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The Effect of Minor Additions of Be on the Microstructure of AlSi5Cu2Mg Alloys

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Abstract

In this work, the effect of minor additions of Be as an alloying element on the structural properties of the low-silicon AlSi5Cu2Mg alloy was investigated. The aim was to implement a non-standard addition to the AlSi5Cu2Mg alloy, which would lead to an improvement in mechanical properties, mainly elongation, carried out crystallization and stabilize intermetallic phases of the preparation. The results show that Be additions in the range of 0.05 wt. %, 0.08 wt. % and 0.12 wt.% in the low-silicon AlSi5Cu2Mg alloy affect crystallization by refining the grain size and affecting the structural integrity of undesirable iron-rich phases. Be acts as a grain refiner in low-silicon AlSi5Cu2Mg alloys, refining α-(Al). Be had a significant effect on the shape, size and morphology of the intermetallic phases. Compact skeletal Fe-based phases were destabilized and fragmented into Chinese-character particles and fine spherical particles. The change contributed to the improvement of mechanical properties and reduced the degradation effect of the Fe plate phases. The refining effect increased with higher Be addition. This refining significantly improved tensile strength (R_m) and elongation (A_{50}), with the strongest effect at 0.12 wt. % Be. The separate melting and the addition of AlBe5 in the liquid state were shown to be effective and correct.

Keywords: AlSi5Cu2Mg, Alloying Be, Mechanical characteristics, Microstructure

1. Introduction

Currently, almost every car manufacturer offers vehicles with an alternative powertrain (LPG, CNG, electric drive). Vehicles with electric drive (fully electric or hybrid) form the largest part of the alternative powertrain portfolio. The boom in these vehicles also affects component manufacturers. Electric vehicles contain parts made of aluminum alloys, such as traction battery casings and covers, electric motor housings, parts of electric drive axles, and structural parts (reinforcements, strut towers). A significant portion of these parts is manufactured by casting, which is why the transition to electromobility also represents a challenge for foundries to produce new alloys that meet specific criteria for castings intended for electric vehicles.

For these reasons, it is necessary to focus on the development of new types of aluminum alloys that would meet the required criteria, such as high ductility, low weight, thermal conductivity, corrosion resistance, wear resistance, etc. Currently, development is focused on alloying existing alloys, for example, with transition elements, as well as non-standard alloying elements. These elements are characterized by the formation of, for example, thermodynamically stable intermetallic phases, which manifests itself in an improvement of mechanical, chemical, and physical properties at ambient temperature and at elevated temperatures [1].

Al-Si-Cu-Mg type aluminum alloys are among the most important alloys, constituting 85 to 90% of the total castings used in the automotive industry. Thanks to very good specific strength (strength-to-density ratio), good castability, and thermal conductivity, these alloys are used, for example, in the production of cylinder heads and engine blocks. In addition to use in the automotive industry, these alloys are often used in the production of structural components for aircraft and helicopters, compressor casings, compressor pistons, fuel pumps, and the like.

A large area of new alloy development is also focused on ultra-large, structurally very complex castings, the so-called gigacasts (castings with dimensions of 2.5 x 2.5 x 0.5 m) cast by HPDC (High-Pressure Die Casting), for which standardly available alloys are no longer suitable. A near-eutectic composition (10 wt.% – 12 wt. % Si) helps with fluidity and reduces shrinkage, but significantly reduces tensile ductility, even with modification. Several authors recommend using low-Si alloys to achieve higher ductility, e.g., [2, 3], as well as a balanced content of Cu and Mg.

As is generally known, magnesium together with copper allows Al-Si-Cu-Mg alloys to be heat-treated using precipitation hardening. Strengthening precipitates are formed, which significantly affect the improvement of the strength characteristics of these alloys. However, the use of castings made of Al-Si-Cu-Mg alloys in the automotive and aerospace industries is limited by a maximum operating temperature of up to approximately 200 °C. Exceeding these temperatures leads to the degradation of the basic strengthening phases, such as Mg_2Si and Al_2Cu. The degradation of such phases at temperatures above 200 °C is manifested by a loss of their stability, rapid coarsening, and subsequent dissolution. This leads to a significant decrease in mechanical properties.

