

Effect of refining time on porosity and mechanical properties of low-pressure casting made of AlSi7Mg alloy

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Abstract: The study determines the effect of gas-bubbling refining time on porosity and mechanical properties of low-pressure AlSi7Mg alloy castings under industrial conditions. Refining was performed with an NH_2 mixture (90% N + 10% H_2) for 5.0–9.0 min. Porosity, density index, HB hardness, tensile strength R_m , 0.2% proof stress $R_{p0.2}$ and elongation A were evaluated. The optimum refining time was 7 min, giving minimum porosity and mechanical properties meeting customer requirements. Longer refining increased porosity and reduced selected mechanical properties.

KEYWORDS: ALUMINIUM ALLOYS, POROSITY, LOW-PRESSURE CASTING, MECHANICAL PROPERTIES.

1. Introduction

The mechanical properties of aluminium alloys depend, among other factors, on structural heterogeneity resulting from the manufacturing process. The course of this process affects the morphology and size of constituents such as $\alpha(Al)$ solid-solution dendrites, silicon crystals in the $\alpha(Al)+\beta(Si)$ eutectic, and intermetallic phases such as Mg_2Si . Individual production stages also influence casting defects, including shrinkage and gas porosity [1–4]. This is particularly important because, in many foundries, porosity is a major product-quality criterion that must meet customer requirements. This is because porosity adversely affects many service properties, especially the strength and ductility of castings.

The porosity of aluminium-alloy castings is affected by numerous technological, material and process-related factors. The most important include [5–10]:

1. hydrogen content – an excessive amount of hydrogen dissolved in liquid aluminium leads to gas porosity. During solidification, hydrogen is released in the form of gas bubbles,
2. hydrogen sources – e.g. moisture in the furnace atmosphere, wet tools and alloy contamination,
3. presence of oxides and inclusions – Al_2O_3 particles and other contaminants may initiate pore formation. Inclusions disturb solidification and facilitate hydrogen entrapment,
4. refining process – improper refining fails to remove hydrogen and oxides. A process that is too short or too intensive may be ineffective or even detrimental,
5. chemical composition of the alloy – some alloying additions increase susceptibility to porosity; for example, a high magnesium content increases the tendency towards oxidation and hydrogen absorption.

It follows from the above that most factors affecting porosity are related to the refining process; therefore, investigations were undertaken in this area.

2. Prerequisites and means for solving the problem

As already mentioned, for manufacturers of many cast products, porosity is the most common criterion for compliance with customer specifications and therefore determines whether a product can be sold. On the one hand, foundries should reduce the defect rate; on the other hand, because of corporate constraints, they cannot directly modify the technology or the type of casting alloy. Such changes require customer approval each time and involve costly pre-production tests. Therefore, solutions that improve profitability, are inexpensive, easy to implement and do not require customer approval are preferred. One such measure is optimisation of the AlSi7Mg alloy refining parameters towards reducing the process duration, since the customer also specifies the type of refining.

3. Solution of the examined problem

The aim of the study was to determine the shortest possible refining time for the AlSi7Mg alloy. The porosity fraction and mechanical properties were adopted as evaluation criteria.

Importantly, the effect of changes in refining time on selected output characteristics was investigated under industrial conditions. The scope of the study included:

1. gas-bubbling refining at different times followed by casting of test specimens,
2. microstructural examination with respect to porosity fraction,
3. measurement of the density index,
4. HB hardness and mechanical-property testing (R_m , $R_{p0.2}$, A).

3.1. Material and research methodology

AlSi7Mg alloy (chemical composition according to EN 1706:2020) was selected for the investigations. It is a standard alloy used for the production of automotive wheels by low-pressure casting (approximately 0.2 MPa, i.e. 2 bar). Refining tests, according to the experimental plan shown in Fig. 1, were carried out in a holding ladle with a capacity of 1.8 Mg (1.6 Mg of liquid metal). An NH_2 mixture (90% N + 10% H_2) was used for refining at a flow rate of approximately $18.5\text{--}19.5\text{ L}\cdot\text{min}^{-1}$. After refining, samples were taken from the central part of the ladle for metallographic examination, density-index measurement and mechanical-property testing. The previously used refining time was 9 min.

Microstructural images of the samples were acquired using an Olympus GX-51 optical microscope in bright-field mode at $50\times$ magnification. Metallographic specimens prepared according to the recommendations of the Buehler expert system were polished and not etched. For quantitative assessment of porosity, 15 images were acquired in randomly selected fields of view, giving a total analysed area of approximately 70.5 mm^2 . Image binarisation was performed using Otsu's method. Porosity was measured by quantitative metallography using ImageJ image-analysis software. The number and size of pores were determined. The density index was measured hydrostatically (Archimedes' principle) using a laboratory balance by weighing the specimen in air and in distilled water.

