INFLUENCE OF NICKEL AND GERMANIUM ON THE MECHANICAL PROPERTIES OF ALUMINUM ALLOYS

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Abstract - The aim Among non-ferrous alloys, aluminum alloys occupy an important position in the machine-building industry due to their high mechanical and service properties. In this paper, the microstructure and mechanical properties of an aluminum alloy were investigated during melting in an electric induction furnace, with varying amounts of germanium and nickel added. In the experiments, the aluminum alloy was melted up to 750 °C, and samples with different compositions were cast into sand–clay molds. Germanium was added to the charge in the form of GeO_2 in amounts ranging from 1 % to 3 % relative to the charge, while 2 % nickel powder was introduced into each sample. Mechanical property tests, including hardness and wear resistance, were carried out on the samples. The hardness of the specimens was measured using a THBRV-187.5DX hardness testing device. Hardness was measured on the HRA scale, and the addition of nickel increased the hardness of the aluminum samples. The highest hardness values were achieved when 2 % germanium and 2 % nickel were added relative to the charge. The wear resistance of the cast samples was determined using a special device equipped with a diamond disk. Wear resistance was evaluated based on the mass loss of the samples during testing. The diamond disk caused wear under a 5 N load applied to the specimens. In addition to mechanical property analysis, the samples' microstructure was also investigated. Microstructural studies revealed that the addition of germanium transformed the grain morphology from plate-like to more rounded. At the same time, a reduction in grain size was observed. Based on the analyses and experimental results, the paper presents valuable conclusions.

Keywords: Germanium, Modification, Aluminum, Nickel powder, Hardness, Induction furnace, Microstructure.

1. Introduction

Currently, many materials are used in the machine-building industry, including iron–carbon alloys, non-ferrous alloys, polymers, composite materials, and ceramics [1–7]. However, despite the variety of materials, aluminum alloys hold a special and significant place. As industrial demand for aluminum alloys grows each year, their property requirements are becoming increasingly stringent [8].

In industry, pure aluminum is rarely used. Even the highest-grade primary aluminum, grade A0, contains only about 99% pure aluminum [9]. The distinctive features of aluminum alloys—such as low density, high strength, good corrosion resistance,

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dx.doi.org/10.17683/ijomam/issue23.14

and excellent machinability—make them widely used compared to other materials and alloys [10].

To date, numerous experimental studies on aluminum alloys have been conducted in various countries worldwide. In particular, numerous studies have focused on enhancing the mechanical properties of aluminum alloys by adding various modifying elements [11–15].

Mahmoud A. Alzahrani et al. extended the service life and improved the strength and deformation resistance of aluminum alloys through modification. In their study, calcium (Ca) and antimony (Sb) were introduced as modifiers into an Al–Mg_2Si–based aluminum alloy. The Mg_2Si phase provides strength in aluminum alloys; however, its coarse eutectic morphology reduces ductility. The addition of Ca and Sb as modifiers promoted the crystallization of the Mg_2Si phase into a finer and smoother morphology. As a result, introducing Ca and Sb into the Al–Mg_2Si aluminum alloy at a 1:1 ratio improved mechanical properties, including increased strength, hardness, and elongation, while achieving a balance between deformation resistance and plasticity [16]. Wei Li et al. conducted experimental studies to improve the microstructure and mechanical properties of AA7056 aluminum alloy by adding small amounts of germanium (Ge). Experimental results showed that the 7056 aluminum alloy, when rapidly cooled in its unmodified state, occasionally developed cracks and undesirable phases. By adding germanium at 0.05–0.2%, a fine, uniformly distributed microstructure was obtained, cooling sensitivity was reduced, and strength, as well as resistance to high pressure and stress, were enhanced [17]. Malla, A. D. et al. investigated a Zn–Mg–Al aluminum alloy, with and without germanium (Ge) addition. Germanium was added at 0.19%, 0.87%, and 1.8%, after which the alloy was heated to 1000 °C and air-cooled. The microstructure, strength, and hardness were subsequently evaluated. The researchers found that adding Ge to the Zn–Mg–Al alloy led to the formation of a new "Mg_2Ge" phase. Grain refinement was observed in the microstructure, which in turn resulted in enhanced mechanical properties of the alloy [18]. Chen, H. et al. conducted experiments to improve the high-temperature strength of the Al–7Si–1.5Cu–0.4Mg aluminum alloy. In this study, nickel (Ni) was added to the alloy in several stages at concentrations of 0%, 0.3%, 0.6%, and 0.9%. The most favorable results were obtained with the addition of 0.6% Ni. The incorporation of nickel led to the formation of fine Ni-rich particles in the microstructure, thereby refining and strengthening the grains.