For this reason, the use of Al-Si-Cu-Mg alloys in current combustion engines is limiting, as operating temperatures in the most thermally stressed parts of the engines (e.g., bridge areas between exhaust valves in cylinder heads) often exceed 200 °C. A similar problem may also arise when using such alloys for thermally loaded castings intended for electric vehicles (electric motor housings, battery cooling modules, etc.) [1].

Understanding the effects of various alloying elements on aluminum alloys is fundamentally important for potential applications in the metallurgical process. Fig. 1 shows the periodic table with the marked alloying elements divided into specific groups with their effect on Al-Si type alloys [4-6].

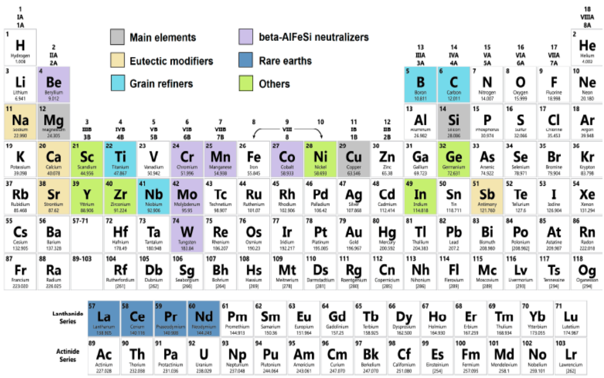


Fig. 1. Representative periodic table with indication of the main elements covered in this review, classified into specific groups according to different colors [6]

The research also involves varying the heat treatment processes. Within the heat treatment processes, emphasis is placed on the resulting ductility of the castings as well as the yield strength ($R_{p0.2}$). In newly developed alloys, T7 and T4 heat treatments are preferred. The effect of different heat treatment processes on the yield strength and ductility of selected alloys for the production of electromobility components are shown in Fig. 2 [7].

According to [6, 8-9], beryllium (Be) has the ability to mitigate the brittleness of castings caused by plate-like iron-based intermetallic phases, i.e., it acts as an iron-phase corrector. Due to Be, the morphology of AlFeSi changes from plate-like morphology to a skeletal or Chinese script morphology. This transformation positively affects the strength-to-ductility ratio. T4 heat treatment with the use of graded amounts of Be also had a positive effect on grain refinement and the uniform distribution of iron phases in the microstructure [6, 8 -13].

The reduction of oxidation of aluminum alloys has been confirmed by several authors [e.g. 10].

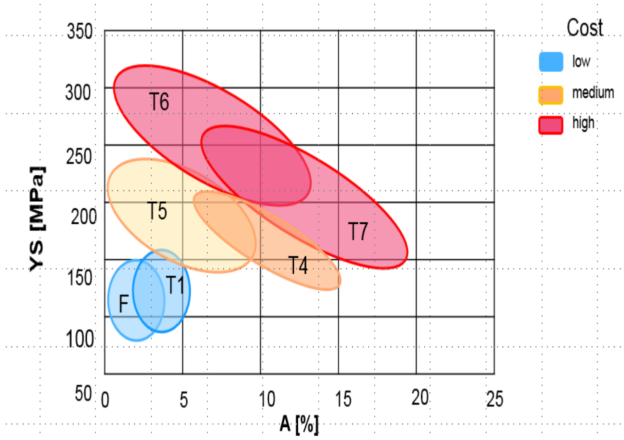


Fig. 2. Impact of various heat treatment processes on the yield strength and elongation of selected alloys for production of e-mobility components [7]

The aim of the work was to determine the effect of a minor addition of Be on the mechanical properties and microstructure of a low-Si aluminum alloy.

2. Experimental work

2.1. Methodology of experimental work

The aluminum alloy AlSi5Cu2Mg was selected for the experiments. In comparison with standard Al alloys, it differs in:

- low silicon content,
- limited titanium content (max. 0.03 wt.%).

