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THE INFLUENCE OF COOLING RATE AND HEAT TREATMENT ON MICROSTRUCTURE AND MECHANICAL PROPERTIES OF Al-Si-Cu ALLOY CASTINGS MADE IN GYPSUM MOLDS

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The influence of cooling rate and heat treatment on the mechanical properties of Al-Si-Cu alloy castings made in gypsum molds were presented in the article. A series of identical T6 heat treated strength samples were made for three variants of mold temperature: 30 °C, 200 °C, 300 °C. The cooling rate in the thermal axis of the sample, the Dendrite Arm Spacing microstructure parameter were measured. Analyzed parameters were correlated with the obtained values of mechanical properties.

Keywords: Al-Si-Cu, cooling rate, heat treatment, microstructure, mechanical properties

INTRODUCTION

Casting aluminum alloys from the group of Al-Si-Cu have found wide application include in the automotive industry as castings of e.g. engine heads and blocks, gearbox or timing gear housings. They should have increased strength and corrosion parameters and requirements in terms of their tightness.

Castings from the analyzed alloy are mainly made with the use of sand-molding and die-casting technology. The use of the above-mentioned methods may be limited due to the complicated shape of the product, and thus the costly production of foundry equipment in conjunction with small-lot production.

In this case, the alternative is the use of additive technologies, which are ideally suited for unit or small-lot production of complex parts.

According to the producers, 3D printing is used in the foundry industry mainly for the production of complex casting molds and in the jewelry industry, where there is practically no limitation in forming the shape and for making prototypes.

The main limitation of the use of 3D printing are, among others: costs of large printers for casting molds and the time of their implementation, dimensional accuracy and time-consuming of post-processing [1-3].

In order to make castings, e.g. precise, prototype or in unit production of complex and thin-walled castings, you can use printed models e.g. High Impact Polystyrene, Polymethylmethacrylate, which are placed in a gypsum form and then gasified in a furnace. The process scheme is shown in Figure 1.

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The mold formed in this way is annealed and poured with any casting alloy using the technology of gravity, centrifugal pouring or using negative pressure.

The disadvantage of using plaster molds is their low thermal conductivity $\lambda = 0{,}18 \div 0{,}43$ W/m/°C [4, 5], which causes a very slow solidification process of the aluminum casting. This causes a coarse-grained structure, porosity, and thus a reduction in the strength properties of the casting [6-8]. A significant problem during

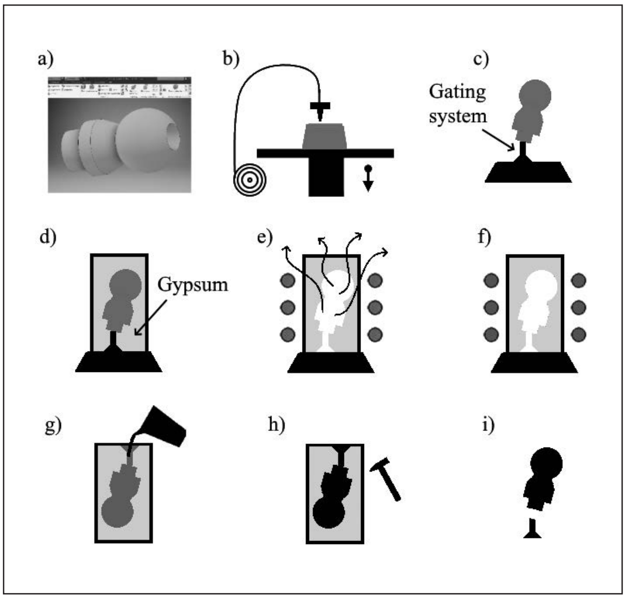

Figure 1 Gypsum mold process: a) Computer Aided Design (CAD) model, b) Fused Deposition Modeling (FDM) printing, c) insert gating system, d) gypsum mold making e) degassing model, f) mold annealing, g) mold pouring, h) mold destruction, i) cutting and finishing casting

slow solidification of aluminum alloys with silicon and other elements is the iron content in the liquid alloy, which causes the formation of long β-Al_5FeSi phase plates, which may limit the supply of castings and its brittleness [9-12]. In addition, the alloy component in the form of copper in the analyzed alloy causes the crystallization of intermetallic phases $Al_5Mg_8Cu_2Si_6$ at a temperature lower than the crystallization temperature of the eutectic α_{Al+Si}, which additionally contributes to increase porosity in the casting [7, 13].