Mechanical testing revealed increased hardness and improved strength, and most importantly, the alloy retained its strength at elevated temperatures [19]. Wang, K. et al. investigated the effect of nickel (Ni) addition on the microstructure and tensile strength of 7075 (Al–Zn–Mg–Cu) aluminum alloy. The addition of nickel resulted in the formation of new Ni-rich particles in the microstructure, refined and homogenized the grain size, and improved the tensile strength of the alloy by 1.95% [20]. Puspitasari, P. et al. conducted experimental studies on casting aluminum–nickel alloys in sand–clay molds under laboratory conditions, focusing on changes in the aluminum matrix grain size resulting from nickel addition. The study analyzed morphological and phase changes resulting from nickel additions and compared the outcomes. In the experiments, 98% pure aluminum was cast into sand–clay molds (80% silica sand, 10% bentonite, and 5% water) at 700 °C. Pure nickel (92.19% purity) was added to the charge at 1%, 2%, and 3%. Morphological analysis was performed on four Al–Ni samples with dimensions of 1 × 1 × 0.5 cm using an FEI Inspect S50 scanning electron microscope (SEM), while phase analysis was conducted on four Al–Ni samples of 1 × 1 × 2 cm using a Nikon ME5 optical microscope. The results showed that the addition of 1% nickel produced a uniform fine-grained structure in the Al–Ni samples. With 2% nickel addition, a granular structure was still observed, although some grain coarsening due to grain agglomeration occurred. At 3% nickel content, elongated grains appeared in the Al–Ni samples. Phase analysis revealed that in samples containing 1% nickel, Ni was distributed along the grain boundaries of the aluminum matrix. As the nickel content increased to 3%, Ni increasingly occupied the aluminum grain boundaries. Overall, the results demonstrated that Al–Ni alloys can be successfully produced by casting into sand–clay molds. However, careful selection of nickel content is necessary, as it significantly affects the mechanical properties of aluminum alloys [21].

In this study, the authors modified the aluminum–silicon alloy by introducing germanium and nickel modifiers in various combinations. Despite the extensive research discussed above, this study shows that adding different combinations of germanium and nickel to a casted aluminum alloy improves both its mechanical properties and its microstructure. From this point of view, the present study differs from the previously analyzed research works.

2. Materials and Methods

2.1. Alloy Composition

For the present study, the ADC12 aluminum alloy grade, which is traditionally used in the machine-building industry, was selected. The chemical composition of this alloy is presented in Table 1. Various cast products are manufactured from this aluminum alloy (Table 1). ADC12 aluminum alloy is widely used in casting for manufacturing various complex-shaped parts. It is used in the automotive industry for transmission and engine housings, covers, pump and compressor housings, as well as for producing various housing and shell-type components in mechanical engineering and electrical engineering. This alloy is distinguished by its good castability, sufficient mechanical properties, and good machinability [22].

Table 1. Chemical composition of the ADC12 aluminum alloy

Al	Si (%)	Mg (%)	Mn (%)	Zn (%)	Fe (%)
Bal.	10.56	1.91	0.21	0.55	0.85

To modify the aluminum alloy, germanium oxide (GeO_2) and 98% pure nickel (Ni) powder were used (Fig. 1). These modifiers were wrapped in special aluminum foil and then introduced into the molten alloy. The samples were melted in an induction furnace (Fig. 2) and cast into sand–clay molds at 750 °C. This temperature is considered optimal for casting aluminum alloys [22–24]. The percentage amounts of the modifiers added to the samples relative to the charge mass are presented in Table 2.