Due to the restriction in Ti, the standard grain refiner AlTi5B cannot be applied for the refinement of AlSi5Cu2Mg.

A primary AlSi5Cu2Mg (Tab. 1) alloy with a mass of 7 kg was melted in an electric resistance furnace in a graphite crucible. Experimental alloys were prepared by alloying the primary AlSi5Cu2Mg alloy with 0.05, 0.08, and 0.12 wt. % Be, which was added in the form of the AlBe5 master alloy. The amounts of Be addition used were selected based on a study of the literature [8-13]. Due to better utilization of the alloying element, reduced oxidation, and health protection against negative effects, the AlBe5 master alloy was melted separately and briefly (2 to 3 min.) in an electric induction furnace in a closed graphite crucible. The molten

AlBe5 master alloy was then poured into the molten aluminum alloy and thoroughly mixed. The alloying temperature ranged from 730 to 740 ºC. Due to possible influence and synergistic effects, the prepared alloys were intentionally not inoculated, modified, or degassed by us. Casting was performed by gravity into a permanent steel mold coated with a refractory coating at a temperature of 740 to 750 ºC. The mold temperature ranged from 140 to 150 ºC. The chemical composition of the obtained alloys is given in Tab. 2.

10 samples were cast from each series. Five samples were evaluated in the as-cast state, and 5 samples were evaluated after heat treatment.

The heat treatment was selected with an emphasis on Fig. 2, using the T7 regime (artificial aging with overaging of the alloy) with the parameters:

- Solution heat treatment at 500 ± 5 °C for 6.5 hours;
- Rapid cooling (quenching) in water with a temperature of 85 ± 5 °C;
- Artificial aging at 250 ± 5 °C for 4 hours.

Heat treatment in the T7 regime affects some mechanical properties of aluminum alloys (some are purposefully reduced, e.g., UTS (R_m), Yield Strength ($R_{p0.2}$), with the aim of improving the dimensional stability of castings, elongation, reducing residual stresses, increasing physical properties, etc.

Mechanical property tests were performed in accordance with the standard STN EN ISO 6892-1 using the WDW-20 testing machine, with deformation recorded throughout the test using an extensometer. The crosshead speed was kept constant for all samples at 0.083 $mm \cdot s^{-1}$. The resulting values are the average values from 5 samples rounded to one decimal place. Fig. 3 shows the experimental form and dimensions of the test specimens.

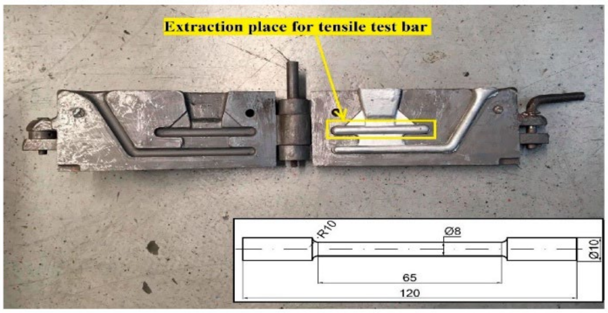


Fig. 3. Metal mold and scheme of the tensile test bar

The microstructure of the experimental alloys was evaluated by standard procedures, and images were taken on a Keyence VHX - 7000 digital microscope in the as-cast state and after heat treatment. The DAS index (Dendrite Arm Spacing) was determined using the integrated image analysis software of the Keyence VHX - 7000 microscope. The calculation was performed according to formula 1 and the simple scheme in Fig. 4.

$$DAS = L/(n-1) \quad (1)$$

n - number of secondary axes

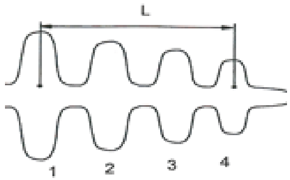


Fig. 4. DAS index measurement methodology

Phase identification was performed using a scanning electron microscope (SEM) via mapping.

