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Relation between Porosity and Mechanical Properties of Al-Si Alloys Produced by Low-Pressure Casting

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Abstract

The aim of the research was to evaluate influence of porosity size on mechanical properties of AlSi7Mg0.3 (EN AC 42 100) alloy before and after thermal treatment. The castings from the same production type (forms used for tires production) were used for the analysis. They were casted using low-pressure casting technology. Since the negative influence of porosity on mechanical properties of Al alloys is generally known that there is no quantitative assessment. The relation of porosity size in the structure of AlSi7Mg0.3 alloy and its mechanical properties is verified and quantified in this research. Static tensile testing has proven the relation between porosity size in a structure of an Al material and its mechanical properties. The image analysis was applied in quantitative measurement of the porosity. The measurement was performed on prepared metallographic specimens. Porosity size is considered as a fraction of pore area to the total area of the analyzed specimen and is taken in percentage. As far as the theoretical part of the issue the possible causes of porosity formation and its influence on particular Al alloy types are described [1, 2, 3].

Keywords: Mechanical Properties, Castings Defects, Porosity, AlSi7Mg0.3 alloy, Intermetallic Phases.

1. Theoretical Aspects of the Issue

Main reasons for existence of porosity and cavities in casts are volume changes during solidification process and cooling of casts and amount of gases in molten metal and alloy or their combination. It is well known that hydrogen mostly participates on higher amount of gases in metals and alloys. The small radius of its atom facilitates its motion by diffusion in a lattice of solid metals and alloys and positioning in inter atomic spaces of crystalline metals and alloys [4, 5, 6, 7, 8]. The main source of atomic hydrogen is humidity and hydrocarbons present in atmosphere of melting devices [9]. Humid batch, rest of lubricants, wood in a batch, covering layer of salts, modification products, fuel etc. may supply humidity in a form of free and bound water. Basic chemical equation describing the creation of hydrogen is presented in the form:

$$2\,Al + 3\,H_2O = Al_2O_3 + 3\,H_2 \quad (6\,H^{1+}) \qquad (1)$$

Strong overheating of a melt at high temperatures can make worse density index, cause excessive generation of oxides and increase grain size in casted shapes. It can be noted that the range of casting temperatures is chosen from 50 to 100 °C above the melting temperature of pure metal or in the same range above the temperature of liquid of the casted alloy. The following general relation holds – every 10 °C above the melting temperature represent approx. 0.1 % increase of gassing as it is presented in literature [10, 11, 12].

The porosity of material significantly negatively influences mechanical properties (strength, material fatigue) of casted Al alloys as it is presented in literature [13, 14]. It can be inter-dendritic porosity and porosity due to a gassing with hydrogen. Despite of the origin, porosity significantly decreases mechanical properties of aluminum and its alloys (see Fig. 1). Fig. 1 shows that 3 % of porosity in AlSi5 alloy decreases its tensile strength from 225 MPa to approx. 150 MPa (i.e. decrease of 40 %).

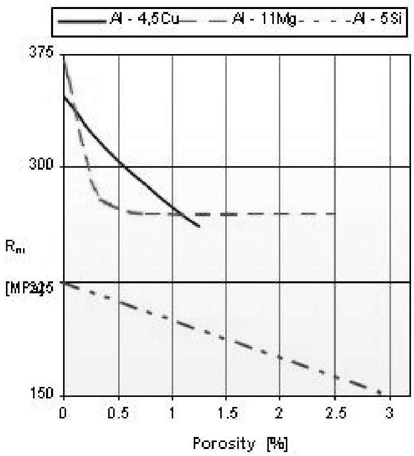

Fig. 1. Dependence of tensile strength on porosity

2. The preparation of the casts

Approx. 530 kg of pure batch of alloyed AlSi7Mg0.3 alloy was prepared in a form of ingots. The melt was after melting and alloying in a furnace for 5 hours. Further, the melt was refined by refining salt in amount of 0.6 kg. Degassing was performed in FDU equipment using argon. Next, modification using AlSr10 in amount of 0.9 kg followed. Casts were produced by low-pressure casting using cast iron riser pipe covered by Vuktop coating. The weight of casts reached 42 kg and casting time was 24 minutes.

Chemical composition (see Tab. 1) shows higher amount of iron due to partial dissolution of the filling pipe during casting. Amount of main alloying elements present in the final alloy corresponds to the alloy EN AC 42 100 with respect to the norm ČSN EN 1706. Amount of used modifier in a form of strontium perfectly fits in the optimal range 0.03 – 0.05 % as recommended in literature.