Table 2. Modifier content (%)

№	Ge	Ni
Sample 1	0%	0%
Sample 2	1%	2%
Sample 3	2%	2%
Sample 4	3%	2%

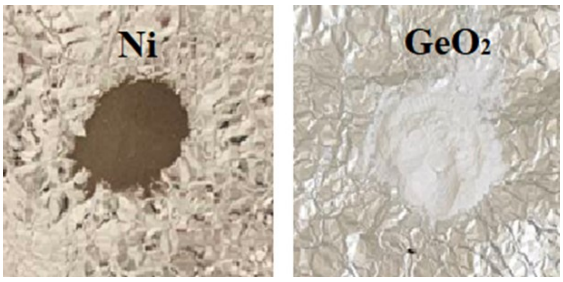

Figure 1: Nickel powder and germanium oxide.

The sand–clay molds and the casting process are shown in Fig. 3. The mixture for the sand–clay mold is made up of 85% silica sand, 11% bentonite clay, and 4% water. After casting, the samples were removed from the molds and mechanically machined for hardness testing [25]. The aluminum specimens were machined to a diameter of 20 mm and a height of 5 mm. The machined samples were ground and polished to achieve a smooth finish for hardness measurement (Fig. 4).

Figure 2: Induction furnace

The hardness of alloys is defined as the property of a material to resist indentation by a harder object pressed into its surface. It is one of the most important characteristics of alloy materials and plays a significant role in ensuring the long service life of products. In general, the higher the hardness, the greater the alloy's resistance to wear and its strength. To determine the hardness, a THBRV-187.5DX hardness testing device was used (Fig. 5).

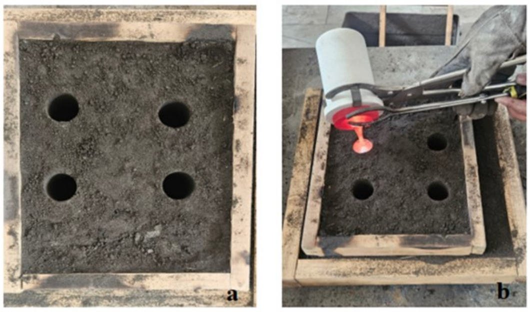

Figure 3: a — sand–clay mold; b — sample casting process

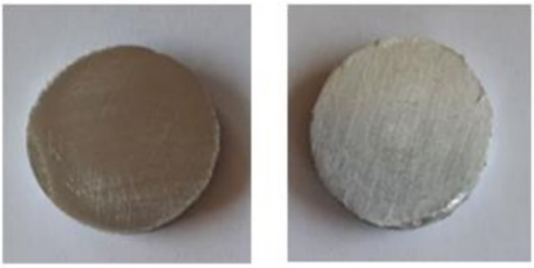

Figure 4: Samples for hardness test

Figure 5: THBRV-187.5DX hardness testing device

There are several methods for determining the wear resistance of metals, one of which is based on surface friction using specialized testing devices. In this method, the specimens are held against a diamond disk under a specified applied load (5 or 10 N) [26–28]. Proper alignment of the contact between the specimen and the disk is required to ensure effective friction at the surface interface [29].

The wear resistance of the aluminum samples was determined using a special diamond-disk apparatus; a schematic diagram of the device is shown in Fig. 6.

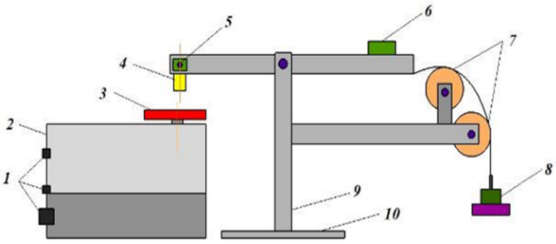

Figure 6: Schematic diagram of the diamond disk wear testing device: 1—control buttons; 2—electric motor; 3—diamond disk; 4—specimen; 5—specimen holder; 6—balancing weight; 7—rollers; 8—applied loads (5 or 10 N); 9–10—supports.

