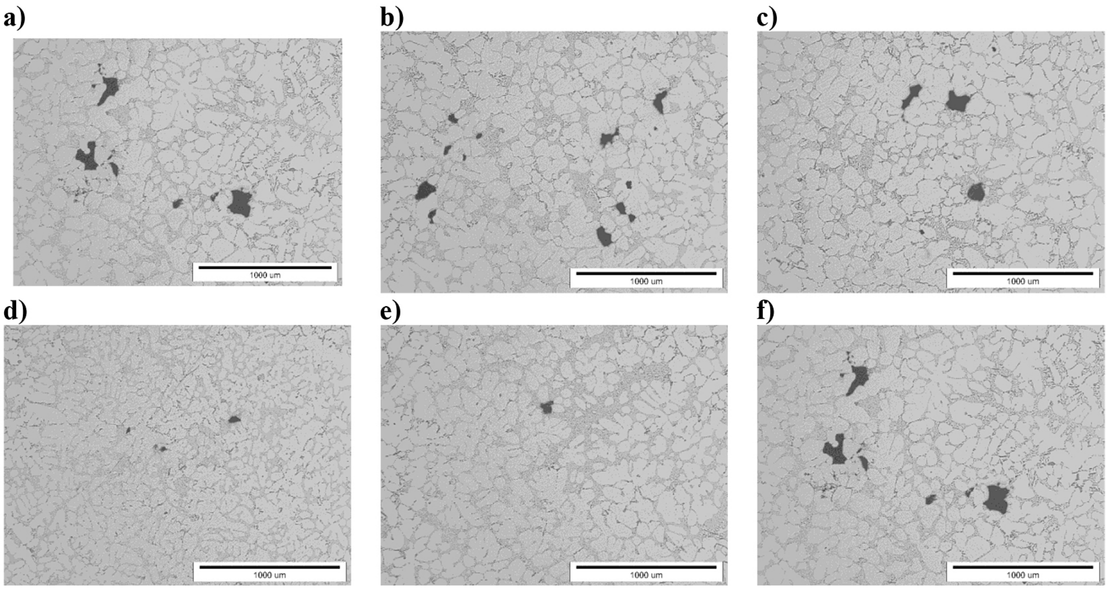

Figure 6. Microstructure of AlSi7Mg alloy after the time of mixture dosing of NH_2: (a) 30 s (sample 1); (b) 35 s (sample 2); (c) 40s (sample 3); (d) 50 s (sample 4); (e) 55 s (sample 5); (f) 60 s (sample 6)

Table 4. Results of measurements of quantitative metallography parameters of AlSi7Mg alloy porosity

No. of sample	Dosing time of NH_2, s	Number of pores		Size of pores	
		Volume proportion of pores, V_V, %	Number of pores per 1 mm², NA, mm^{-2}	Average surface area of a flat pore cross-section A, μm²	The average Feret diameter of the flat pore cross-section D, μm
1	30	1.000	2.77	3630	63
2	35	0.920	2.91	3162	58
3	40	0.612	4.14	1476	49
**	45	3.160	1.96	16123	95
4	50	0.132	0.26	2378	54
5	55	0.002	0.04	466	30
6	60	0.873	3.02	2648	53

Note: ** The same as in Table 3.

(R_m; $R_{0.2}$; A) evolve in a similar manner. The highest results are observed for samples 4 and 5 (with NH_2 mixture dosing times of 50 to 55 s). This is a content of about 17.5 to 19.25 l·min^{-1}. It is worth noting that the time of dosing the mixture NH_2 during the refining of AlSi7Mg alloy from 50 to 55 s results in:

- brinell hardness of about 86 HB (an increase of approximately 7.5% compared to the required level of 80 HB),
- elongation of the sample after break A about 7% (ensuring the required level),
- tensile strength R_m approximately 258 to 260 MPa (an increase of about 8% compared to the required level of 240 MPa),
- yield strength $R_{0.2}$ approximately 180 to 182 MPa (an increase of about 6% over the required level of 170 MPa).

After the dosing time of the NH_2 mixture is exceeded, the hardness and mechanical properties (R_m; $R_{0.2}$; A) decrease. It is also worth noting that the results of hardness and mechanical properties coincide with the results of porosity (Table 4).