3. Quantitatively Measured Values of Porosity

Four representative specimens with different porosity were chosen from particular casts based on the presence of a macro-porosity. The specimen marked P1 showed the highest porosity while the specimen P4 the lowest one. Metallographic specimens used for quantitative measurements of porosity and specimens used for mechanical testing were prepared from specimens P1 – P4. Five measurements of porosity size were performed for each specimen P1 – P4. The porosity was measured at different areas using laser optic microscope Olympus LEXT OLS 3100 and image analysis methods (measurement percent of image area).

3.1. Porosity of the specimen P1

The specimen P1 showed the highest porosity of material among all specimens. Bigger pores seen by eyes only appeared in some areas of the specimen P1. Areas with biggest pores are presented in Fig. 2 and Fig. 3 (porosity 4.465 % of the image area).

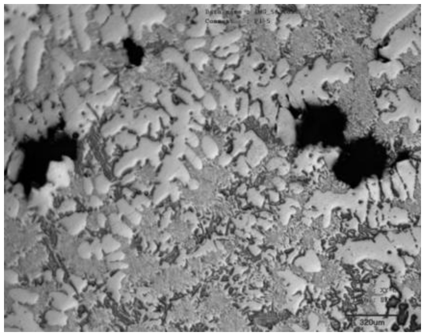

Fig. 2. Microstructure with porosity of the specimen P1

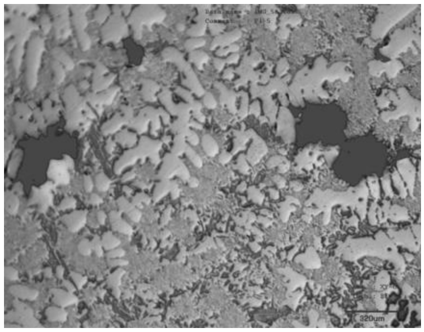

Fig. 3. Microstructure of the specimen P1 with highlighted porosity, used for quantitative measurement by image analysis methods

Table 1.
Chemical composition of AlSi7Mg0,3 alloy

Element	Si	Fe	Cu	Mn	Mg	Ni	Ti	Sr	Al
Amount [wt. %]	7.57	0.477	0.055	0.388	0.352	0.056	0.109	0.032	90.94

Tab. 2 presents measured values of porosity of the specimen P1, which was prepared from the most porous part of the cast of AlSi7Mg0.3 alloy (average value porosity 2.368 % of the image area).

Table 2.
Porosity measurement for the specimen P1 cast from AlSi7Mg0.3 alloy

Specimen	# Measurement	Value [% of image area]	Average value [% of image area]
P1	1	0.851	2.368
	2	0.930	
	3	1.904	
	4	3.691	
	5	4.465	

3.2. Porosity of the specimen P2

Microstructure of the specimen P2 with the worst measured porosity (porosity 2.119 % of the image area) is seen on Fig. 4 and Fig. 5. Compared to microstructure images of the specimen P1, difference in size and shape of dendritic cells and excluded intermetallic phases is apparent. Size of dendritic cells is in tens of micrometers and their shape is elongated (in a direction of more intensive heat transfer out from the cast). Values of measured porosity of the specimen P2 are presented in Tab. 2 (average value porosity 1.507 % of the image area).

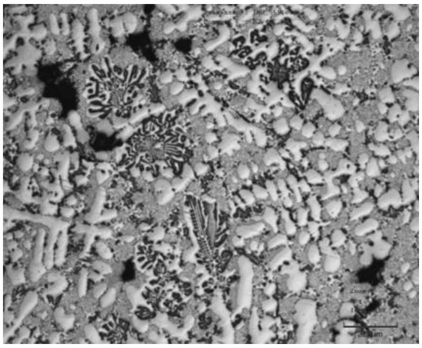

Fig. 4. Microstructure with porosity of the specimen P2

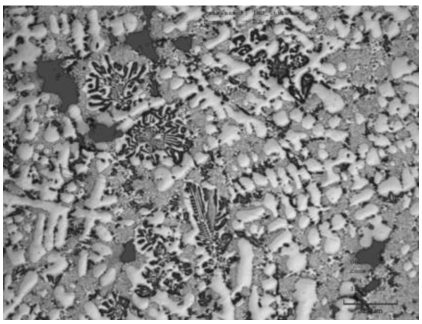

Fig. 5. Microstructure of the specimen P2 with highlighted porosity, used for quantitative measurement by image analysis methods

