# MECHANICAL PROPERTIES AND EVOLUTION OF THE MICROSTRUCTURE OF Al-Cu-Mg SYSTEM ALLOYS UNDER THE INFLUENCE OF ALLOYING ELEMENTS (GE AND SI)

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**Abstract -** As the industrial use of aluminum alloys increases, scientists around the world conduct research aimed at improving their properties. This study analyzes the mechanical properties and phase changes of aluminum-copper-magnesium alloys with the addition of germanium and silicon. The samples were liquefied in foundry furnaces and poured into sand-clay molds. The temperature of pouring samples into molds was 750 °C. Germanium oxide and pure silicon were included in the composition of the samples during melting, germanium oxide was added in an amount of 1%, 2%, and 3% of the total weight, and silicon was added in an amount of 5% of the total weight. Cast samples were mechanically processed and tested. The change in hardness from mechanical properties was studied. In addition, microscopic analyses of the samples were carried out and changes in the size of grains constituting the microstructure of the alloy were analyzed. The results of the analysis show that the introduction of germanium and silicon into the composition of the samples reduced the dispersity of the grains of their microstructure and, as a result, increased the hardness. At the end of the article, the authors present the corresponding analysis and conclusions based on the results obtained in the experiments.

**Keywords**: Aluminum, Copper, Germanium oxide, Silicon, Mechanical properties, Microstructure's evolution, Casting furnace, Hardness, Magnesium.

## 1. Introduction

Aluminum alloys are the most widely used industrial alloys after iron-carbon alloys. The growth of the aluminum alloy market is due to the increasing demand for lightweight and high-strength materials in the automotive, aerospace, and construction industries [1-5]. This poses a challenge for scientists around the world to improve the properties of aluminum. It is common to add other elements to the composition of metal alloys and improve their mechanical, physical, and casting properties [6-14]. In particular, G.T. Abdel-Jaber investigated the mechanical properties of silicon content (3-15%) in Al-Si alloys. As the Si content increased, the solidification time also increased, and it was observed that the liquid temperature decreased in accordance with the percentage of silicon up to 12%, with an increase in silicon content from 3% to 8%, the tensile strength slightly increased [15]. Research on the effect of Germanium element on the microstructure and properties of Al-Si welding material by Zhiwei Niu, Jihua Huang, Shuhai Chen, Xingke Zhao, staff members of the Department of Material Science and Engineering, Beijing University of Science and Technology conducted experiments on adding germanium as an alloying agent in different percentages to the aluminum-silicon alloy. In the experiments, the Al-Si-Ge alloy was first liquefied. For this purpose, the elements of 99.99% pure aluminum, 99.99% pure silicon, and 99.999% pure germanium were used. Aluminum and silicon were melted in a vacuum furnace at a temperature of 700°C, and then the furnace temperature was increased to 1000°C. Then, different amounts of germanium were added to the molten Al-12Si alloy and stirred for 30 minutes to homogenize the amount of lumen. When 10% Ge was added to the alloy, the eutectic microstructure consisted of more dispersed particles.

When the Ge content reaches 20%, the eutectic structure gradually increases and large primary Si-Ge particles are formed [16]. In their paper “Precipitation and Hardening in Al-Si-Ge”, researchers from the University of California, D. Mitlin, et al., investigated the precipitation strengthening resulting from the addition of 1% Ge and 1% Si to an aluminum alloy. The samples analyzed were Al-1% Si-1% Ge. Micropeak analysis showed that the dispersed Si-Ge conglomerate was formed as nuclei with a cubic-cubic orientation toward the matrix. EDXS analysis showed that the stoichiometry of the dispersions was different, the average composition was about Si-44.5% Ge. High-resolution TEM analysis showed that all dispersed concentrations of Si-Ge were added multiple times. Binary systems have a rounded appearance due to the loss of coupling of cubic directions between the binary matrix and the focus [17]. M. Victoria Castro Riglos et al. in a research paper titled "Accelerated Crystallization by Plastic Deformation in Al-Cu Alloy by Addition of Very Small Amounts of Si and Ge" showed that the very fast crystallization of Al-Cu alloy without recovery had a maximum hardness of 8% before artificial aging, and a small amount of alloying elements Si and Ge were included in the deformation. The transmission mechanism during the accelerated crystallization was determined by a detailed study of the properties using an electron microscope.