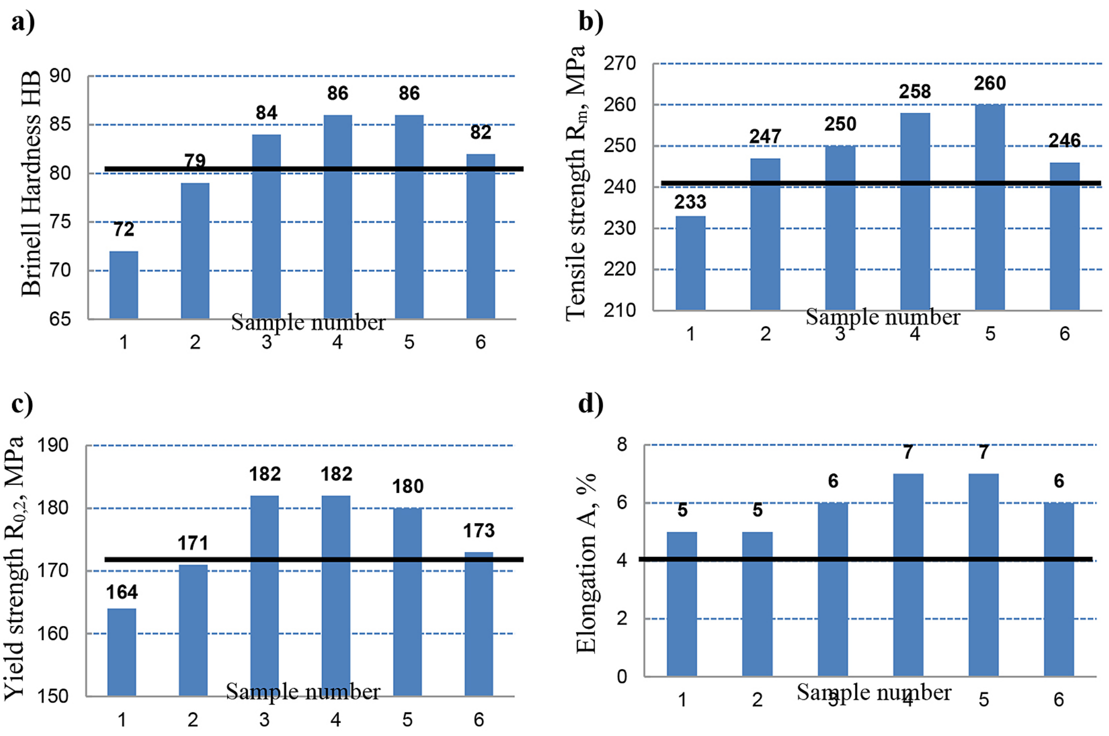

Figure 7. Effect of NH_2 mixture dosing time on: a) HB hardness; b) tensile strength R_m; c) yield strength $R_{0.2}$; d) elongation of the sample after break A (the solid line indicates the minimum values of the tested strength characteristic – Table 1)

CONCLUSIONS

Refining is an important step in the metallurgical processing of cast aluminum alloys. Depending on the type of alloy and the impurities present in it, this process can be carried out in various ways. The most common method is mechanical refining (known as barbotage), which involves the introduction of an inert gas (nitrogen or argon) into the liquid alloy.

Although a lot of research has already been carried out on the effect of the refining process on selected material characteristics of aluminum alloys, the issue is still relevant. This is mainly due to the fact that the various stages of the technology of melting and casting aluminum alloys are changing, (mainly under pressure), and especially the requirements for metallurgical purity of castings as measured, for example, by the permissible proportion of porosity.

The literature also reports a number of studies on the influence of microstructure on certain mechanical properties of aluminum alloys. However, there is still no clear answer to the question of whether the phase composition, stoichiometry and morphology of structural components, or the contribution of gaseous impurities, eliminated by refining, are more significant in shaping certain mechanical properties of aluminum alloys.

Regardless of whether or not views in this area diverge, refining remains one of the main stages of liquid alloy preparation. However, it is often considered as a single process, although the present study showed otherwise.

Out of the barbotage refining stage, the density value of the AlSi7Mg alloy is influenced, among others by the amount and time of introduction of NH_2 (90%N + 10%H_2). Accordingly, the effect of changing the time (the amount of NH_2 mixture) on the porosity and mechanical properties of AlSi7Mg alloy used for car rim castings was studied. It was found that the use of this mixture during the refining of AlSi7Mg alloy in a ladle with a capacity of about 2.000 kg provides the best results in terms of reducing porosity and improving mechanical properties when its content does not exceed 19.25 $l \cdot min^{-1}$ (approximately 55 s. of introduction into the alloy). Exceeding these values causes both deterioration of porosity (qualitatively and quantitatively), as well as selected mechanical properties: R_m; $R_{0.2}$; A.

It was found that the time of introducing theNH_2 mixture has a significant effect on the metallurgical purity of the tested alloy, and its amount must be closely matched to the capacity of the ladle in which the refining process takes place.In industrial production conditions, regulating the refining time (even every few seconds) is possible, especially when the manufacturer has a modern refining device.

Based on the research, the following final conclusions were made:

- The activity that influences the density, and therefore the proportion of porosity of castings is the amount of NH_2 introduced into the AlSi7Mg alloy during refining.
- Extending the time of introduction the mixture (90%N + 10%H_2), thereby increasing its content above 19.25 $l \cdot min^{-1}$ during the refining process, causes a decrease in the density of the AlSi7Mg alloy, and thus an increase in the porosity of castings made from it.
- The lowest porosity and the best mechanical properties (R_m; $R_{0.2}$; A) are obtained when dosing the mixture NH_2 during up to about 55 s. After that, there is a deterioration of the studied resultant characteristics of the AlSi7Mg alloy.
- By varying the dosing time of the NH_2 mixture during the refining process of AlSi7Mg alloy, a directly proportional relationship between the proportion of porosity and selected mechanical properties (R_m; $R_{0.2}$; A) was demonstrated.

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