3. Results

3.1. Mechanical properties

Fig. 5 shows the graphical dependencies of ultimate tensile strength (R_m), yield strength ($R_{p0.2}$), and elongation (A_{50}) on the graded amount of Be in wt. % in the as-cast state and after T7 heat treatment. In the as-cast state, the use of 0.08 wt. % Be resulted in an increase in ultimate tensile strength of approximately 10 % compared to the alloy without beryllium. The yield strength also increased by approximately 10 % for the alloy alloyed with 0.08 wt. % Be. Elongation for the same alloy increased by approximately 30 %.

After T7 heat treatment, the samples with Be addition had higher ultimate tensile strength but lower yield strength in all evaluated cases. Beryllium had a significant effect on ductility, where a significant increase occurred.

It can be stated that a significant effect of Be on some mechanical characteristics was demonstrated, and the selected T7 heat treatment regime is suitable for increasing R_m and A_{50}.

3.2 Microstructure

Microstructural images are shown in Figs. 6–8. Phase mappings are presented in Figs. 9–10.

The as-cast microstructure of AlSi5Cu2Mg consists of the α-(Al) phase, eutectic Si, and intermetallic phases based on Cu and Fe. Since the alloy was partly grain-refined and modified in its base state, the α-phase was refined (Figs. 6a, 7). In all investigated alloys, increasing Be content led to further refinement of the α-phase and dendrite fragmentation, as evidenced by the decrease of the dendrite arm spacing index (DI) from 32.414 µm to 23.096 µm (approx. 30% refinement). Metallographic sections revealed eutectic Si in the form of imperfect and perfect rounded particles, without plate-like morphology (Fig. 7). This indicates that the alloy exhibits optimal phase morphology for balanced mechanical properties.

The microstructure of AlSi5Cu2Mg without Be after T7 heat treatment is shown in Fig. 6b. T7 treatment promoted intensive spheroidization of eutectic Si. With increasing Be content, eutectic Si precipitated as very fine, perfectly globular particles.

Phases based on Fe, Cu, and Mg were identified. With higher Be content, both in the as-cast and T7 heat-treated conditions, fragmentation of Fe-rich phases such as β-Al_5FeSi, $Al_{12}(FeMnMg)_3Si_2$, and $Al_{15}(FeMn)_3Si_2$ occurred, changing from skeletal morphologies to fine Chinese-script or globular particles (Figs. 9, 10). The complex phase Al_8Fe_2BeSi [8] was not detected. Cu- and Mg-based intermetallics decreased in size and fragmented with increasing Be content, both in as-cast and heat-treated conditions.

Thus, the stepwise addition of Be to alloys with low Si content significantly altered the morphology of intermetallics.

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.