It was found that plastic deformation increases the rate of Si–Ge crystal formation, which leads to an increase in the bulk density. Such dispersed concentration catalyzes the formation of θ' and causes concentration [18]. But in the researches carried out, they were conducted for alloys of binary systems. In this article, based on the above studies, the authors introduced germanium oxide and pure silicon element into the aluminum-copper-magnesium ternary alloy and analyzed the changes in its properties and microstructure.

## 2. Materials and Methods

The D16 alloy in the aluminum-copper-magnesium system was chosen as the object of the research. The composition of the D16 alloy is given in Table 1 below [19]. This alloy is an alloy of aluminum with copper and magnesium. Due to the elements contained in this alloy, it is a strong and lightweight material. Its hardness and mechanical strength are not inferior to steel, and its specific gravity is 3 times less [20].

*Table 1. Chemical composition of alloy D16*

| Fe | Si | Mn | Cr | Ti | Al | Cu | Mg | Zn | Inclusions | - |
|---|---|---|---|---|---|---|---|---|---|---|
| to 0.5 | to 0.5 | 0.3 - 0.9 | to 0.1 | to 0.15 | 90.9 - 94.7 | 3.8 - 4.9 | 1.2 - 1.8 | to 0.25 | 0.15 | Ti+Zr < 0.2 |

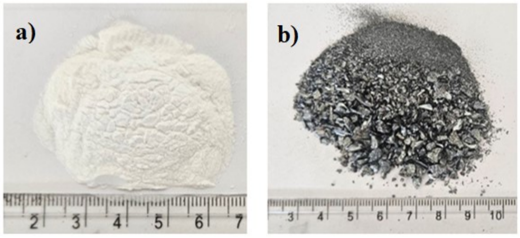


*Figure 1: (a) germanium oxide and (b) pure silicon.*

Germanium oxide and pure silicon were introduced into the samples as microalloying elements (Fig. 1). Germanium oxide is a binary inorganic compound, an amphoteric oxide. There are two types of modification: crystalline and amorphous. It has the appearance of a white powder. Germanium oxide varies in granulometric composition and mass density. It melts at +1115 °C. Density: 4.7 g/cm$^3$. It dissolves poorly in water. It is a toxic compound, and in small doses, it can be found in the atmosphere [21, 22].

Silicon is a shiny, grey, hard, brittle substance with a melting point of 1410 °C and a boiling point of 2350 °C. Amorphous silicon is brown and is more active than crystalline silicon. It is widely used in the production of many alloys, in radio and electrical engineering, in the conversion of solar energy into electricity, as batteries, in construction, and as an alloying element in the manufacturing industry [23].

## 3. Experiments

The samples were melted in a resistance furnace and poured into sand-clay molds (Fig. 2). The sand-clay molding mixture consists of quartz sand – 85%, bentonite clay – 11% and water 4%.

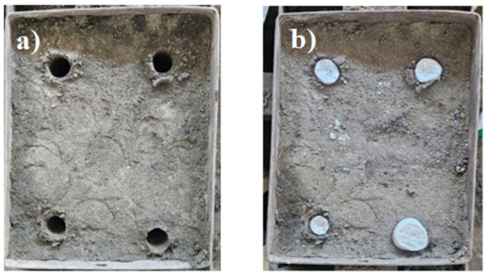


*Figure 2: Sand-clay mold (a) and cast samples (b).*

The samples were cast into molds at a temperature of 750 °C. This temperature is the optimum temperature for casting aluminum alloys [24]. The composition of the main elements of the samples in percentages is given in Table 2. The first sample was cast without adding any additives. In the following samples, 1% to 3% germanium oxide and 5% pure silicon were added to each sample.

Cast samples were separated from molds and cut on a lathe to measure hardness [25]. The cut samples are illustrated in Figure 3.

