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Microstructure and Mechanical Properties AlSi7Mg Alloy with Sr, Al and AlSi7Mg

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Strength and malleability are important reasons for increasing applications of Al-Si alloys. Mechanical properties of Al-Si cast alloys depend not only on chemical composition but, more importantly, on microstructural features such as morphologies of dendritic α-rich in Al, eutectic β-rich in Si particles and other intermetallics that are present in the microstructure. The microstructure of an unmodified hypoeutectic AlSi7Mg alloy is responsible for the alloy's low strength parameters, and it limits the extent of practical applications. The mechanical properties of hypoeutectic silumins can be improved through chemical modification as well as traditional or technological processing. The improvement in mechanical properties generally has been attributed to the variations in the morphology and size of the eutectic silicon phase particles.
This study presents the results of modification of an AlSi7Mg alloy with Sr, Al+ 10% Sr alloy and AlSi7Mg + 10% Sr master alloy. The tests were carried out on modified primary silumin alloy obtained at slow and fast cooling. Modifying additives in granular form and in the form of a rod were used. All additions were introduced into the alloy in an amount that guaranteed a constant strontium contribution to the modified alloy. The influence of the analyzed modifiers on the microstructure and mechanical properties of the processed alloy was presented in graphs. The modification of a hypoeutectic AlSi7Mg alloy improved the microstructure and alloy's properties. The results of the tests indicate that the microstructure and mechanical properties of the modified alloy are determined by the cooling rate of the modifier and its form. Higher parameters were obtained after modification of the AlSi7Mg alloy with a master alloy composed of Sr and AlSi7Mg alloy produced by rapid cooling and introduced in granular form.

Keywords: Silumin, Modification, Strontium, Mechanical properties

1 Introduction

Hypoeutectic Al-Si alloys have the potential for excellent castability, good weldability, good thermal conductivity, high strength at elevated temperatures and excellent corrosion resistance [1-6]. That is why the alloys are among the one of the most popular casting alloys. In hypoeutectic alloys of aluminum and silicon, solid solution dendrites which crystallize first are typical crystals, showing isotropic properties. Similarly to pure aluminum, solid solution α (solid solution of silicon in aluminum) has a regular cubic face-centered lattice of the type A1. The growth rate of those crystals, and the growth rate of eutectic mixture crystallizing at the next stage (α+β), is a function of cooling at the crystallization front [7-11]. This dependence is a complex function of: the chemical composition of the liquid and solid phase, surface curvature of the crystallization front, crystallization heat emission and structural defects [10-16]. The microstructure of an unmodified hypoeutectic silumin is responsible for the alloy's low strength parameters, and it limits the extent of practical applications. Morphology of microstructure silumin may be changed by e.g. adding to the alloy chemical elements and compounds which affect the process of solidification [7, 17-22]. The process of modification of Al-Si alloys is a complex process and until now there is no clear explanation for it. There are a number of theories that substantiate the occurring changes in the microstructure and properties of the alloy. These changes can be formed through the impact of technological processes, which can include temperature gradient impact, modification, heat treatment, etc. Chemical modification of aluminum foundry alloys has gained the greatest popularity. Historically, modification began with the addition of strontium and sodium. The action of Sr is to neutralize the AlP particles present in the alloy, therefore, after introducing it into the liquid metal at a temperature of 730^{o}C, a certain incubation period of 1-2 hours is required. Sodium reacts faster, but the modification effect disappears after about 40 minutes. Sr-modified alloys have better castability than Na-modified alloys, most likely due to the thick oxide layer. With further development of processes that increase the properties of silumins, complex modifiers are used. They combine several chemical substances recognized as modifiers, sometimes also refiners of alloys. There are so many hypotheses of alloy modification that it is difficult to present them in a short paper. It was demonstrated that the engineering properties of silumins can be also improved by homogeneous modification, which involved alloy treatment with modifiers with the chemical composition of the treated alloy, obtained by fast crystallization. The modification method led to the lamellar structure of silumins, with constant interplanar distances, thus testifying about the stability of the process [23-24]. Good results were also obtained after modification with an exothermic modifier [25-28] and technological processes [29-35].