RESEARCH METHODOLOGY

The research on the influence of the cooling rate and heat treatment on the microstructure and mechanical properties was carried out on the $AlSi_5Cu_2$ alloy, the chemical composition of which is presented in the Table 1.

Samples for strength tests were made in a specially designed form according to the concept presented in the work [14]. The designed form with a central gating system enables the execution of 10 standardized strength samples with identical microstructure properties in one pour.

CAD geometry models of strength samples (Figure 2a) were printed using a 3D printer in FDM technology made of Z-HIPS material (Figure 2b).

The mold was made of Ransom & Randolph's Plasticast casting gyspum and was heat treated to gasify the models and anneal the mold. The form prepared for pouring and the castings made are shown in Figure 3.

Table 1 **Chemical composition of the $AlSi_5Cu_2$ alloy / wt. %**

Si	Mg	Cu	Fe	Ti	Mn	Zn	Ni	Al
4,19	1,17	1,65	0,83	0,04	0,43	0,19	0,16	rest

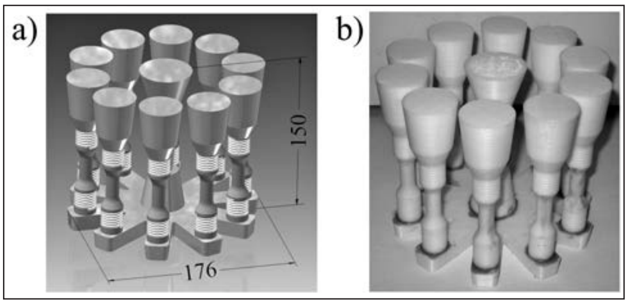

Figure 2 Set of strength samples: a) CAD model, b) printed models

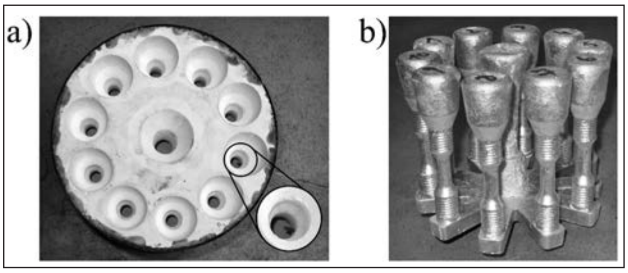

Figure 3 a) Casting gypsum mold with thermo-couple, b) cast strength specimens

The molten alloy was prepared in a Nabertherm K4/13 resistance furnace in a SiC crucible. Before the mold was poured, the process of refining the liquid alloy was carried out to remove oxides Al_2O_3 and hydrogen. The hydrogen content of the liquid alloy before pouring the mold was 0,15 ccm/100 g.

The mold was poured with an alloy at a temperature of 750 ± 5 °C. 10 identical samples were made from one pouring, of which 8 samples were subjected to strength tests, and from 2 the parameters of the (DAS) microstructure and the cooling rate were determined.

The variation in the intensity of the solidification process for the castings of strength specimens, expressed by the cooling rate ‹R›, was differentiated by the mold temperature, which was 30 ± 5 °C, 200 ± 5 °C and 300 ± 5 °C. The temperature value was measured along the thermal axis of the sample according to the scheme presented in Figure 4, on the device EUROTHERM 6100V with sampling time of 0,5 seconds.

The Dendrite Arm Spacing (DAS) microstructure parameter was measured in the center of the sample (Figure 5a). In order to analyse the influence of the