The cut samples were polished and buffed. The hardness of the polished samples was measured. The device "Rockwell FR Hardness Tester" (Fig. 4) was used to measure the hardness. The hardness of the samples was measured at three points on the surface of the polished part.

*Table 2: Amount of major elements in samples*

| № | Al | Cu | Mg | Ge | Si |
|---|---|---|---|---|---|
| Sample-1 | 90.9 - 94.7% | 3.8 - 4.9% | 1.2 - 1.8% | 0% | 0% |
| Sample-2 | 90.9 - 94.7% | 3.8 - 4.9% | 1.2 - 1.8% | 1% | 5% |
| Sample-3 | 90.9 - 94.7% | 3.8 - 4.9% | 1.2 - 1.8% | 2% | 5% |
| Sample-4 | 90.9 - 94.7% | 3.8 - 4.9% | 1.2 - 1.8% | 3% | 5% |

*Figure 3: Samples cut to measure hardness.*

In the following experiments, the chemical composition and microstructure of the samples were analyzed. The necessary small pieces were cut out of the samples for the study. The samples for sectional microscopic analysis were ground and then polished (Fig. 5).

For microscopic studies, the microscope "Quattro S" (Fig. 6) was used. With this microscope, the chemical composition and microstructure of the samples were studied.

*Figure 4: Hardness measuring device*

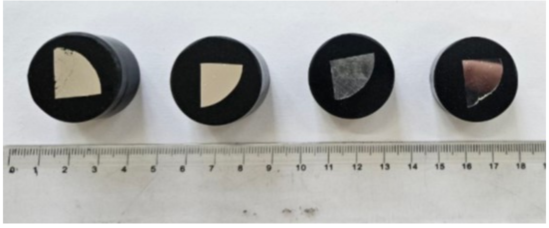

*Figure 5: Samples for microscopic analysis.*

For microscopic studies, a Quattro S microscope was used (Fig. 6). With this microscope, the chemical composition and microstructure of the samples were studied.

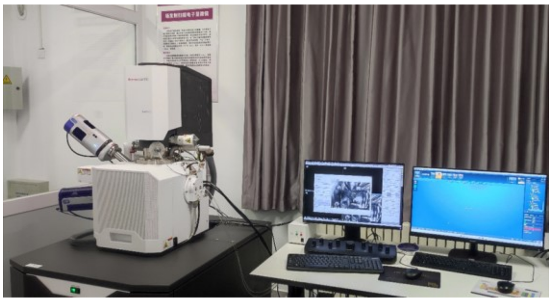

*Figure 6: SEM microscope*

## 4. Results and Discussions

The hardness of the samples was measured at three points of the polished surface. The measurement results are given in Table 3. The average value of the results measured at three points was taken as the final result according to the ISO standard [26]. Based on the results, a graph of the hardness of the germanium and silicon samples was constructed (Fig. 7). As can be seen from the results of the table and graph, it is clear that the hardness of the samples increased as a result of adding germanium and silicon as microalloying additives. It is clear from the graph that the hardness of the samples begins to increase at a germanium content of 1% and silicon of 5% of the total mass, and with an increase in germanium to 2%, the maximum hardness increases, and this is 3% germanium and 5% silicon, it is clear that the hardness decreases.

*Table 3. Hardness measurement results*

| **№** | **Al-Cu-Mg** | **Al-Cu-Mg-1%Ge-5%Si** | **Al-Cu-Mg-2%Ge-5%Si** | **Al-Cu-Mg-3%Ge-5%Si** |
|---|---|---|---|---|
| 1 | 18.2 | 21.1 | 20.8 | 22.7 |
| 2 | 12.8 | 22.2 | 23.9 | 16.8 |
| 3 | 19.2 | 18.5 | 21.8 | 19.2 |
| **Average** | 16.7 | 20.6 | 22.1 | 19.5 |