HB hardness was measured in accordance with PN-EN ISO 6506-1 using a Zwick ZHF hardness tester under a load of 187.5 kg, with a 2.5 mm diameter steel ball and a test duration of 35 s.

Mechanical properties were determined from a static tensile test at 20°C in accordance with PN-EN ISO 6892-1 using an Instron 3382 testing machine, with a 20:1 ratio and a constant crosshead speed of $4\text{ mm}\cdot\text{min}^{-1}$. Eight measurements were performed; the two extreme values were rejected, and the arithmetic mean of the remaining results was calculated and rounded to the nearest integer. The results obtained were compared with the customer requirements.

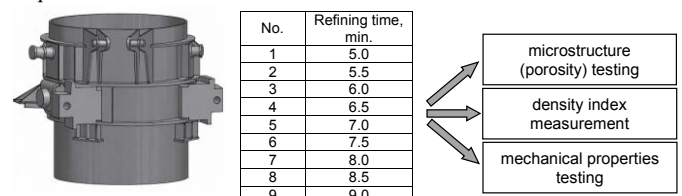


Fig. 1. Test stand and experimental scheme.

4. Results and discussion

4.1. Effect of refining time on porosity and density index of the AlSi7Mg alloy

Microstructural examination showed that samples 1, 6, 7, 8 and 9 were characterised by a high porosity fraction and are therefore not shown. The effect of different refining times on the AlSi7Mg microstructure with respect to porosity for the remaining samples is presented in Fig. 2. Selected quantitative metallography measurements of porosity parameters are shown in Table 1.

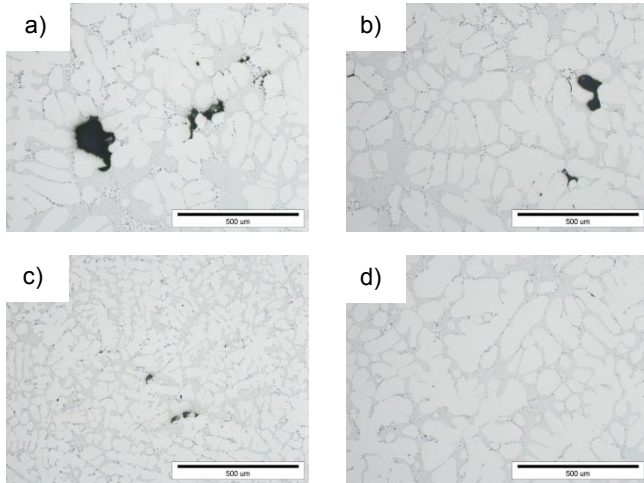


Fig. 2. Microstructure of the AlSi7Mg alloy after different refining times: (a) 5.5 min (sample 2); (b) 6.0 min (sample 3); (c) 6.5 min (sample 4); (d) 7.0 min (sample 5).

Table 1. Results of quantitative metallographic measurements of porosity parameters in the AlSi7Mg alloy.

Sample No.	NH ₂ mixture refining time, min.	Number of pores		Pore size	
		Volume fraction of pores, VV, %	Number of pores per 1 mm ² , NA, mm ⁻²	Mean area of planar pore cross-section A, μm ²	Mean Feret diameter of planar pore cross-section D, μm
1	5.0	1.230	4.97	3630	73
2	5.5	0.910	2.91	3162	52
3	6.0	0.512	2.14	1476	48
4	6.5	0.132	0.26	2378	42
5	7.0	0.002	0.04	466	30
6	7.5	0.873	1.02	2648	53
7	8.0	2.112	2.89	7681	71
8	8.5	3.160	2.96	11123	95
9	9.0	5.478	4.16	16433	110

Analysis of the quantitative metallography results presented in Table 1 shows that reducing the NH₂-mixture dosing time during refining of the AlSi7Mg alloy to approximately 7 min decreases the porosity fraction. For sample No. 5, the volumetric fraction of pores falls within the range of 0.002–0.132%. The number of pores per 1 mm² ranges from approximately 0.04 to 0.26 mm⁻², while the mean diameter of the planar pore cross-section is approximately 30–35 μm. When the refining time exceeds 7 min, the trend begins to reverse and porosity increases, both quantitatively and qualitatively. Taking the above into account, it can be concluded that refining approximately 1.6 Mg of AlSi7Mg alloy should last 7 min. Exceeding this value may increase porosity and consequently the proportion of casting defects in finished products. This is probably caused by the increasing hydrogen content in the alloy (10% H₂), which reduces alloy density [11]. This is consistent with the results reported in [12–14]; however, confirmation of this assumption requires additional investigations.

The results of the density-index measurements for the AlSi7Mg alloy are presented in Fig. 3.