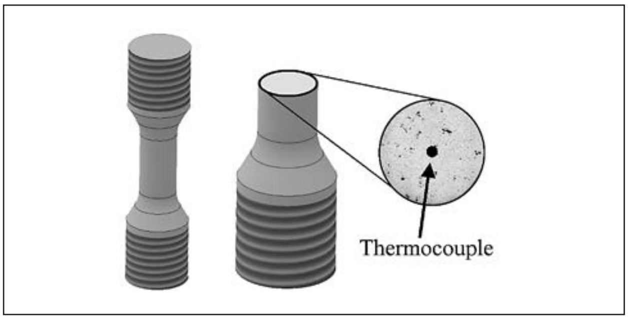

Figure 4 Scheme of sample cooling rate measurement

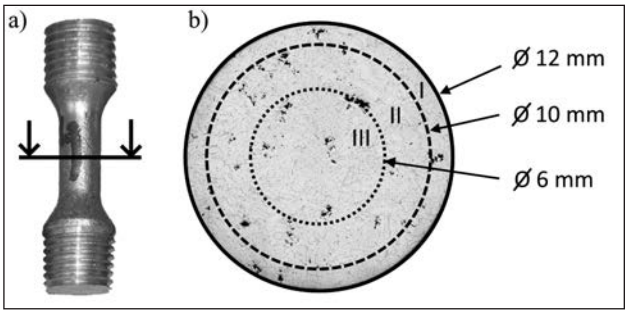

Figure 5 Diagram of the measurement of the (DAS) microstructure parameter: a) place of cutting sample, b) measurement zones