To determine the wear resistance, the specimens were mechanically machined to a height of 20 mm and a diameter of 10 mm. The mass of each specimen was measured using a balance before testing, and the mass loss after testing was calculated. The wear-testing process for the specimens is shown in Fig. 7.

Figure 7: Wear-resistance testing process for the specimens

Figure 8: Metallographic microscope

3. Results

The hardness results of the specimens are presented in Table 3. Hardness measurements were taken from three different surfaces of each specimen, and the average value was calculated [30]. The hardness was measured using the Rockwell method on the HRA scale [31].

Table 3. Hardness measurement results

№	HRA$_1$	HRA$_2$	HRA$_3$	HRA$_{aver.}$
Sample 1	34.3	35.8	35.7	35.2
Sample 2	40	36.5	35.5	37.3
Sample 3	39.6	42.1	36.4	39.3
Sample 4	36	46.1	43.3	41.8

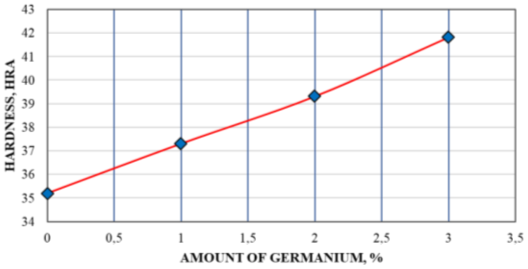

Figure 9: Relationship between germanium content and hardness of the specimen

Figure 9 illustrates the relationship between the germanium content in the alloy and its hardness. As shown in the figure, the hardness of the first specimen was approximately 35.2 HRA. With the addition of germanium starting from 1% and a constant 2% nickel relative to the charge, an increase in hardness was observed in the subsequent specimens. The average hardness of the second specimen reached 37.3 HRA when 2% germanium and 2% nickel were added. For the third specimen, containing 3% germanium and 2% nickel, the average hardness increased further to 41.8 HRA. The results indicate that the difference in hardness between the unmodified aluminum specimen (first specimen) and the alloy modified with 3% germanium and 2% nickel (final specimen) was 18.8%. Thus, modification of the aluminum alloy with germanium and nickel resulted in a significant increase in hardness.

In subsequent experiments, parameters such as the wear resistance and wear rate of the specimens were investigated [32]. The wear rate (ω) of each specimen volume was calculated under a load of 5 N using the following formula:

$$\omega = \frac{m_2 - m_1}{\rho F S} \qquad (1)$$

Here, m_1 and m_2 represent the mass of the specimens before and after the wear test, respectively; ρ is the density of the main element in the specimen (Al); F (N) is the applied normal load; and S (m) is the sliding distance [33]. The wear resistance test results are shown in Table 4.

Table 4. Results of the wear resistance tests

№	Ge content added to the specimen (%)	Ni content added to the specimen (%)	Initial mass of the specimen, m_1 (mg)	Final mass of the specimen, m_2 (mg)	Difference in specimen mass (mg)	Wear rate of specimen volume (ω), N·m
Sample 1	0	0	51.89	49.16	2.73	3.73
Sample 2	1	2	50.78	48.51	2.37	3.23
Sample 3	2	2	51.34	49.16	2.18	2.97
Sample 4	3	2	51.26	49.91	1.35	1.84

By substituting the obtained results into Equation (1), the wear rate of the specimen volume (ω) was determined. In the calculations, the density of aluminum was taken as $\rho = 2.71$ g/cm^3, the applied load was $F = 5$ N, and the sliding distance was $S = 54$ m. Based on these parameters, the wear rate of the specimen volume (ω) was calculated.