Phase transformations in aluminum alloys can be described by means of mathematical equations but it can be presented in various ways on the example of a change in the microstructure, which results in a change in the mechanical properties of the alloy [36-39]. Further investigation may involve advanced image analysis method [40]. The use of mechanical properties of alloys is a more readable form of presenting results for a wider number of readers.

The results of modification of eutectic and hypoeutectic aluminum-silicon alloys by sodium, strontium, antimony and other additions in the metallurgic process have been already analyzed and described by numerous authors. However, literature on the topic provides scant information on silumin modification with modifiers obtained from the treated alloy by fast cooling and introduced into the modified alloy in granular form and in the form of a rod. In view of the growing popularity of modified alloys, the aim of this study was to determine the properties of hypoeutectic silumin AlSi7Mg alloy with Sr, AlSr10 alloy and AlSi7Mg + 10% Sr master alloy. The study was to determine the influence of cooling rate and modifier form on microstructure and mechanical properties hypoeutectic alloy, too.

2 Materials and methods

The experimental material was AlSi7Mg alloy which was regarded as representative of hypoeutectic silumins. The alloy was obtained from industrial piglets. Real mean chemical composition of the AlSi7Mg alloy is present at Table 1.

Tab. 1 *Real chemical composition of the AlSi7Mg alloy [wt. %]*

Si	Cu	Mg	Mn	S	Cr	Fe	Ti	Zr	Al
7.2	0.05	0.32	0.36	0.02	0.01	0.15	0.02	0.05	Bal.

The alloy was melted in a ceramic crucible in an electric furnace, and the modification process was carried out with: 1) Sr at 0.06% by weight, 2) Al+ 10% Sr alloy and 3) AlSi7Mg + 10% Sr master alloy.

2.1 Preparation of modifiers

In the first series, the additives were introduced into the alloy in the form of 0.06% Sr as a powder (item 1 Table 2). In the second series, the master alloy (modifier) was made by adding Sr to liquid aluminum (99.99%) at 720^{0}C (Al+10 wt.% Sr). After 5 minutes of holding, the liquid Al+10 wt.% Sr alloy was poured in three variants: in first onto a metal washer heated to 720^{0}C with a groove 12 mm wide and 2 mm deep and cooled in air (item 2 and 3 Table 2); in the second variant poured onto a similar metal disk and next cooled at speed about 200^{0}C/s (symbol c-cold position 6 and 7 table 2). In the third variant, 10% Sr was introduced into the liquid AlSi7Mg alloy (850^{0}C) and the master alloy (modifier) was produced in the same way as for aluminum (as in first and econd variants - items 4 and 5 or 8 and 9, respectively, Table 2). After cooling down to ambient temperature, the bars were prepared in two variants: in the first one, mechanically ground into 0.40-0.63 mm fractions (symbol g-grain – items 2, 4, 6 and 8 respectively, Table 2), in the second, an equivalent section of 0.06% wt. Sr with respect to the treated alloy was cut off (symbol r-rod – items 3, 5,7 and 9 respectively, Table 2). The designation research variants shown in Figs 1-3 are summarized in Table 2. Strontium was chosen as the basic AlSi7Mg silumin modifier due to its popularity in hypoeutectic Al-Si alloy modification.

Tab. 2 *The designation of research variants*

Nr	Symbol	Manufacturing method and modifier composition (wt %)	Sr content at modified alloy
1	Sr	powder Sr	0.06 wt.%
2	(Sr+Al)g	master alloy Al+10% Sr cooled in air in granular form	
3	(Sr+Al)r	master alloy Al+10% Sr cooled in air in rod form	
4	(Sr+AlSi7Mg)g	master alloy AlSi7Mg+10% Sr cooled in air in granular form	
5	(Sr+AlSi7Mg)r	master alloy AlSi7Mg+10% Sr cooled in air in rod form	
6	(Sr+Al)g-c	master alloy Al+10% Sr cooled at 200^{0}C/s in granular form	
7	(Sr+Al)r-c	master alloy Al+10% Sr cooled at 200^{0}C/s in rod form	
8	Sr+AlSi7Mg)g-c	master alloy AlSi7Mg+10% Sr cooled at 200^{0}C/s in granular form	
9	Sr+AlSi7Mg)r-c	master alloy AlSi7Mg+10% Sr cooled at 200^{0}C/s in rod form	