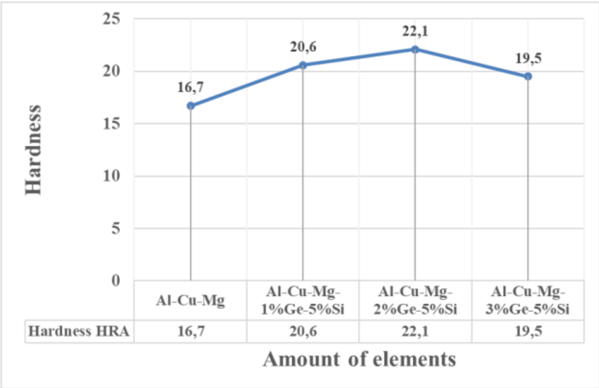


*Figure 7: Dependency graph*

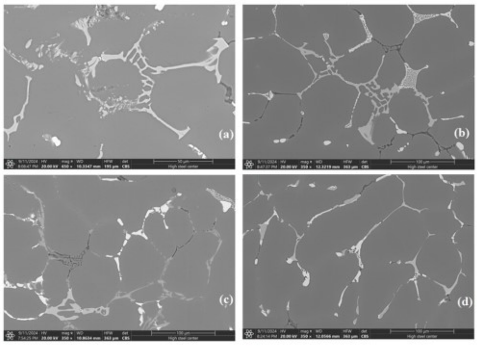


*Figure 8: Microstructure of samples: (a) Al-Cu; (b) Al-Cu-1.0 wt.% Ge-5.0 wt.% Si; (c) Al-Cu-2.0 wt.% Ge-5.0 wt.% Si; (d) Al-Cu-3.0 wt.% Ge-5.0 wt.% Si.*

*Table 4. Standard grain sizes (GOST 5939-82)*

| **Number grains (*G*)** | **Average area grain cross sections *a*, mm²** | **Number of grains per area 1 mm², *m*** | | | **Average number of grains in 1 mm³ (*N_v*)** | **Average grain diameter (*d_m*), mm** | **Average conditional grain diameter (*d_L*), mm** |
|---|---|---|---|---|---|---|---|
| | | minimum | medium | maximum | | | |
| 1 | 0.0625 | 12 | 16 | 24 | 64 | 0.250 | 0.222 |
| 2 | 0.0312 | 24 | 32 | 48 | 181 | 0.177 | 0.157 |
| 3 | 0.0156 | 48 | 64 | 96 | 512 | 0.125 | 0.111 |
| 4 | 0.00781 | 96 | 128 | 192 | 1448 | 0.088 | 0.0783 |
| 5 | 0.00390 | 192 | 256 | 384 | 4096 | 0.062 | 0.0553 |
| 6 | 0.00195 | 384 | 512 | 768 | 11585 | 0.044 | 0.0391 |
| 7 | 0.00098 | 768 | 1024 | 1536 | 32768 | 0.031 | 0.0267 |
| 8 | 0.00049 | 1536 | 2048 | 3072 | 92682 | 0.022 | 0.0196 |

The change in the microstructure of the samples is shown in Fig. 8. The microstructure of the samples was studied using a Quattro S microscope. According to the analysis, the microstructure of the samples is shown in Fig. 8 (a). The microstructure of the Al-Cu-Mg alloy is the base metal, where the main structural component is a solid solution of copper and magnesium in aluminum and the intermetalloid phases are $Al_2CuMg$ and $Al_2Cu$.

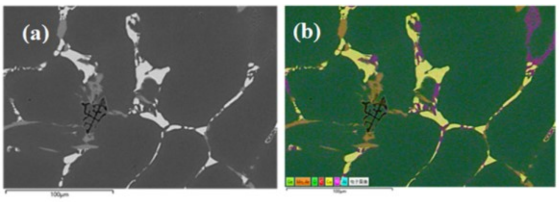


*Figure 9: (a) – part of the sample for analysis (b) – image of the obtained sample with elements separated by different colors*

According to GOST 5939-82, the grain size of the microstructure of this sample corresponds to size group No. 7-8 (Table 4). Figure 8 (b) shows that the addition of 1.0 wt.% Ge and 5.0 wt.% Si to the Al-Cu-Mg alloy reduced the size of the intermetalloid compounds in it.