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**

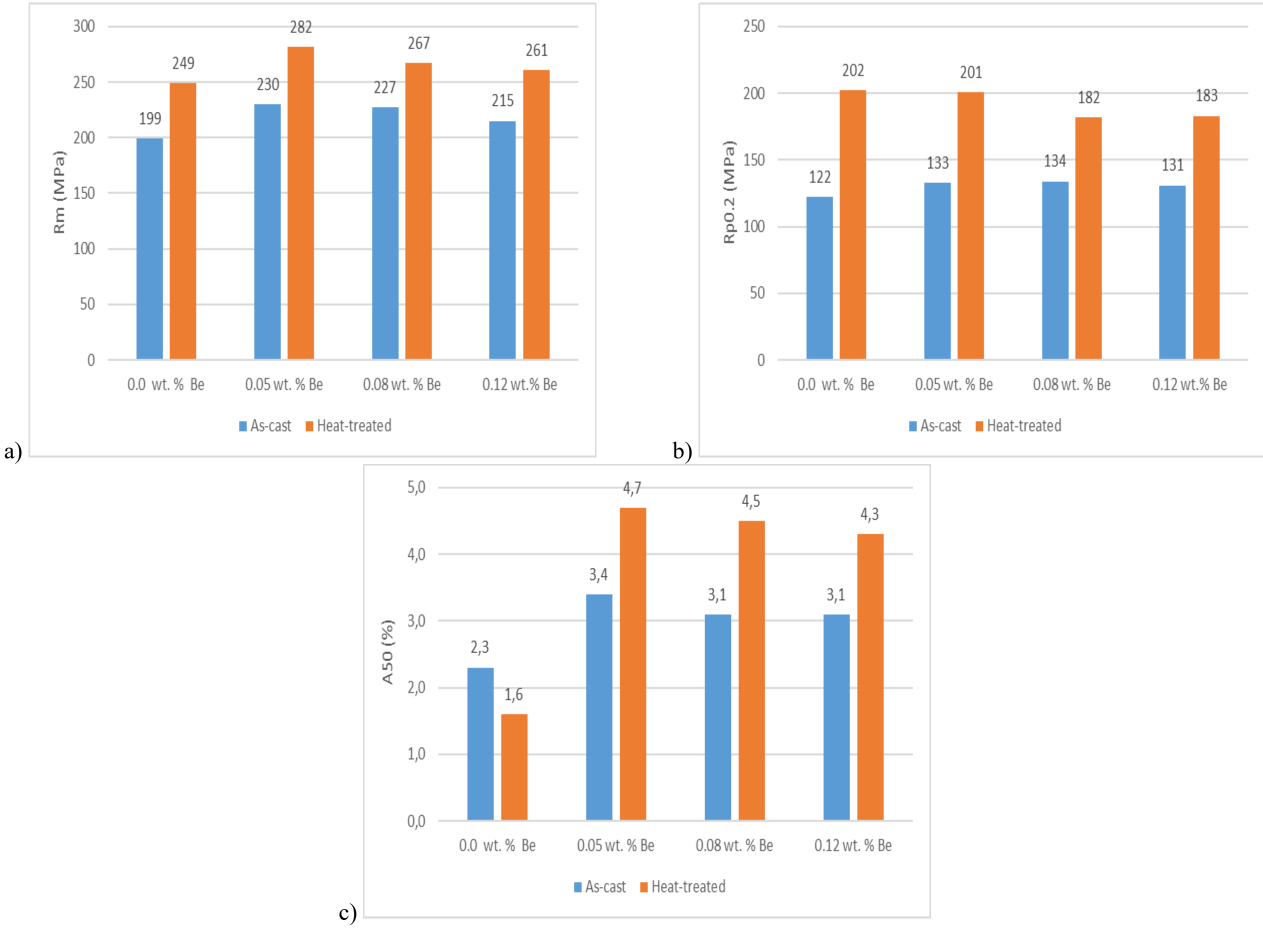
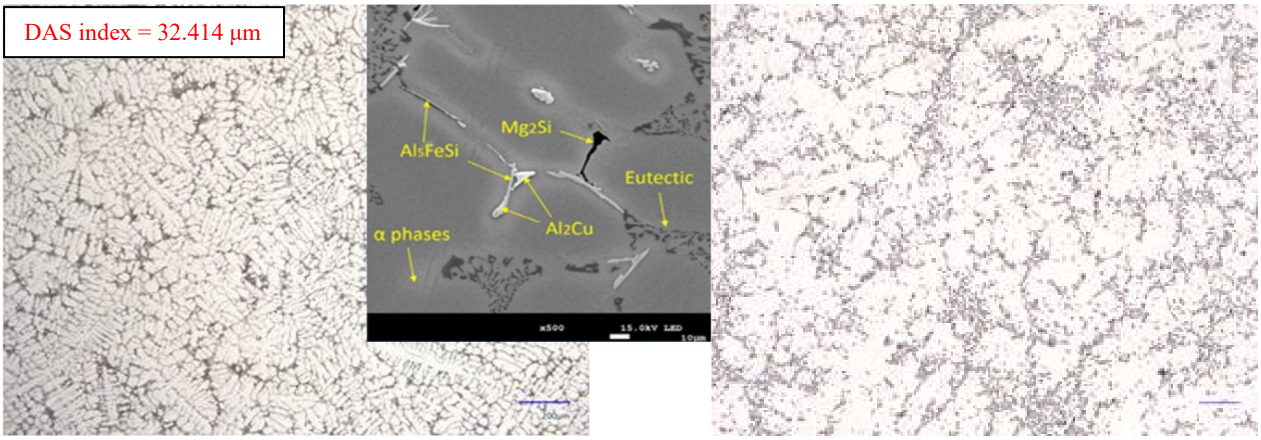
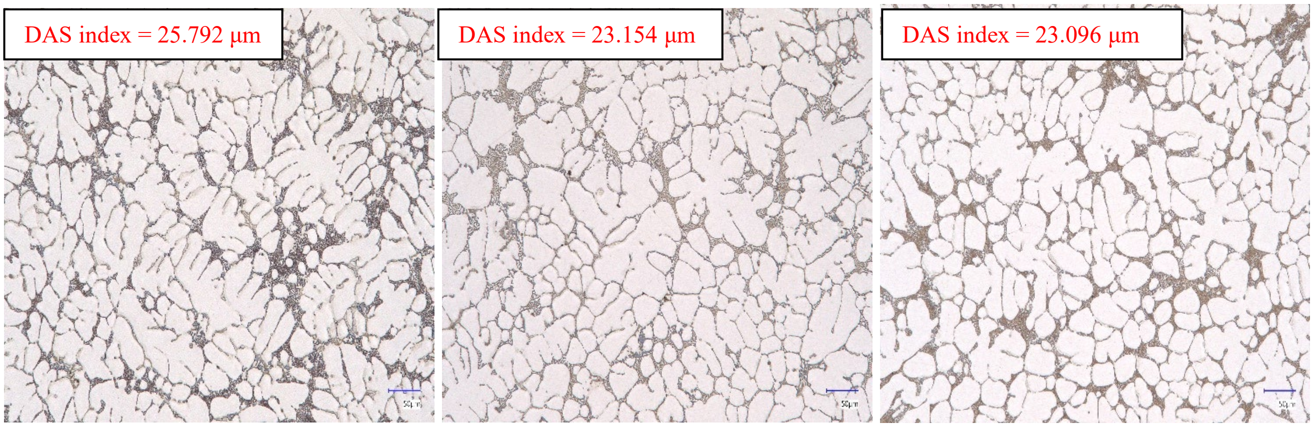