The alloy was modified at a temperature of 850°C. Cylindrical samples, 8 mm in diameter and 75 mm in length, were poured into dry sand molds. The tensile stress test was performed on a specimen with a length-to-diameter ratio of 5:1 in the ZD-30 universal tensile tester. A tensile strength test was performed on two samples, ϕ 6 mm, for each melting point, according to the standard ISO 6892-1:2016-09 „Metallic materials. Tensile testing. Method of test at ambient temperature". Brinell hardness was performed according ISO 6506-1:2014 "Metallic materials — Brinell hardness test — Part 1: Test method" , by Brinell/Vickers HPO-250, steel ball at diameter 2.5 mm, stress 612.9 N.

A 10 mm strip was cut off at the bottom of each sample. The face of cut served as metallographic specimen for microstructure analysis. Samples for mechanical tests were obtained from the upper part of the casting. A structural analysis was performed using an OLYMPUS IX70 microscope (magnification 25-600x), and OLYMPUS DP-SOFT.

3 Results and discussion

The microstructure of the basic AlSi7Mg alloy is presented in Figure 1. The microstructure consists of coniferous eutectic (α+β) on background the dendrytic of α-phase (bright fields - a solid solution of silicon in aluminum). The large needles and grain of eutectic β-phase (dark fields – a solid solution of aluminum in silicon) are the main reason of low tensile strength. In the raw state, the alloy had tensile strength Rm = 143 MPa, elongation A = 0.8% and hardness 55 HB. Microstructure of the AlSi7Mg alloy with 0.06% Sr is presented in Figure 2, with (Sr+Al)g is presented in Figure 3, with (Sr+Al)r is presented in Figure 4, (Sr+AlSi7Mg)g is presented in Figure 5, with (Sr+AlSi7Mg)r is presented in Figure 6, with (Sr+Al)g-c is presented in Figure 7, with (Sr+Al)r-c is presented in Figure 8, with Sr+AlSi7Mg)g-c is presented in Figure 9, with Sr+AlSi7Mg)r-c is presented in Figure 10.

On Figures 2 - 10 visible are grey fine grains of eutectic mixture (α+β) in the inter-dendrite spaces of phase α. The dark Mg2Si phase is also present, similar to Figure 1.