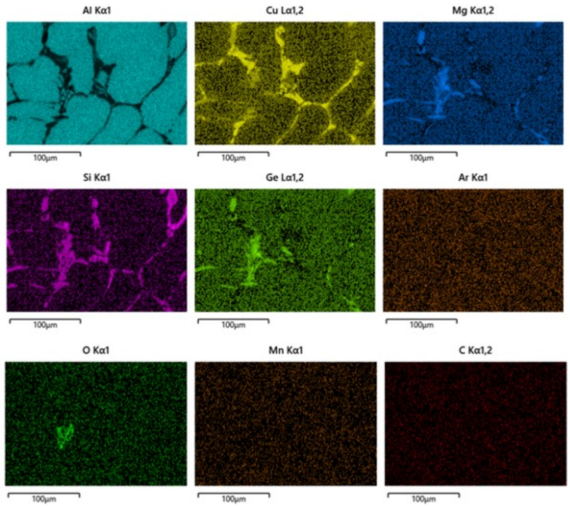


*Figure 10: Illustration of the chemical elements in the sample in separate color sections.*

According to GOST 5939-82, the grain size by microstructure corresponds to the numerical size group No. 6-7. In Fig. 8 (c) and (d), respectively, the content of the Al-Cu-Mg alloy does not change, and 5.0 wt.% Si is added to the germanium element without changing the amount of silicon, and 2.0 wt.% Ge and 3.0 wt.% Ge is in equal quantities.

It is evident that its introduction reduces the size of intermetalloid compounds in it to the maximum. According to GOST 5939-82, the grain size by microstructure corresponds to the numerical size group No. 5-6. In addition to the above analysis, an analysis of the microstructure of individual parts of the samples was carried out. It is clear from the graph in Figure 7 that when 2% germanium and 5% silicon were added to the aluminum-copper-magnesium alloy, its hardness reached the maximum level, and then its decrease was observed. The sample was carried out in addition to the general analysis. The portion taken for analysis from the 2nd sample is shown in Fig. 9.

In Fig. 10, the chemical elements in the sample from Fig. 9 are shown in separate-colored sections. As can be seen from Fig. 9 and Fig. 10, the element germanium entered the sample in a very small amount, and silicon - 3.4-3.5 wt. %, included in the alloy.

The introduction of germanium oxide served to reduce the microstructure of the samples and the dispersion of the grains. In this case, the oxygen contained in the germanium oxide reacts with a certain part of the aluminum element to form $Al_2O$, and this oxide enters the slag and leaves the liquid alloy. As a result, germanium and aluminum together form the intermetalloid $Al_3Ge$. And the silicon in the composition formed $Al_3Si$ intermetallic. These intermetalloids have a positive effect on the hardness, strength and microstructure of the alloy. However, it is not recommended to increase their amount because the increase in the composition of these additives causes a decrease in the properties of the alloy.

## 5. Conclusions

Based on the above experience, the following conclusions can be made:

1. Microalloying the Al-Cu-Mg alloy with germanium and silicon increased its hardness. It can be seen that the hardness increases to 32%, especially when adding 2% germanium and 5% silicon to the alloy. When adding 1% germanium and 5% silicon, the hardness increased by 23%. When we increased the amount of germanium to 3%, the hardness began to decrease. This means that adding 5% silicon and 1% to 2% germanium by weight of the alloy will significantly increase the hardness, and since the amount of germanium exceeds 2%, its hardness will decrease.

2. Analysis of the microstructure of the obtained samples showed that the introduction of the germanium element leads to a decrease in the grains of the sample microstructure. The grain size in the microstructure is reduced to size group No. 5-6 according to GOST 5939-82 with the addition of germanium from 1% to 3% by weight. However, it is not recommended to increase the germanium element in the alloy composition due to the decrease in the mechanical properties of the sample. 3. Adding silicon to the Al-Cu-Mg alloy contributed to the increase in its mechanical properties. In this case, it is advisable to add silicon in the same amount in the amount of 5% in relation to the total mass.

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