Table 3.
Porosity measurement for the specimen P2 cast from AlSi7Mg0,3 alloy

Specimen	# Measurement	Value [% of image area]	Average value [% of image area]
P2	1	0.776	1.507
	2	1.043	
	3	1.673	
	4	2.119	
	5	1.924	

3.3. Porosity of the specimen P3

Fig. 6 presents microstructure of the specimen P3 and Fig. 7 shows highlighted porosity used for image analysis (porosity 0.879 % of the image area). Measured values of the porosity of the specimen P3 are presented in Tab. 4 (average value porosity 0.707 % of the image area). As for the specimen P2, apparently oriented dendritic cells are seen on microstructure of the specimen P3. The primary axis of dendrites is significantly elongated along one axis due to intensive heat transfer in one direction. Size of dendritic cells as well as intermetallic phases is significantly smaller compared to the specimen P1.

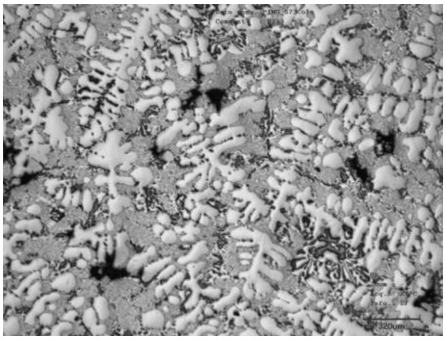

Fig. 6. Microstructure with porosity of the specimen P3

Fig. 7. Microstructure of the specimen P3 with highlighted porosity, used for quantitative measurement by image analysis methods

Table 4.
Porosity measurement for the specimen P3 cast from AlSi7Mg0,3 alloy

Specimen	# Measurement	Value [% of image area]	Average value [% of image area]
P3	1	0.483	0.707
	2	0.851	
	3	0.925	
	4	0.879	
	5	0.399	

3.4. Porosity of the specimen P4

The specimen P4 was prepared from the part of the cast with the smallest visible porosity. Microscopic analysis confirmed that among all measured specimens, the specimen P4 has the smallest measured porosity size. Values of the porosity of the specimen P4 are presented in Tab. 5 (average value porosity 0.125 % of the image area). The most significant identical directional orientation of dendritic cells caused by intensive heat transfer in one direction in this part of the form is seen on microstructure of the specimen P4 (see Fig. 8, porosity 0.079 % of the image area – lowest measured value). In literature, these grains are described as feathernar or columnar.

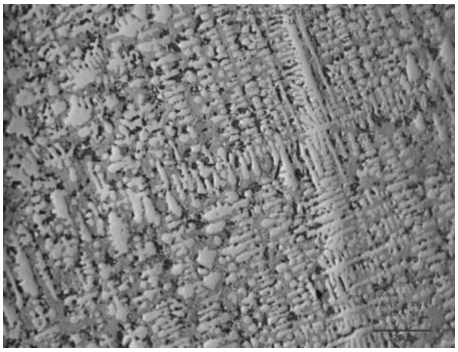

Fig. 8. Microstructure with porosity of the specimen P4

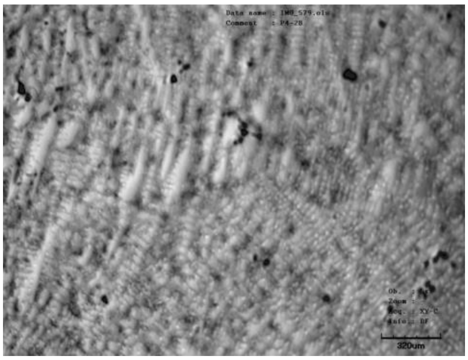

Fig. 9. Microstructure of the specimen P4 with highlighted porosity, used for quantitative measurement by image analysis methods

Fig. 9 shows the most porous measured area of the specimen P4. Due to small dimensions of excluded intermetallic phases and their dispersal in the structure the image had to be put out of focus for the porosity identification (see Fig. 9). Porosity measurement was performed using this defocused image. Fig. 9 shows the area of the specimen with the highest value of measured porosity – 0.225 % of the image area.