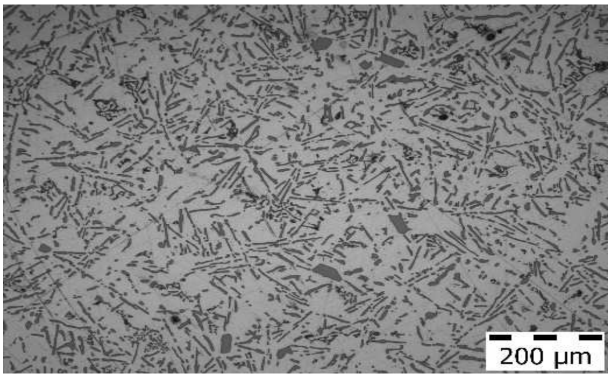

Fig. 1 *Microstructure of the master AlSi7Mg alloy*

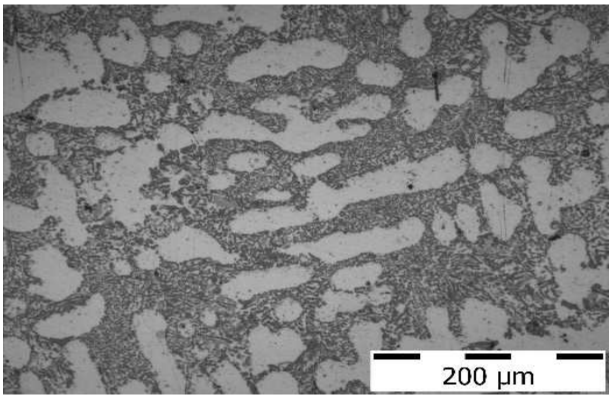

Fig. 2 *Microstructure of the AlSi7Mg alloy with 0.06% Sr*

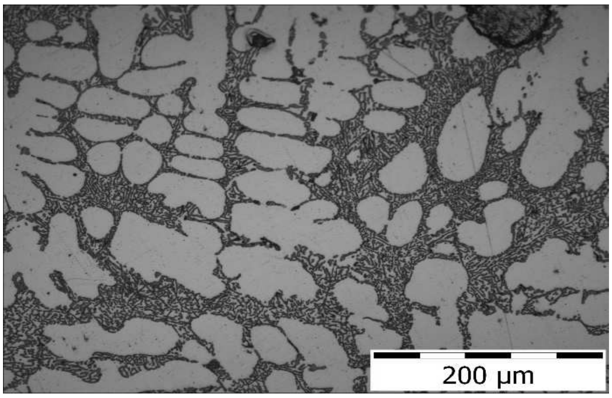

Fig. 3 *Microstructure of the AlSi7Mg alloy with 0.06% (Sr+Al)g*

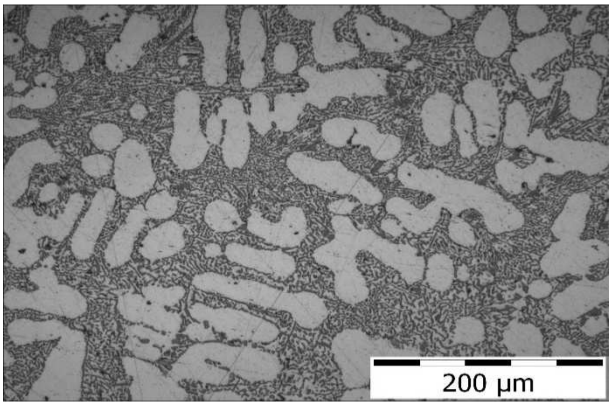

Fig. 4 *Microstructure of the AlSi7Mg alloy with 0.06% (Sr+Al)r*

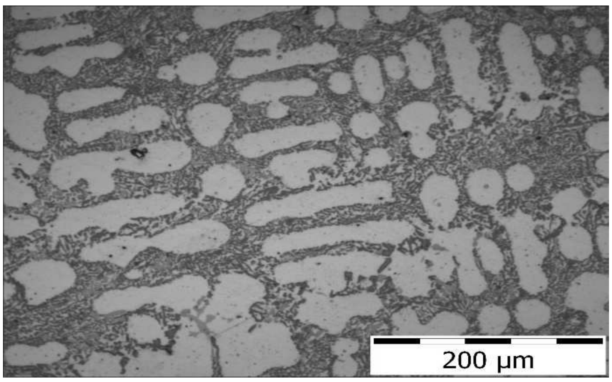

Fig. 5 *Microstructure of the AlSi7Mg alloy with 0.06% (Sr+AlSi7Mg)g*

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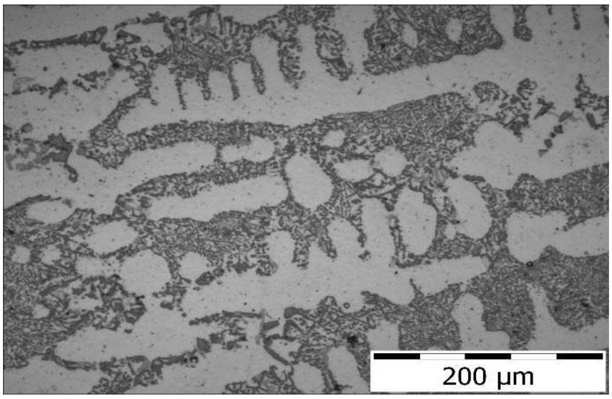