Fig. 5. Mechanical properties of the experimental alloys AlSi5Cu2Mg with addition of Be in wt.% a) tensile strength R_m b) yield strength $R_{p0.2}$ and c) elongation (A_{50})



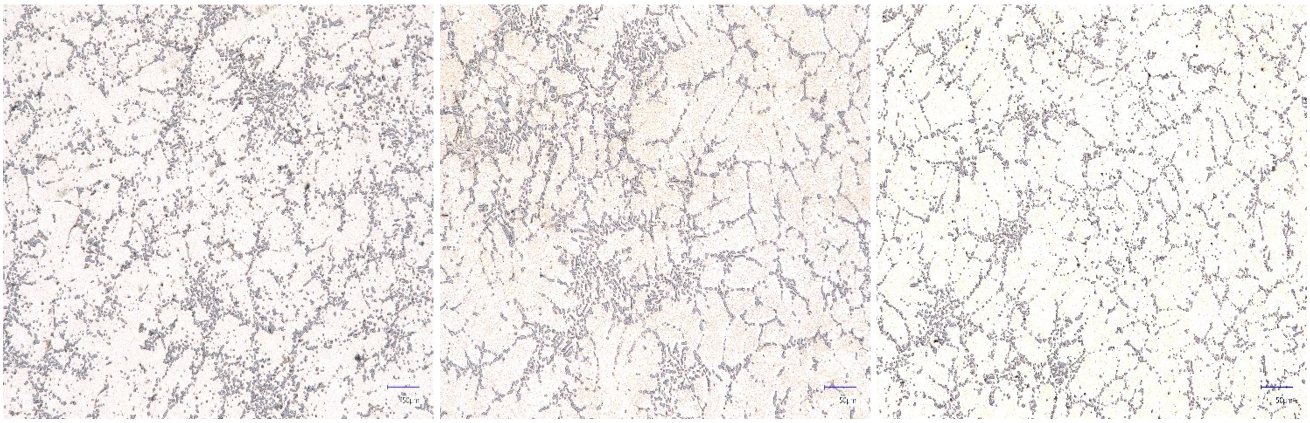
a) b)

