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# DEVELOPMENT OF THE AL-SI ALLOY WITH NIOBIUM ADDITION FOR GIGACASTINGS

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**Abstract**

*The article focuses on developing a new aluminum alloy based on Al-Si that is alloyed with the non-standard element niobium (Nb). The research aims to evaluate the effect of Nb addition on the microstructure and porosity area fraction of the AlSi5Cu2Mg alloy. The study will determine the optimal amount of Nb to add. Microstructural analysis revealed that adding Nb refines the primary phase, α-(Al), and the eutectic Si and reduces the size of the iron-rich phases. Nb's effectiveness as a modifier and inoculant increases with greater additions. Adding Nb resulted in a favorable decrease in the area fraction of porosity in the aluminum alloy, with the area fraction of porosity decreasing with increasing Nb additions.*

***Keywords**: aluminum alloys, niobium, gigacastings.*

## 1. INTRODUCTION

The automotive industry is under increasing pressure to reduce emissions, improve energy efficiency, and optimize manufacturing processes. Amid these challenges, large-scale aluminum castings, or "gigacasts," are gaining prominence by combining multiple vehicle parts into one component [1]. The advantages of using large-scale castings include reduced weight, fewer welded joints, and enhanced structural integrity. In electromobility, large-scale castings contribute to an extended driving range, higher energy efficiency, and reduced overall energy consumption. However, the practical application of large-scale castings presents several design and technological challenges. These include difficulty ensuring a uniform microstructure, risk of porosity and cracking, and limited repairability. Nevertheless, large-scale castings have the potential to become a key element in the future of automotive manufacturing. [2,3]

Aluminum-silicon (Al-Si) alloys with approximately 10 wt.% Si are standard structural materials for large-scale castings. While these alloys have excellent casting properties, their mechanical properties often fail to meet requirements for large-scale structural castings, limiting their application. An effective way to optimize the mechanical properties of Al-Si alloys is to lower the silicon content. Decreasing the silicon content reduces the amount of brittle eutectic phases, thereby improving the mechanical properties. Another promising approach to improving the properties of aluminum alloys for large-scale applications is using transition elements (e.g., Nb, Zr, and Ni) as alloying elements. These elements are notable for their tendency to form thermodynamically stable $Al_3X$ dispersoids. Thermally stable niobium-based phases play a significant role in maintaining mechanical properties under elevated operating conditions. Current research focuses on developing a novel, low-silicon, Al-Si-based aluminum alloy with niobium as an unconventional alloying element for large-scale structural castings [4,5].

## 2. EXPERIMENTAL METHODOLOGY

For experimental purposes, a hypoeutectic aluminum alloy, AlSi5Cu2Mg, was selected. This alloy is characterized by a low silicon content (5.0 – 6.5 wt.% Si). The chemical composition of the AlSi5Cu2Mg alloy is provided in Table 1.

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

| Alloy | Si | Cu | Mg | Mn | Fe | Cr | Sr | Al |
|---|---|---|---|---|---|---|---|---|
| **AlSi5Cu2Mg** | 6.48 | 1.92 | 0.29 | 0.013 | 0.19 | 0.004 | 0.03 | Bal. |

The hypoeutectic aluminum alloy AlSi5Cu2Mg was melted in an electric resistance furnace using a graphite crucible. Experimental alloys were prepared by alloying the AlSi5Cu2Mg base alloy with 0.1, 0.15, and 0.20 wt.% Nb. Niobium was added to the melt in the form of an AlNb10 master alloy. This master alloy was melted separately in an electric induction furnace within a graphite crucible and then added to the main melt. Experimental samples were cast using a gravity casting technique in an open atmosphere with a permanent mold. The permanent mold, treated with a graphite coating, was maintained at a temperature of 150 ± 5 °C. The casting temperature was set at 750 ± 5 °C. The chemical composition of the experimental alloys is provided in Table 2. Chemical analysis revealed a discrepancy between the nominal and actual measured Nb additions. This difference could be attributed to the limited solubility of Nb, Nb segregation during solidification, or losses during melt handling.