Fig. 6 *Microstructure of the AlSi7Mg alloy with 0.06% (Sr+AlSi7Mg)r*

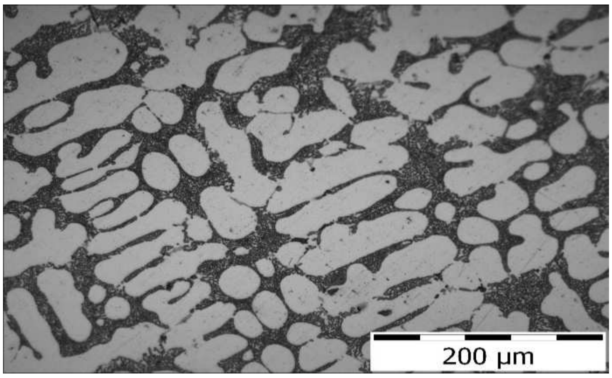

Fig. 7 *Microstructure of the AlSi7Mg alloy with 0.06% (Sr+Al)g-c*

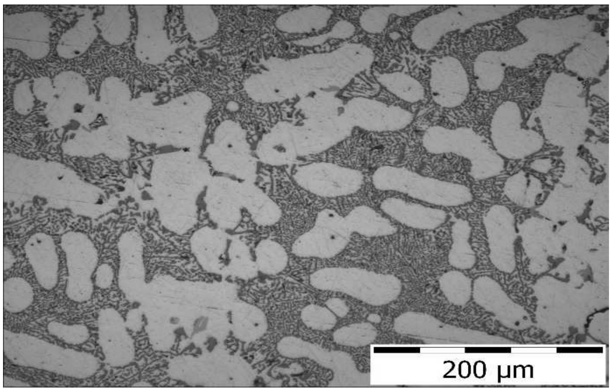

Fig. 8 *Microstructure of the AlSi7Mg alloy with 0.06% (Sr+Al)r-c*

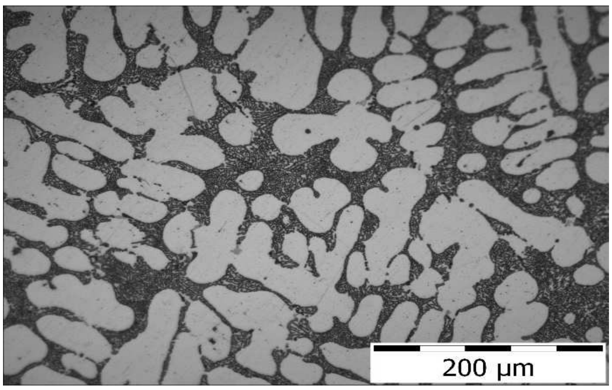

Fig. 9 *Microstructure of the AlSi7Mg alloy with 0.06% (Sr+AlSi7Mg)g-c*

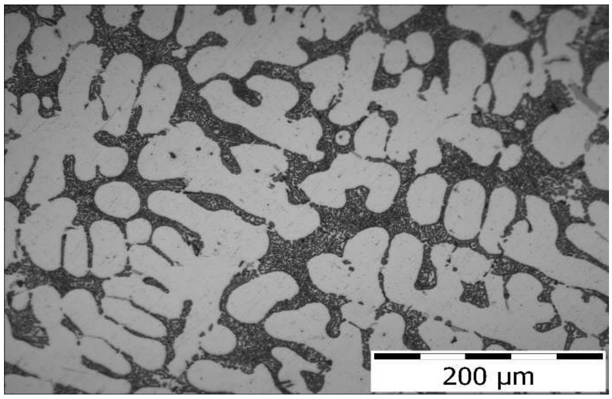

Fig. 10 *Microstructure of the AlSi7Mg alloy with 0.06% (Sr+AlSi7Mg)r-c*

Tensile strength of the AlSi7%Mg alloy with Sr or mixture consisting Al+ 10% Sr alloy and AlSi7Mg + 10% Sr master alloy as a powder are show in Figure 11.