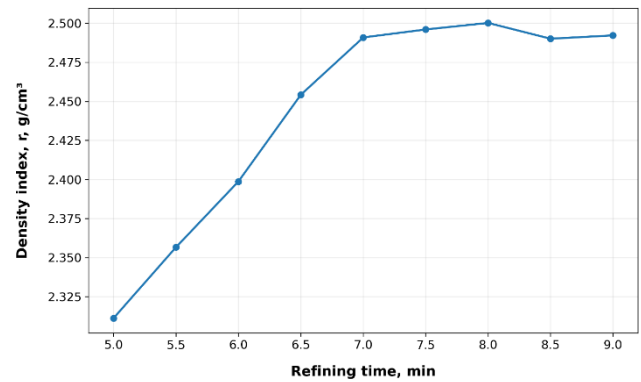


Fig. 3. Density index (ρ) of the AlSi7Mg alloy as a function of refining time.

In addition to porosity and density index, which are key quality criteria determining whether a product is approved for sale, hardness and mechanical properties (R_m , $R_{p0.2}$, A) are also important. Therefore, further investigations focused on the effect of NH₂-mixture dosing time on strength characteristics determined from the static tensile test.

4.2. Effect of refining time on the mechanical properties of the AlSi7Mg alloy

The effect of refining time with the NH₂ mixture on hardness and selected mechanical properties of the AlSi7Mg alloy is presented in Fig. 4.

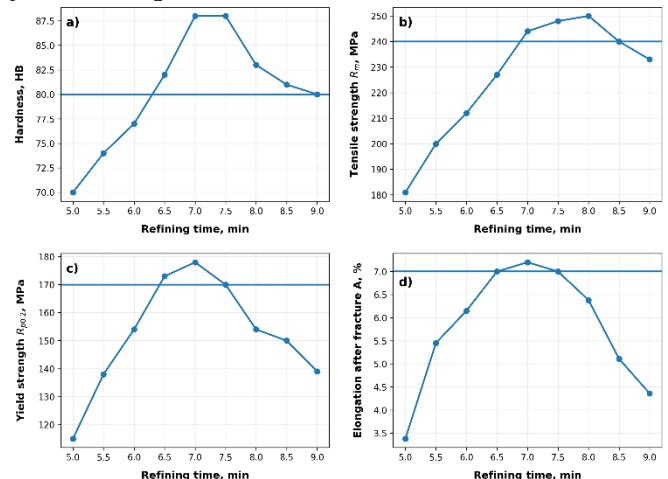


Fig. 4. Effect of NH₂-mixture refining time on: (a) HB hardness; (b) tensile strength R_m ; (c) 0.2% proof stress $R_{p0.2}$; (d) elongation after fracture A (the solid line indicates the minimum strength-property values specified by the customer).

The results presented in Fig. 4 show that both hardness and the mechanical properties (R_m , $R_{p0.2}$, A) change in a similar manner. The highest values are observed for samples No. 5 and 6 (NH₂-mixture dosing time of 7–7.5 min). It is worth noting that this refining time results in:

- hardness of approximately 88 HB (minimum required level: 80 HB),
- tensile strength R_m of 244–250 MPa (required level: 240 MPa),
- 0.2% proof stress $R_{p0.2}$ of approximately 178 MPa (required level: 170 MPa),
- elongation after fracture A of approximately 7% (meeting the required level).

At shorter refining times, or when the NH₂-mixture dosing time exceeds 7 min, hardness and mechanical properties decrease. It should also be noted that the hardness and mechanical-property results are consistent with the porosity results (Table 1) and the density index (Fig. 3).

5. Conclusion

Although many studies have already been conducted on the effect of refining on selected mechanical properties of aluminium alloys, the subject remains relevant. This is mainly because individual stages of aluminium-alloy melting and casting technologies, particularly pressure casting processes, continue to change, as do the requirements concerning the metallurgical cleanliness of castings, measured for example by the permissible porosity fraction.

The literature also reports numerous studies on the effect of microstructure on specific mechanical properties of aluminium alloys [11]. However, there is still no unequivocal answer as to whether the phase composition, stoichiometry and morphology of structural constituents, or the fraction of gaseous impurities removed by refining, plays the more significant role in determining specific mechanical properties of aluminium alloys.

Regardless of whether views on this issue differ [10–14], refining remains one of the main stages in preparing liquid alloy both for pressure casting and for gravity casting of other non-ferrous metal alloys [15].

Among the parameters of gas-bubbling refining, the density of the AlSi7Mg alloy is influenced mainly by the duration of introduction of the NH_2 mixture (90% N + 10% H_2). Therefore, the effect of refining time on porosity and mechanical properties was investigated for AlSi7Mg alloy used for automotive-wheel castings. It was found that the optimum refining time for AlSi7Mg alloy in a ladle with a capacity of approximately 1.8 Mg (1.6 Mg of liquid metal), with respect to limiting porosity and maintaining mechanical properties, is 7 min. Exceeding this value results in deterioration of porosity, both qualitatively and quantitatively, as well as hardness and selected mechanical properties (R_m , $R_{p0.2}$, A).

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6. References

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