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

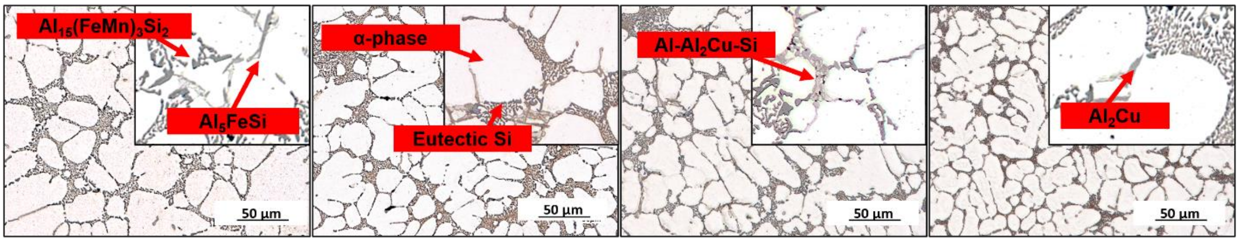
| Alloy | Si | Cu | Mg | Mn | Fe | Sr | Nb | Al |
|---|---|---|---|---|---|---|---|---|
| **AlSi5Cu2Mg + 0.10 wt.%** | 6.52 | 2.40 | 0.25 | 0.012 | 0.23 | 0.004 | **0.049** | Bal. |
| **AlSi5Cu2Mg + 0.15 wt.%** | 6.58 | 2.46 | 0.19 | 0.014 | 0.23 | 0.005 | **0.063** | Bal. |
| **AlSi5Cu2Mg + 0.20 wt.%** | 6.82 | 2.34 | 0.19 | 0.012 | 0.22 | 0.006 | **0.076** | Bal. |

For each experimental variant, a set of 10 test samples was prepared for the analysis of mechanical and physical properties. Half of these samples were subjected to a T7 heat treatment regime, which consisted of solution heat treatment (500 ± 5 ºC for 6.5 h), rapid cooling (85 ± 5 ºC), and aging (250 ± 5 ºC for 4 h). Microstructural analysis and evaluation of area fraction porosity were performed on samples that demonstrated an optimal combination of mechanical and physical properties. The microstructure of the experimental alloys was examined in both the as-cast condition and after T7 heat treatment using a Keyence VHX – 7000 digital microscope. Porosity was determined based on the assessment of the area fraction of pores, which was evaluated using the graphical software Quick Photo Industrial 3.1.

## 3. RESULTS AND DISCUSSION

### 3.1 Microstructure analysis

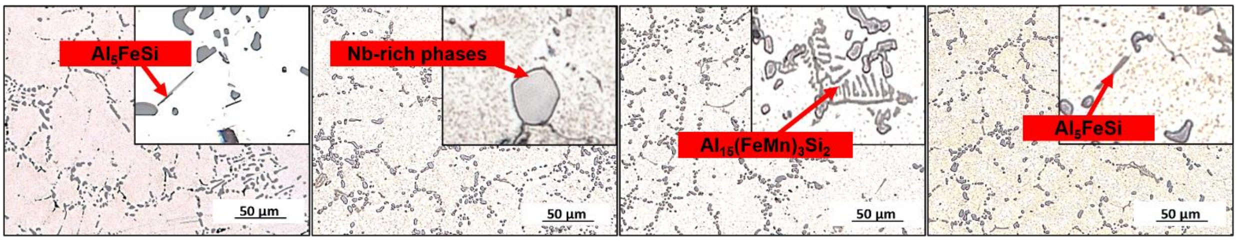
The microstructure of the AlSi5Cu2Mg alloy without Nb addition consists of the primary α-(Al) phase, eutectic Si, and Cu- and Fe-based phases (Figure 1a). In the plane of the metallographic cross-section, the eutectic Si appears as imperfectly rounded grains. The morphology of the as-cast eutectic Si does not exhibit the typical plate-like shape because the AlSi5Cu2Mg alloy was supplied in a pre-modified state. The Fe-based intermetallic phases were observed in two morphologies: plate-like β-$Al_5FeSi$ and segmented chinese script-like $Al_{15}(FeMn)_3Si_2$. Cu-rich intermetallic phases were precipitated as a compact ternary eutectic of Al-$Al_2Cu$-Si or as isolated $Al_2Cu$ particles. Microstructures of the alloys with graded Nb additions are shown in Figure 1b-d. The addition of Nb led to a significant grain refinement of the primary α-(Al) phase and refinement of the eutectic Si. A reduction in size and fragmentation of the Fe-based intermetallic phases were also observed in the metallographic cross-sections of the Nb-containing alloys. Microstructural analysis demonstrated a clear correlation between the Nb addition and the refinement of the AlSi5Cu2Mg alloy's microstructure, with the most significant refinement achieved at the highest Nb content. In the alloy with a 0.10 wt.% Nb addition, large compact particles were locally observed. These particles were identified as Nb-rich phases. These phases were not observable in the alloys with 0.15 and 0.20 wt.% Nb additions.