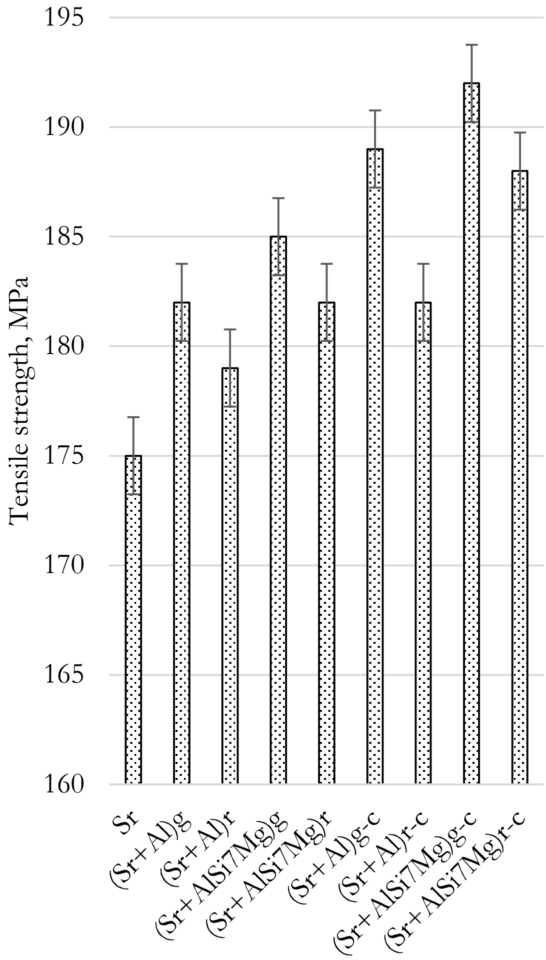

Fig. 11 *Tensile strength of the AlSi7Mg alloy after modification*

Elongation of the AlSi7%Mg alloy with Sr or mixture consisting Al+ 10% Sr alloy and AlSi7Mg + 10% Sr master alloy as a powder are show in Figure 12.

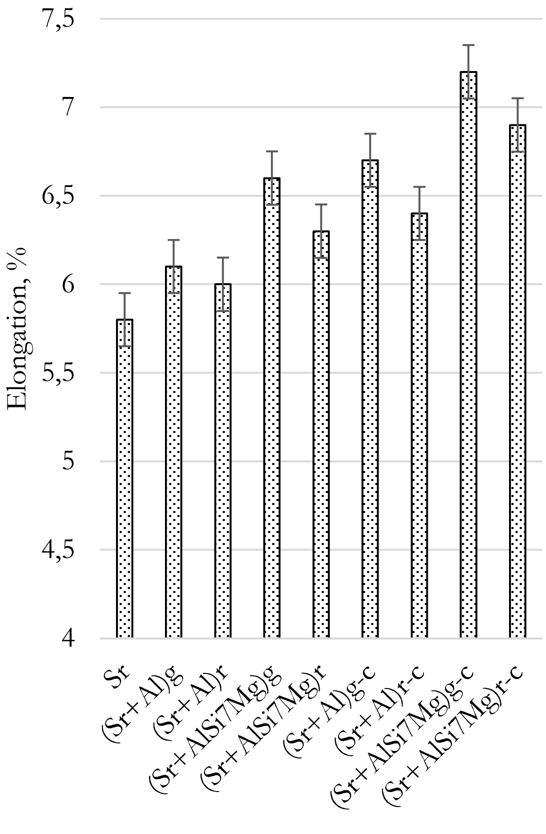

Fig. 12 *Elongation of the AlSi7Mg alloy after modification*

Brinell hardness of the AlSi7%Mg alloy with Sr or mixture consisting Al+ 10% Sr alloy and AlSi7Mg + 10% Sr master alloy as a powder are show in Figure 13.