Fig. 6. Microstructure of the AlSi5Cu2Mg alloy 0 hm.% Be in the a) as-cast state, SEM b) after T7



a) b) c)

Fig. 7. Microstructure of the AlSi5Cu2Mg alloy in the as-cast state: a) 0 wt. % 0.05 Be, b) 0.08 wt. % Be, c) 0.12 wt. % Be



a) b) c)

Fig. 8. Microstructure of the AlSi5Cu2Mg alloy after T7: a) 0.05 wt. % Be, b) 0.08 wt. % Be, c) 0.12 wt. % Be

a) b) c)

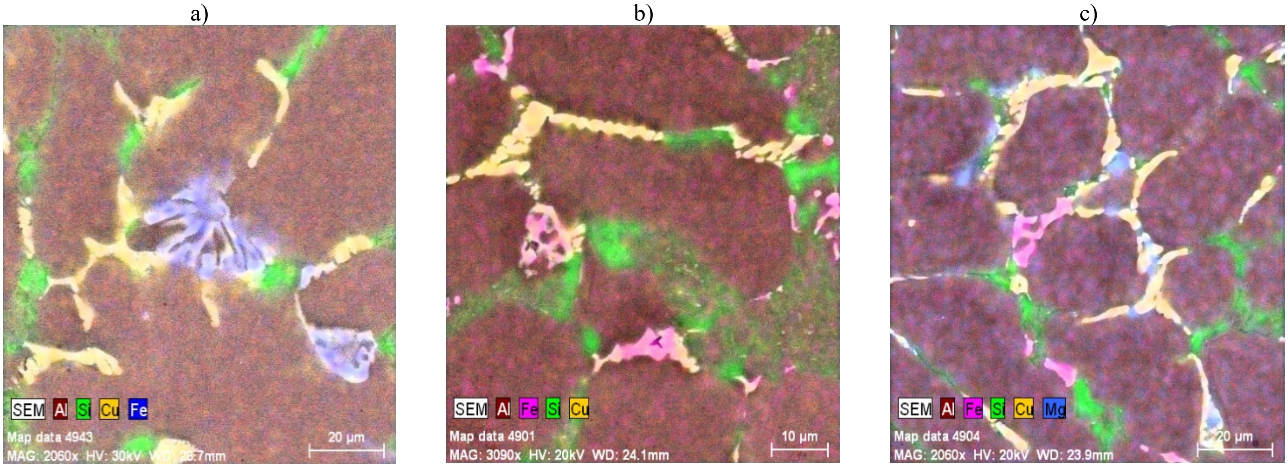


Fig. 9. Microstructure of the AlSi5Cu2Mg alloy in the as-cast state mapping: a) 0 wt. % 0.05, b) 0.08 wt. % Be, c) 0.12 wt. % Be

a) b) c)

