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EFFECT OF BERYLLIUM ADDITION ON THE MICROSTRUCTURE AND PHYSICAL PROPERTIES OF Al-Si ALLOYS WITH LOW SILICON CONTENT

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Abstract

This article analyzes the influence of beryllium (Be) as an alloying element on the structural properties of the AlSi5Cu2Mg alloy. Specifically, it examines the ability of Be to affect crystallization and the electrical and thermal conductivity. The goal is to implement a non-standard alloy into a low-silicon aluminum alloy that would show improved physical properties, refined structure, and stabilization of intermetallic phases. Such a modified alloy could be used for large aluminum castings in the automotive industry, especially for lightweight electric vehicles. It's also suitable for castings requiring balanced mechanical properties and high ductility, as well as for special high-pressure die casting (HPDC) parts that demand higher physical properties than standard aluminum alloys. The analysis shows that adding Be in the range of 0.05, 0.08, and 0.12 wt.% to the AlSi5Cu2Mg alloy refines the grain and changes the morphology of the eutectic silicon. Using a separated remelting method with AlBe5, no Be burnout occurred in the alloy. An addition of 0.12 wt.% Be to the tested alloy resulted in an increase in both electrical and thermal conductivity.

Keywords: *AlSi5Cu2Mg, alloying, beryllium, electrical conductivity, thermal conductivity, microstructure*

1. INTRODUCTION

Currently, the field of aluminum castings production and metallurgy is facing significant challenges in developing new materials. Standard aluminum alloys are often unable to meet many of the required properties, such as high ductility (10-20%) while maintaining high strength, hardness, or specific electrical and thermal demands for castings. Challenges also arise when casting exceptionally large aluminum components (~1-2 m x 1.5-2 m x 0.5 m) and ensuring they have the necessary properties, with a strong emphasis on quality. When developing new aluminum alloys for the automotive industry, it is crucial to focus not only on mechanical and chemical properties but also on physical properties like thermal and electrical conductivity. In aluminum-silicon (Al-Si) alloys, silicon (Si) is a key element that influences both fluidity and shrinkage. However, alloys with a eutectic composition have low ductility, and the eutectic Si cannot be effectively modified to achieve non-standard values. A common compromise is to use aluminum alloys with a lower silicon content, around 7 wt.% Si or less, which is not typical for high-pressure die casting (HPDC) in our region. These alloys are expected to have balanced flowability and suitable mechanical characteristics, including ductility. In addition to low Si content and a small amount of Mg, researchers are searching for elements and alloys that would be active in these processes, despite being significantly more expensive than standard alloys [1-4]. Therefore, the objective of this paper is to determine the effect of adding beryllium on the microstructure and physical properties of low-silicon Al-Si alloys. Due to the limited scope of this paper, only partial results will be presented.

2. METHODOLOGY OF EXPERIMENTAL WORK

For the experimental work, the aluminum alloy AlSi5Cu2Mg was selected. This is a hypoeutectic alloy with a low silicon content. The chemical composition of the base AlSi5Cu2Mg alloy is shown in Table 1.

Table 1. Chemical composition of the AlSi5Cu2Mg alloy [wt.%].

Alloy as-cast state	**Si**	**Cu**	**Mg**	**Mn**	**Fe**	***Be***	***Ti***	***Sr***	**Al**
AlSi5Cu2Mg **+ 0 wt. % Be**	6.77	2.54	0.153	0.015	0.23	*0.0002*	*0.016*	*0.01*	Bal.

The primary AlSi5Cu2Mg alloy was melted in an electric resistance furnace using a graphite crucible. Experimental alloys were prepared by alloying the primary AlSi5Cu2Mg with 0.05, 0.08, and 0.12 wt. % Be, which was added in the form of an AlBe5 master alloy. The amounts of added Be were chosen based on a literature review. To improve the utilization of the alloying element, reduce oxidation, and prevent excessive burnout, the master alloy was melted separately for a short time (2 to 3 minutes) in an electric induction furnace in a graphite crucible. It was then poured into the molten aluminum alloy. The alloying temperature was in the range of 730 to 740 °C. The melted alloy was consequently gravity casted into a metal mold at a temperature of 740 to 750 °C. The mold temperature was maintained between 140 and 150 °C. The chemical composition of the experimental alloys is shown in Table 2.