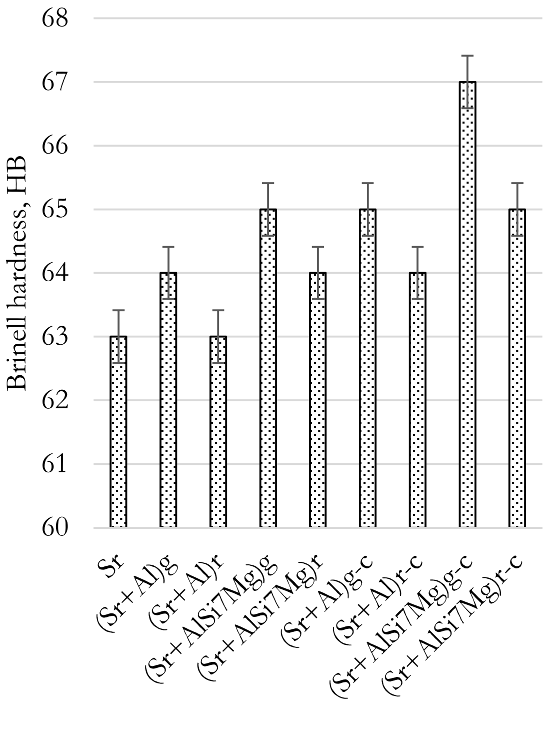

Fig. 13 *Brinell hardness of the AlSi7Mg alloy after modification*

Modification AlSi7Mg alloy with 0.06% Sr (item 1 Table 2) increased all of the analyzed parameters in the resulting alloy: tensile strength increased by 32 MPa to 175 MPa (Figure 10), elongation increased by 5% to 5.8% (Figure 11), and Brinell hardness increased by 8 HB to 63 HB (Figure 12). The alloy's mechanical properties increased through phase transformation. Grinding of the coniferous and granular phase β was found (Figure 1). A fine of grained eutectic (α + β) and α-phase, clearly separating from the eutectic arose (Figure 2). Treatment the silumin with primary alloy Al+10% Sr cooled in air in granular form (item 2 Table 2) increased tensile strength increased by 39 MPa to 182 MPa (Figure 10), elongation increased by 5.3% to 6.1% (Figure 11), and Brinell hardness increased by 9 HB to 64 HB (Figure 12). For this modifier, fineness of the microstructure was observed (Fig. 3) in relation to the master alloy (Fig. 1), but greater precipitations of both eutectic and α phase were found in relation to the alloy modified with 0.06% Sr. After using the same modifier but in rod form (item 3 Table 2), fragmentation of the primary a-phase was observed (Fig. 4) in relation to all previous modification variants. The effect of changing the microstructure are mechanical properties: Rm = 179 MPa, A = 6% and hardness 63 HB was obtained. After processing the AlSi7Mg alloy with primary alloy Al + 10% Sr cooled at 200^{0}C/s in granular forms (item 6 Table 2) high fragmentation of the eutectic (α+β) of the a phase was observed (Fig. 7) in relation to all previous modification variants. Unfortunately, the fragmentation of eutectic had to result in the development of a dendritic, but plastic, a phase. Tensile strength increased by 46 MPa to 189 MPa, elongation increased by 5.9% to 6.7% and hardness increased by 10 HB to 65 HB (Figures 10, 11 and 12 respectively). Lower strength parameters were obtained for primary alloy Al + 10% Sr cooled at 200^{0}C/s in rod form (item 7 Table 2) a finer eutectic microstructure was obtained (Fig. 8) compared to the master alloy (Fig. 1), but at the same time coarser than for the modifier (Sr+Sl)g-c., Rm = 182 MPa, A = 6.4% and hardness 64 HB.