a) b) c) d)

*Figure 1. Microstructure of the AlSi5Cu2Mg alloy in the as-cast state: a) 0 wt.% Nb, b) 0.10 wt.% Nb, c) 0.15 wt.% Nb, d) 0.20 wt.% Nb.*

The microstructure of the AlSi5Cu2Mg alloy without Nb after T7 heat treatment is shown in Figure 2a. The T7 treatment leads to the spheroidization of eutectic Si, which precipitates in the form of perfectly rounded grains. The Mg- and Cu-rich intermetallic phases were dissolved during the T7 heat treatment and subsequently reprecipitated as strengthening precipitates. Fe-based phases were observed in the metallographic cross-section of the AlSi5Cu2Mg alloy in the form of plate-like β-$Al_5FeSi$. Similar to the as-cast state, grain refinement of the primary α-(Al) phase and refinement of the eutectic Si were also observed after the T7 treatment due to the Nb addition. Locally, fragmentation of the eutectic Si was observed, appearing as very small, perfectly rounded particles. The T7 heat treatment did not cause a change in the morphology or size of the segregated Nb-based phases, which were observed as large compact particles. This observation indicates the high thermal stability of the Nb-based phases.




a) b) c) d)

*Figure 2. Microstructure of the AlSi5Cu2Mg alloy after T7: a) 0 wt.% Nb, b) 0.10 wt.% Nb, c) 0.15 wt.% Nb, d) 0.20 wt.% Nb.*

### 3.2 Evaluation of the area fraction of porosity

The area fraction of porosity was determined based on the average of five measurements taken at randomly selected locations on the metallographic cross-sections of the experimental alloys. The values for the area fraction of porosity are listed in Table 3. The area fraction of porosity of the alloy without Nb addition was 0.6%. Alloys with an Nb addition showed a decrease in the area fraction of porosity compared to the alloy without Nb, with the area fraction of porosity decreasing as the Nb wt.% increased. An addition of 0.1 wt.% Nb led to a minimal decrease in the area fraction of porosity by 3% compared to the alloy without an Nb addition. The addition of 0.15 and 0.20 wt.% Nb resulted in a more significant decrease in the area fraction of porosity by 27% and 37%, respectively, compared to the alloy without Nb. In this case, Nb acts as an effective inoculant and also favorably modifies the eutectic Si. Due to the inoculating and modifying effects, a finer microstructure is formed, which minimizes porosity formation [6].

*Table 3. Area fraction of porosity of experimental alloys.*

| **Alloy** | AlSi5Cu2Mg | + 0.10 wt.% Nb | + 0.15 wt.% Nb | + 0.20 wt.% Nb |
|---|---|---|---|---|
| **Area fraction of porosity** | 0.60 % | 0.58 % | 0.44 % | 0.38 % |

## 4. CONCLUSION

The article focused on evaluating the effect of graded Nb addition on the microstructure and surface porosity of the AlSi5Cu2Mg aluminum alloy. Based on the summarized results, the following conclusions can be drawn:

- Microstructural analysis showed that the Nb addition led to grain refinement of the primary α-(Al) phase, refinement of the eutectic Si, and a reduction in the size and fragmentation of the Fe-based phases.
- The effectiveness of Nb in refining the microstructure of the AlSi5Cu2Mg alloy increased with a higher Nb content (wt.%).
- Due to the inoculating and modifying effect of Nb, a favorable decrease in the area fraction of porosity was observed. The area fraction of porosity of the aluminum alloys decreased with an increasing wt. % of Nb.

This article demonstrated that, due to its effective grain refinement and modifying effect, niobium has a beneficial influence on the microstructure and area fraction of porosity of the investigated AlSi5Cu2Mg aluminum alloy. Nb appears to be a promising alloying element for aluminum alloys intended for large-scale castings. Therefore, in the next step, the research will focus on investigating the influence of Nb on the foundry, mechanical, and physical properties of the AlSi5Cu2Mg aluminum alloy.

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