Table 2. Chemical composition of the experimental alloys [wt.%].

alloy as-cast state	**Si**	**Cu**	**Mg**	**Mn**	**Fe**	**Ti**	**Sr**	**Be**
AlSi5Cu2Mg **+ 0.05 wt.% Be**	6.84	2.66	0.157	0.0146	0.247	0.016	0.043	*0.0487*
AlSi5Cu2Mg **+ 0.08 wt.% Be**	6.78	2.54	0.166	0.0155	0.236	0.0153	0.0049	*0.0787*
AlSi5Cu2Mg **+ 0.12 wt.% Be**	6.82	2.49	0.168	0.012	0.233	0.0015	0.072	*0.115*

Five samples were cast from each experimental variant to test and evaluate the physical properties and microstructure. The microstructure was evaluated in the as-cast state using a Keyence VHX-7000 digital optical microscope. The eutectic silicon morphology was assessed on deeply etched samples using and scanning electron microscope SEM LMU II scanning electron microscope with a BRUKER EDX analyzer). According to Nemak Slovakia s.r.o.'s measurement methodology, the electrical conductivity values of the alloys were determined using cylindrical test samples with a diameter of 40 mm and a height of 60 mm. Three measurements were performed on each sample at different locations. The values presented in Table 3 are the averages of these measurements in the as-cast state. The measurements were carried out at a laboratory temperature ranging from 23 to 25 °C. To determine electrical conductivity, a Sigma Check 2 conductometer with a contact measuring probe was used. The device recorded electrical conductivity values in International Annealed Copper Standard (IACS) units as a percentage. These values were then used in empirical relationship (1) to calculate thermal conductivity. The relationship is based on the recommended calculation method for determining the thermal conductivity of the AlSi5Cu2Mg alloy from Nemak Slovakia s.r.o.

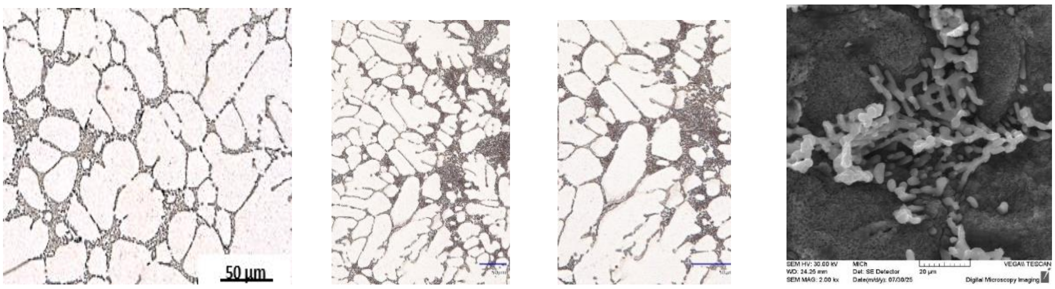
$$\lambda = 4.29 \cdot \sigma - 13.321 \tag{1}$$

where: λ = thermal conductivity [$W \cdot m^{-1} \cdot K^{-1}$]; σ = electric conductivity [% IACS]

2. RESULTS AND DISCUSSION

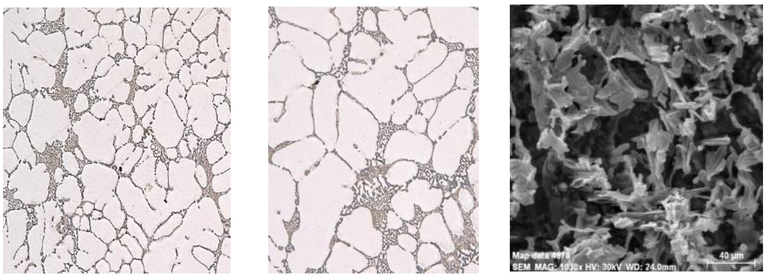
2.1 Microstructure evaluation

The microstructure of the as-cast AlSi5Cu2Mg alloys consists of the α-phase, eutectic silicon, and intermetallic phases based on copper and iron. Because the base alloy composition was inoculated and pre-modified, the structures of all the developed alloy variants (Figs. 1–3) were refined. An increasing addition of wt.% Be led to the refinement of the α-phase and fragmentation of dendrites in all the tested alloys. In the metallographic cross-section plane, eutectic silicon is visible as imperfect and perfect rounded grains. No angular, plate-like forms occurred. Therefore, it can be concluded that the alloy has optimal phase shapes to achieve the expected balanced mechanical characteristics. The morphology of the intermetallic phases was not evaluated in this case.