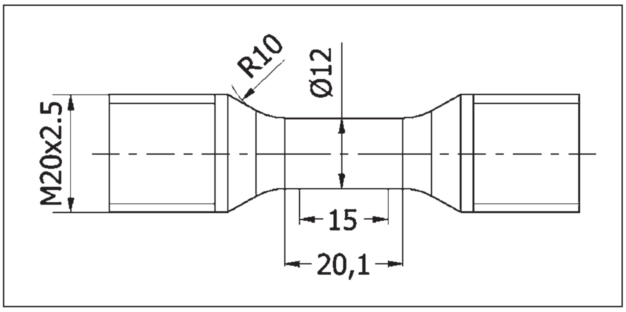

Figure 6 Sample dimensions for tensile strength testing

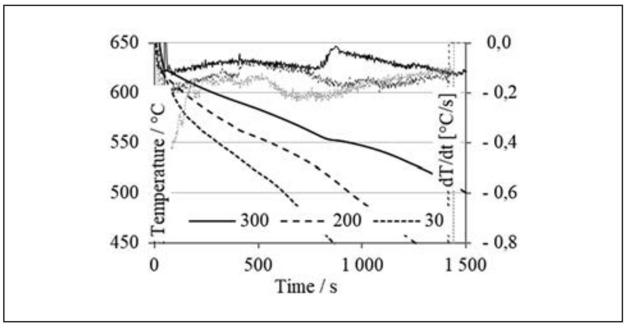

Figure 7 Cast cooling curves depending on the temperature of the casting mold

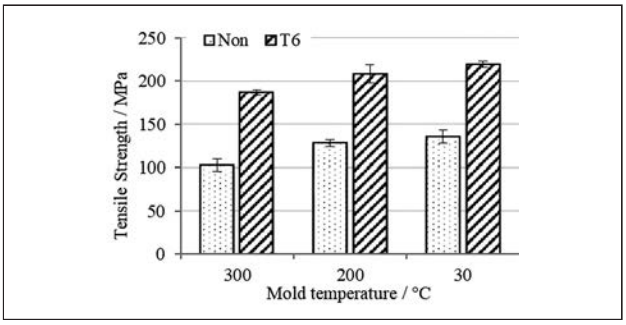

Figure 9 Tensile strength as a function of mold temperature and heat treatment

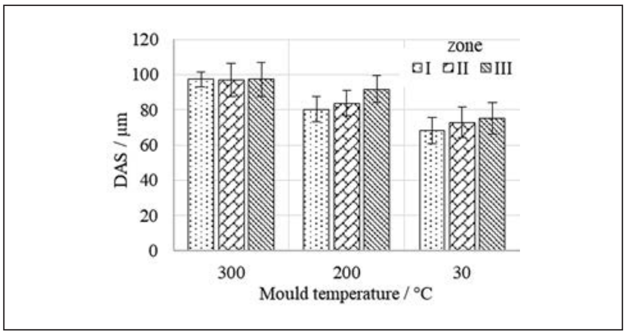

Figure 8 (DAS) parameter as a function of mold temperature and measurement zone

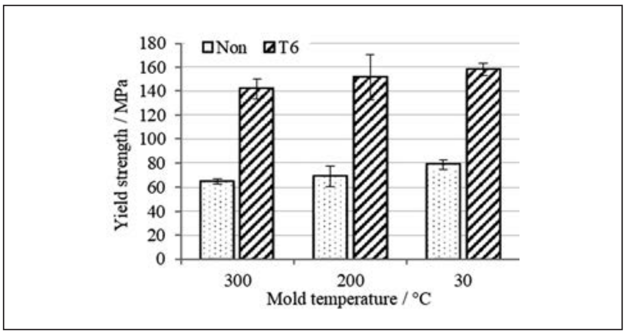

Figure 10 The yield strength as a function of mold temperature and heat treatment

mold temperature on the microstructure in more detail, the cross-section of the sample was divided into 3 zones with the dimensions shown in Figure 5b. In each analyzed zone, 10 measurements of dendrites were made, in which the minimum number of arms was 4.

The cast samples were subjected to the T6 heat treatment (540 ºC/12 hours; water cooling; 160 ºC/4 hours).

Strength tests were carried out on standardized samples (Figure 6) using the INSTRON 4481 testing machine with a tensile speed of 2 mm/min.

RESULTS

The obtained cooling curves in the thermal axis of castings of strength samples depending on the temperature of the casting mold are shown in Figure 7.

The calculated averaged cooling rates of the casting R for the growth range of the α_{Al} phase dendrites are as follows: for the mold with a temperature of 300 °C, R = 0,09 °C/s, molds with a temperature of 200 °C, R = 0,16 °C/s, molds with a temperature of 30 °C, R = 0,35 °C/s.

It follows that despite the use of a mold with ambient temperature (T = 30 °C), the intensity of the cooling rate was achieved at the level of a mold made of molding sand. In the case of castings with thin walls, e.g. 3 mm, such a mold temperature may be too low and cause a casting defect (misrun casting) to be formed. Increasing the value of the mold temperature to 200 °C resulted in an approx. 55 % decrease in the cooling rate of the casting, and when the mold temperature was 300 °C, the value of the cooling rate decreased by as much as 70 % and amounted to 0,09 °C/s.

The values of the (DAS) microstructure parameters depending on the mold temperature and the measurement zone are shown in Figure 8.

The most favourable, and thus the lowest values of the (DAS) microstructure parameter were obtained for the mold at ambient temperature and ranged from approx. 68 µm for zone No. I to 75 µm in the central part of the sample (zone No. III). These values correspond to the structure of castings made in sand molds in the central part of the casting. For a mold temperature of 200 °C, the (DAS) parameter was 80 µm and 91 µm, respectively. In the case of a mold with a temperature of 300 °C, the values of the (DAS) microstructure parameter in all zones are at a similar level and amount to approx. 98 µm.

It follows that for the temperature of the gypsum mold higher than 300 °C, the solidification process takes place simultaneously in the entire section of the casting (dimension Ø 12 mm), which requires further studies of the thermal conductivity of gypsum casting masses at higher temperatures.

Figures 9 and 10 show the change of mechanical properties of the casting depending on the temperature of the gypsum mold and the performed heat treatment.

For castings in the as-poured state (without heat treatment), lowering the temperature of the gypsum mold from 300 °C to the ambient temperature increases the value of tensile strength from 102 MPa to 136 MPa, and the yield strength from 65 MPa to 79 MPa.

Conducting T6 heat treatment on castings of samples significantly increased the value of tensile strength. For a mold at 30 °C by 62 %, and for a mold at 300 °C by 82 %. A similar situation occurred with the yield strength, where there was an improvement by 58 % for the mold at ambient temperature, while for the other molds there was an increase by approx. 120 %.

CONCLUSIONS

Performing the heat treatment of castings made in the masses of gypsum causes a significant increase in the tensile strength and the contractual yield point.

Lowering the temperature of the casting mold favours the reduction of the (DAS) parameter value and the increase the mechanical properties.

Pouring the mold at a temperature of 300 °C causes the simultaneously solidification process from the casting.

It is possible to use gypsum molds to make piece production or prototype castings with mechanical properties corresponding to making castings in molding sands.

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