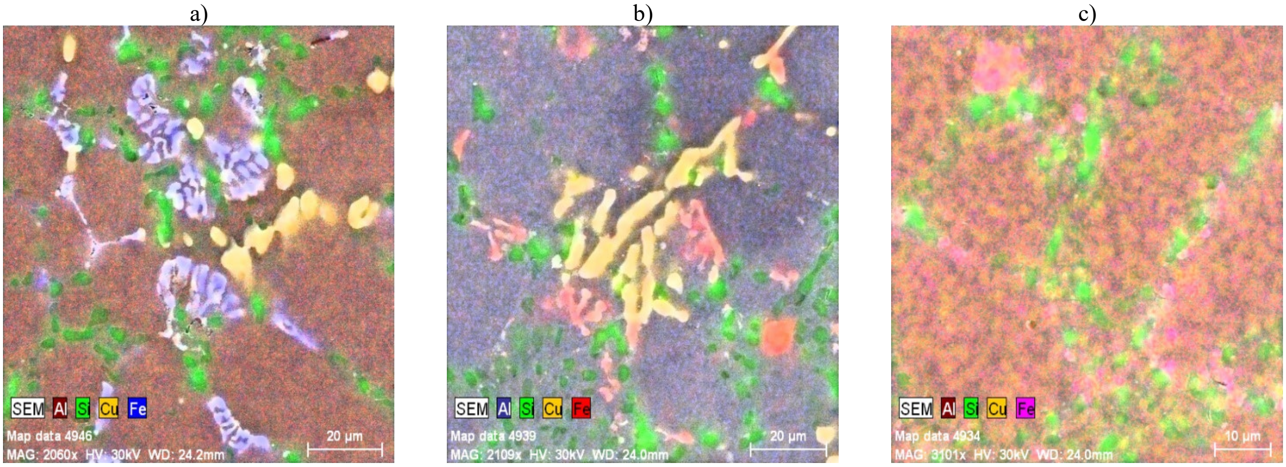


Fig. 10. Microstructure of the AlSi5Cu2Mg alloy after T7 mapping: a) 0.05 wt. % Be, b) 0.08 wt. % Be, c) 0.12 wt. % Be

4. Discussion

The aim of the work was to determine the effect of minor additions of Be (0.05 – 0.12 wt. %) on the mechanical properties and microstructure of AlSi5Cu2Mg, with emphasis on the development of a new alloy for complex and demanding castings in the automotive and aerospace industries. Understanding the effects of trace element additions is crucial in developing new alloys for specific applications (e.g., improved component performance, weight reduction, energy savings, changes in electrical/thermal conductivity, etc.).

The addition of Be refined the α-phase (Figs. 1 – 3), i.e., Be acted as a grain refiner. The most pronounced refinement was obtained with the highest addition (0.12 wt. % Be; Fig. 6c). The presented results thus extend the evidence of Be as a grain-refining elementin aluminum alloys.

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Be additions also altered the morphology and size of intermetallic phases, both in the as-cast and heat-treated conditions. Literature mainly describes effects on Fe-rich intermetallics [4, 6, 8, 10 –12], but fragmentation of Cu-containing phases and their morphological changes have not been widely reported.

Even minor Be additions (0.05 – 0.12 wt. %) had a significant impact on mechanical properties and microstructure, offering a promising balance in improved mechanical characteristics not achievable in traditional Al alloys without such additions.

However, it must be emphasized that Be is a harmful element and its compounds are toxic, mainly in the form of salts, dust, and gases. Further research on the toxicity of Be additions (introduced via AlBe5) and its impact in alloyed form is required. A safe procedure of short separate melting in a closed crucible was therefore applied. Another disadvantage is the relatively high cost of Be. Despite these drawbacks, the observed trends were positive.

5. Conclusions

Based on the summarized (though partial) results, it can be concluded that:

- Be acts as a grain refiner in AlSi5Cu2Mg alloys, refining α-(Al). The refining effect increased with higher Be additions. This refinement significantly improved tensile strength (R_m) and elongation (A_{50}), with the strongest effect at 0.12 wt. % Be.
- Be had a marked influence on the shape, size, and morphology of intermetallic phases. Compact skeletal Fe-based phases were destabilized and fragmented into Chinese-script and fine globular particles. This change contributed to the improvement of mechanical properties and reduced the degrading effect of plate-like Fe phases.
- The separate melting and addition of AlBe5 in the liquid state proved effective and correct.

Further research will focus on the evaluation of physical properties, the influence of Be on density and porosity, the effect of non-standard heat treatment regimes, and the impact of Be on Cu- and Mg-based intermetallics.

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