Table 5.
Porosity measurement for the specimen P4 cast from AlSi7Mg0,3 alloy

Specimen	# Measurement	Value [% of image area]	Average value [% of image area]
P4	1	0.079	0.125
	2	0.225	
	3	0.051	
	4	0.144	
	5	0.128	

4. Thermal Treatment and Mechanical Testing

The thermal treatment involves homogenization (heating up to appropriate dissolution temperature, stay at this temperature and following cooling at overcritical speed by immersing into water) and following artificial aging (hardening). Resistance furnace LAC Microtherm 825 was used for heating and the stay at the required temperature. Following cooling of specimens was performed by immersing of the specimens into water at the temperature 60 °C and keeping them immersed for 5 minutes.

Table 6.
Thermal treatment parameters

Heating at temperature [°C]	Stay at temperature for [min]	Temperature in a lab. furnace [°C]	Stay at temperature in a lab. furnace for [min]
520	45 *	170	240*
* time period for specimens with their width 10 - 12 mm			

Relation between tensile strength and porosity is presented in Figs. 10 – 11. Fig. 10 concerns the specimens with no thermal treatment, while Fig. 11 the specimens with thermal treatment. The x-axis shows values of the measured porosity (using microscopic analysis) in % of the image area. The y-axis shows values of the yield strength. The related porosity and yield strength correspond to specimens prepared from the same part of the cast studied (specimens P1 – P4). There is apparent strong dependence of the yield strength and porosity size in the figures. The decrease of the yield strength about 20 – 30 % can be seen for the increase of the porosity size from 0.125 % to 1.5 – 2.4 %.

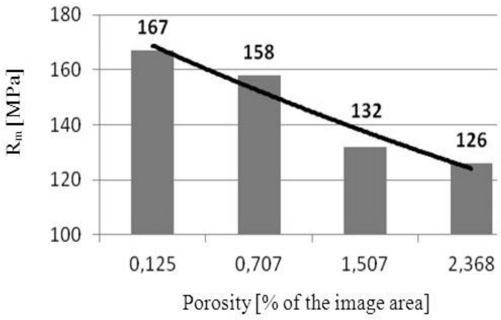

Fig. 10. Dependence of the tensile strength on the porosity, AlSi7Mg0.3 alloy, without thermal treatment

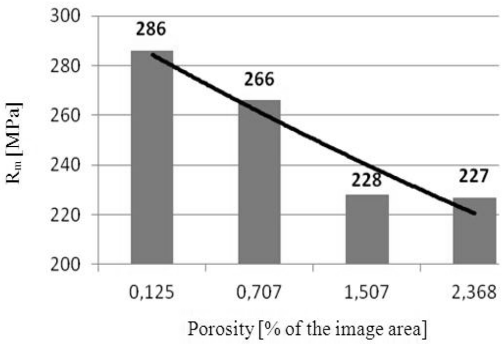

Fig. 11. Dependence of the tensile strength on the porosity, AlSi7Mg0.3 alloy, after thermal treatment

Table 7.
Average values (from 3 testing rods) measured using static tensile test for specimens cast from AlSi7Mg0,3 alloy

Specimen	R_m [MPa]	Ø R_m [MPa]	A [%]	Ø A [%]	Thermal treatment
1	126	146	4,9	5,9	No
2	132		5,2		
3	158		6,3		
4	167		7,0		
1	227	252	5,4	5,7	Yes
2	228		5,4		
3	266		5,9		
4	286		6,2		

5. Conclusion

Quantitative measurement of porosity size was performed for specimens prepared from the alloy AlSi7Mg0.3 and having changing visible porosity. Image analysis methods were used for the quantitative measurement. Porosity size is considered as the rate of the area of pores to the total area of the analyzed image of the structure. Five measurements were performed at different areas of each specimen. Further, the average value was calculated. The range of the measured porosity is wide, starting at 0.125 % and reaching 2.368 %.

Following static tensile testing proved the relation between the inter-dendritic porosity size in the structure of the material and its mechanical properties. Measured values of yield strength of the material of the alloy AlSi7Mg0.3 considering both specimens without and with thermal treatment (hardening) show strong dependence of the yield strength on the porosity size of the material. The decrease of the tensile strength about 20 – 30 % can be seen for the increase of the porosity size from 0.125 % to 1.5 – 2.4 %. It can be concluded that the influence of porosity size on mechanical properties is insignificant when porosity size is below 0.5 %. Porosity size above 1 % already significantly influences mechanical properties.

Based on the static tensile testing performed for the alloy AlSi7Mg0.3, significant positive effect of thermal treatment on increase of yield strength can be confirmed. The yield strength was increased about 70 % from 146 MPa to 252MPa.

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