When the unmodified AlSi7Mg alloy was treated with primary alloy AlSi7Mg+10% Sr cooled in air in granular form (item 4 Table 2) a finer microstructure was obtained (Fig. 5) compared to the master alloy (Fig. 1). Its tensile strength increased by 42 MPa to 185 MPa, elongation increased by 5.8% to 6.6%, and Brinell hardness increased by 10 HB to 65 HB. After using a modifier with the same chemical composition but in rod form (item 5 Table 2) a finer microstructure was obtained (Fig. 6) compared to the master alloy (Fig. 1), but at the same time large α-phase dendrites were obtained, most probably representing a reduction in mechanical properties in relation to the modified alloy (Sr+AlSi7Mg)g: Rm = 182 MPa, A = 6.3% and hardness 64 HB (Figures 10, 11 and 12 respectively). The most favorable mechanical properties were obtained for AlSi7Mg alloy with primary alloy AlSi7Mg + 10% Sr cooled at 200⁰C/s in granular form (item 8 Table 2) a very fine microstructure of the eutectic phase (α+β) and the axes of the α-phase dendrites arranged in different directions were obtained (Fig. 9). For this alloy, tensile strength increased by 49 MPa to 192 MPa (Figure 10), elongation increased by 6.4% to 7.2% (Figure 11), and Brinell hardness increased by 12 HB to 67 HB (Figure 12). These are the highest strength parameters in the tests carried out. When the unmodified AlSi7Mg alloy was treated with the same chemical elements but in rod form (item 9 Table 2), its tensile strength increased by 45 MPa to 188 MPa, elongation increased by 6.1% to 6.9%, and Brinell hardness increased by 10 HB to 65 HB. For the modifier variants: Al+10% Sr cooled at 200^0C/s in rod form (Figure 7), AlSi7Mg+10% Sr cooled at 200^0C/s in rod form (Figure 10) and AlSi7Mg+10% Sr cooled at 200^0C/s in granular form (Figure 9) a modified alloy microstructure was also obtained but with significantly greater fragmentation of the eutectic phase β.

Even taking into account that the transformation of hypoeutectic Al-Si alloy strongly depends on the cooling conditions, with repetitive processes that were provided in the conducted tests, the obtained trends are authoritative.

Comparing the transformations of the AlSi7Mg silumin microstructure (Figures 1-10) subjected to modifications by each of modifiers (Table 2) and the obtained mechanical properties (Figures 11-13) between each other, a modifying effect was found for all the modifiers used. It was found that the use of primary alloy with Sr (Figures 2-13) allows for receiving finer eutectic microstructure and higher alloy mechanical properties than the use of strontium only (Figure 1). It was also found that the modifier added in the form of grain (comparing Figures: 3 with 4, 5 with 6, 7 with 8, 9 with 10, and relevant variants at Figures 11-13)also allows greater fragmentation of the alloy's ethics (α + β) than added in the form of rod. The use of fast cooling primary alloy (modifier) also allowed for a greater transformation of the alloy microstructure (and mainly its eutectic phases α+β) to a finer than for slow cooling primary alloy in the air (comparing Figures: 3 and 4 with 7 and 8, 5 and 6 with 9 and 10 respectively and relevant variants at Figures 11-13). The use of AlSi7Mg for production primary alloy allowed to obtain a finer eutectic phase of modified Al-Si7Mg alloy than after using Al (Comparing Figures: 3, 4, 7, 8 with 5, 6, 9, 10 and 11-13 respectively). Such relationships are also confirmed by [23,24]. Higher degree of microstructure transformation and higher mechanical properties after modification of primary alloy can probably be explained: firstly, better assimilability of primary alloy with chemical composition similar to the modified alloy by modified alloy and secondly, the impact on the alloy through modification and inoculation simultaneously. The confirmation of the first suggestion is the fact of receiving higher transformation effects (microstructure and analyzed mechanical properties) after treatment the AlSi7Mg alloy with the AlSi7Mg + 10% Sr modifier than Al + 10% Sr, regardless of the form of the modifier (grain or rod as well as cooling conditions: by air or fast cooling).

4 Conclusions

Based on the results of the tests carried out, it was found that:

- the modifier produced by melting the modified silumin with strontium has a stronger effect on the phase transformation and mechanical properties of the silumin than the modifier added to the treatment alloy in its pure form,
- the cooling rate of the produced modifier composed of the treated alloy and strontium improves the effectiveness of its impact on microstructure transformations and the resulting mechanical properties,
- a modifier with a chemical composition similar (or identical) to the modified alloy changes the microstructure and mechanical properties of the modified alloy more intensively than the aluminum-based primary alloy,
- the modifier produced in the form of grain affects the changes in the microstructure and mechanical properties of the alloy more intensively than the modifier introduced in the form of a rod.

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