Based on the obtained results, graphs showing the relationship between the chemical composition of the specimens and both the wear rate and mass loss were constructed (Figs. 10 and 11). The results presented in Fig. 10 indicate that the mass loss of the specimens decreased with increasing germanium content. The mass loss of the first specimen was 2.73 mg, while the subsequent specimens exhibited mass losses of 2.37, 2.18, and 1.35 mg, respectively. The difference in mass loss between the first and second specimens was up to 1.34 mg.

In Fig. 11, the wear rate (ω) of the specimens was determined based on the mass loss using Eq.1 [34]. The results show that the wear rate of the specimens decreased correspondingly with increasing germanium content. As illustrated in Fig. 11, aluminum alloys modified with germanium and nickel exhibited lower wear rates than the unmodified alloy.

The introduction of nickel and germanium into the aluminum alloy composition significantly improved its wear resistance. This improvement was particularly pronounced when 3% germanium and 2% nickel were added relative to the charge.

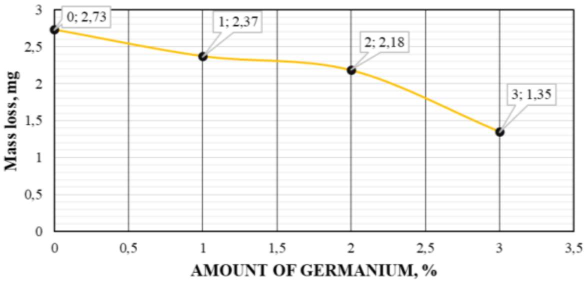

Figure 10: Wear resistance graph based on the mass loss of the specimens

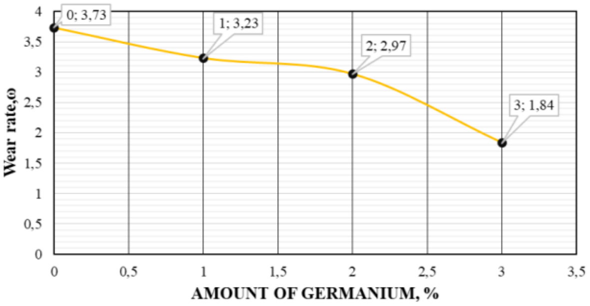

Figure 11: Wear rate graph of the specimens

After polishing the specimens according to the procedure described above for microstructural analysis, chemical etching was performed [35-37]. The microstructures of the chemically etched specimens were observed using a Leica metallographic microscope, and the obtained micrographs are presented in Fig. 12.

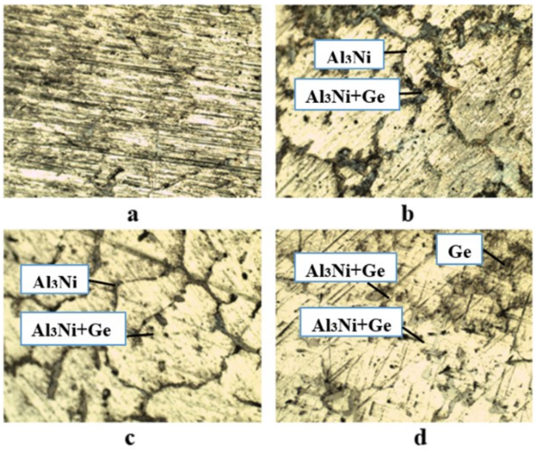

Figure 12: Microstructures of the specimens: (a) Al; (b) Al + 1%Ge + 2%Ni; (c) Al + 2%Ge + 2%Ni; (d) Al + 3%Ge + 2%Ni

Figure 12 shows the effect of germanium and nickel on the microstructural evolution of alloys with the following compositions: (a) Al, (b) Al + 1%Ge + 2%Ni, (c) Al + 2%Ge + 2%Ni, and (d) Al + 3%Ge + 2%Ni. As shown in the micrographs, the addition of germanium and nickel to aluminum alloys results in a noticeable refinement of grain dispersion.