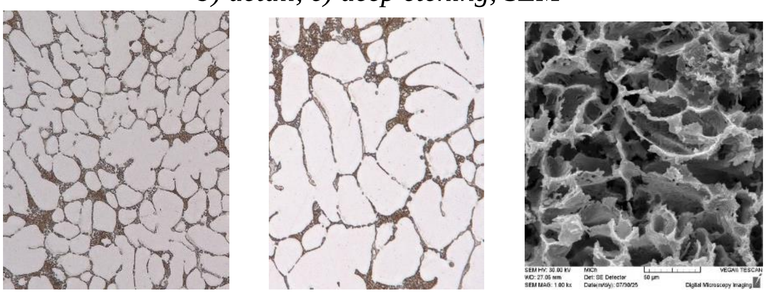
a) b) c) d)

Figure 1. Microstructure of the AlSi5Cu2Mg alloy in the as-cast state: a) 0 wt.% Be, b) 0.05 wt.% Be, c) detail, d) deep etching,0.05 wt.% SEM



a) b) c)

Figure 2. Microstructure of the AlSi5Cu2Mg alloy in the as-cast state: a) 0,08 wt.% Be b) detail, c) deep etching, SEM



a) b) c)

Figure 3 Microstructure of the AlSi5Cu2Mg alloy in the as-cast state: a) 0,12 wt.% Be b) detail, c) deep etching, SEM

The addition of Be led to the refinement of the α-phase (Figs. 1 b,c; 2 a,b; 3 a,b), which indicates that Be has a grain-refining effect in the tested alloy. The most significant structural refinement was achieved with the highest Be addition (Figs. 3a, b). Conversely, the addition of Be caused the eutectic Si in the tested alloy to change its morphology from rod-like shapes (Fig. 1d) to plate-like ones (Figs. 2c, Fig. 3c). This suggests that Be caused a "demodification" of the alloy, even though several authors have confirmed the modifying effect of Be in various aluminum alloys [5-7].

2.2 Evaluation of physical properties

Based on the results of the electrical conductivity measurements and calculation of thermal conductivity values, the highest electrical and thermal conductivity (Table 3) was achieved by the alloy with an addition of 0.12 wt.% Be. Additions of 0.05 wt.% and 0.08 wt.% had a negative impact on the physical properties, performing worse than the alloy without any alloying additions.

Table 3. Electrical and thermal conductivity results

Alloy as-cast state	**Electrical conductivity σ [% IACS]**	**Thermal conductivity λ [$W \cdot m^{-1} \cdot K^{-1}$]**
AlSi5Cu2Mg **+ 0 wt.% Be**	36.4	143.0
AlSi5Cu2Mg **+ 0.05 wt.% Be**	34.9	136.4
AlSi5Cu2Mg **+ 0.08 wt.% Be**	35.5	138.9
AlSi5Cu2Mg **+ 0.12 wt.% Be**	37.5	147.8

3. CONCLUSION

Based on the obtained results, though they are partial, it can be concluded that:

- The structural analysis confirmed the positive effect of adding Be to the AlSi5Cu2Mg alloy.
- The Be has a grain-refining effect on the tested alloy, specifically on the α-(Al) phase.
- The refining effect increased with a higher proportion of the alloying element.
- The Be influences the physical properties of the tested alloy in the as-cast state.
- The most significant effect was observed with an addition of 0.12 wt.% Be.
- The shape, size, and morphology of the phases fundamentally influence electrical and thermal conductivity, which depends on the mobility of free electrons and the vibrational waves of the crystal lattice. Lattice defects (e.g., intermetallic phases, inclusions, and porosity) act as sites where electrons are scattered, leading to decreased conductivity.

The study on the effect of Be on the low-silicon alloy confirmed its positive influence on grain refinement in the as-cast state. Further research will focus on analyzing mechanical characteristics, porosity, the effect of non-standard heat treatment regimes, and the influence of Be on the morphology of iron-rich phases.

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