In Fig. 12(a), the microstructure of the unmodified aluminum alloy is characterized by clearly defined grain boundaries, with no observable precipitates or secondary phases in the matrix. In some regions, gas porosity can be observed. The grains exhibit an elongated morphology.

In Fig. 12(b), corresponding to the alloy containing 1% germanium and 2% nickel, the onset of grain spheroidization is evident. The tendency to form aluminum–nickel intermetallic compounds, particularly Al_3Ni, is evident. Solidification nuclei are located in the vicinity of intermetallic clusters, while primary eutectic phases are not visually detected. Germanium forms fine particles in the alloy, and its presence refines the intermetallic grains to sizes of approximately 5–6 μm.

Figure 12(c) shows that the addition of 2% germanium and 2% nickel results in a significant reduction in grain dispersion, with finely dispersed intermetallic particles measuring about 3–4 μm and exhibiting a rounded morphology. Under the influence of nickel, the Al_3Ni intermetallic phase is also formed in this alloy. Due to the limited solubility of germanium in aluminum, fine germanium particles are formed, which increase the number of nucleation sites and thereby contribute to further refinement and improvement of the microstructure. In addition, aluminum and germanium form a distinct two-phase eutectic layer.

In Fig. 12(d), the introduction of 3% germanium leads to further grain spheroidization and a reduction in grain size to approximately 6–7 μm. However, as germanium content increases, grains begin to lose their uniform spherical morphology and adopt a more dispersed structure. In this composition, the added germanium promotes the formation of two solid phases along with a eutectic structure in the alloy.

4. Discussions

The studies have shown that the addition of germanium affects the motion of dislocations in the aluminum alloy, thereby influencing their slip behavior within the alloy. This, in turn, leads to an improvement in the microstructure.

Results obtained from the experimental study shows that modification of the aluminum alloy with 3% germanium and 2% nickel led to an increase in its brittleness, and with increasing germanium content, the alloy microstructure began to change from a uniform spherical morphology to a more dispersed structure. As a result, the brittleness of the sample also increased.

Some studies have reported that after the addition of germanium to an aluminum alloy, subsequent heat treatment is required [38, 39]. However, the present investigations have shown that since germanium introduced into the molten alloy has a positive effect on the microstructure and mechanical properties, it can be concluded that heat treatment of the aluminum alloy is not necessary.

It is advisable to use this germanium and nickel-modified alloy for the casting production of complex-shaped parts used in the automotive, mechanical engineering, oil and gas industries, and this will lead to an increase in the service life of these components. Components produced using this modification technology are expected to have a longer service life compared to conventional cast parts, which determines their advantage.

5. Conclusions

Based on the conducted studies, the following conclusions can be drawn:

The introduction of germanium and nickel into the aluminum alloy increased its hardness by up to 18.8% compared to pure aluminum. In particular, the maximum hardness was achieved when 3% germanium and 2% nickel were added to the alloy.

Wear-resistance analyses of the specimens also demonstrated improvements in their wear-resistance properties. When germanium and nickel were added to pure aluminum, the mass loss during wear tests decreased. As a result, the specimens' wear rate was reduced. As shown in Fig. 11, the wear rate increased consistently with increasing germanium content in the aluminum alloy.

Microstructural analysis revealed that nickel formed the Al_3Ni intermetallic compound with aluminum, while germanium formed a separate hard phase. Due to the limited solubility of germanium in aluminum, the microstructure consisted of two solid phases plus a eutectic structure. When the germanium content in the alloy exceeded 2%, germanium particles coarsened in the microstructure, increasing the alloy's brittleness.

Nickel in the aluminum alloy mainly contributed to strengthening through the formation of beneficial intermetallic phases (Al_3Ni), whereas germanium (Ge) predominantly precipitated as particles, thereby strengthening the material but also increasing the risk of brittleness. To achieve optimal properties, the Ge-to-Ni ratio and its total content must be carefully selected. The addition of 1–2% germanium together with 2% nickel provided the most balanced combination of properties. Therefore, adding up to 2% germanium to aluminum is recommended.

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