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Improving Mechanical and Physical Properties of 6061 Al Alloy via Nano-Aluminum and Ceramic Reinforcement using Gravity Casting

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Abstract

This research investigates the effect of reinforcing 6061 aluminum alloy with fine aluminum oxide (Al_2O_3) particles and nanoporous aluminum on its mechanical and thermal performance. The study focused on properties such as hardness, ductility, thermal conductivity, and heat resistance. Samples were prepared using gravity casting with varying proportions of Al_2O_3 (0%, 2%, 4%, and 6%) and nanoporous aluminum (0%, 1%, 2%, and 3%). The hardness showed a gradual increase, rising from 63 HV to 94 HV, indicating the role of reinforcement in strengthening the alloy and reducing structural defects. The tensile strength improved from 278 MPa to 344 MPa, while the thermal conductivity decreased from 168 to 138 W/m·K due to the insulating properties of aluminum oxide (Al_2O_3), enhancing its potential for use in applications requiring high strength, stiffness, and acceptable thermal insulation, such as aircraft structures, car engine pistons and rods, and braking and friction systems. The best balance between strength and thermal resistance was observed for the sample (S4) containing 3% nano-aluminum and 6% Al_2O_3, with minimal impact on ductility. These results support the suitability of the developed composite for high-temperature structural applications.

Keywords: Al_2O_3, Ductility, Die casting, Hardness, Thermal conductivity

1. Introduction

Since they have many of the necessary properties for casting, aluminum alloys are often employed in castings. These consist of excellent surface polish, high fluidity, low melting temperatures, light weight, and a high thermal expansion coefficient. [1, 2]. These qualities are developed through alloy additives. In engineering applications like transportation and construction, where excellent mechanical qualities like tensile strength, hardness, etc., are fundamentally required, 6061Al-alloy is one of the most extensively utilized Al-alloys. [3]. Several content, including SiC, Al2O3, B4C, TiB2, ZrO2, SiO2, and graphite, are being utilized as reinforcements to enhance the 6061Al alloy's characteristics [4].

Nonetheless, the use of Al2O3 or SiC particle reinforced aluminum alloy matrix composites is steadily growing in the automotive and aerospace sectors for components like connecting rods, cylinder heads, and pistons where the materials' tribological qualities are crucial [5].

Because of their special blend of mechanical and physical characteristics, nanocomposites have become a potential class of materials for use in structural applications. Unlike conventional composites, nanocomposites incorporate nano-sized

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reinforcements that can significantly alter the performance of the base material. These tiny particles enhance characteristics such as strength, hardness, and thermal stability, making them suitable for demanding engineering applications. One key advantage of using nano-sized particles is their ability to refine grain structure, leading to improved resistance to deformation and better load distribution. In recent years, aluminum-based nanocomposites have gained notable interest, particularly in industries such as automotive, aerospace, and energy, where materials are required to be both strong and lightweight [6].

The Mechanical and Metal-matrix Nanocomposite (MMNC) materials are classified as 21st-century materials due to these features. The most widely used base matrix metals in MMNCs for lightweight structural materials are aluminum and its alloys. These materials can be used in a wide range of contemporary industries encompassing the fields of engineering, architecture, food and chemical, power, automotive, military, and aerospace [7].

Furthermore, Aluminum Matrix Nanocomposites (AMNCs) exhibit remarkable mechanical qualities, such as high strength, low coefficients of thermal expansion (CTE), excellent ductility, remarkable strength to weight, and high resistance to corrosion and wear [7]. Although continuous fibers are utilized as nano reinforcements to improve mechanical properties, their application is limited by their comparatively high cost. However, the mechanical qualities are substantially improved by nano reinforcing materials in particulate form, which are less expensive than their fiber counterparts [8]. BN, Si3N, TiB2, graphite, carbon nanotubes (CNT), and other nano-reinforcements like oxides (MgO, SiO2, Al2O3, ZrO2, etc.) and carbides (SiC, TiC, etc.) are frequently incorporated into AMNCs at atmospheric and higher temperatures [9]. The ultimate properties of AMNCs are known to be significantly influenced by the number, size, and distribution of nanoreinforcement particles [9]. A vast list of the qualities required in a particular product is compiled by engineers in a variety of professions. For instance, a motor block must have strong mechanical qualities at various temperatures to support low weight [10].

On the other hand, for a wide range of technical applications, aluminium (Al) composites are the most practicable materials due to their exceptional wear resistance, low density, and high strength. Particularly, aluminium alloys are used in the manufacture of engine blocks, brakes, pistons, impellers, and valve parts. These Al alloys' improved castability serves as the main defence for their use in the previously specified applications, weldability, and corrosion resistance. The solidification process, microstructure, and chemical composition all have a major impact on mechanical characteristics [11]. To achieve high strength and wear resistance, a variety of particle types—including fly ash, ZrO2, TiC, SiC, B4C, and Al2O3 are employed as reinforcements in combination with Al. Because of their high modulus and strength, ceramic particles are frequently utilized as the basis for material creation. The stiffness of the resulting composites is improved when the amount of particles in the Al matrix increases. Ceramic particles in aluminum composites contribute to increased hardness, increased resistance to wear, less heat expansion and a lubricating layer on the contact surface. The development of the material's mechanical properties and wear resistance is facilitated by ceramic particles [12].

Al alloy-based composites are mostly utilised in automotive, aerospace, and other technical applications due to their exceptional mechanical performance. The addition of micro and nanohard ceramic reinforcements can enhance the alloy's properties. Because of their superior qualities and the availability of low-cost production techniques, aluminum composites have drawn particular attention for use in automotive applications during the previous two to three decades as potentially upgraded essential materials. The size of the particles, the required particle structure, and the mechanical and chemical properties of the reinforcements and matrix all affect how a composite is manufactured [13].

The ability to produce complex geometries at high production rates has led to the widespread use of aluminum gravity casting [14]. Molten metal is poured into a mold using a ladle or pot in gravity die casting, a permanent die casting technique. Gravity is the only force that fills the mold chamber; tilting the mold helps regulate the filling process. Choosing a reusable or multi-piece mold is the first step in the casting production process. The mold contains operating, feeding, and ventilation systems, as well as a casting footprint. In addition, a casting removal mechanism is included [15].

Sand and hot metal splashes can be easily removed from the mold to maintain casting accuracy. The mold can quickly dissipate the heat of the injected metal and maintain a regular production cycle. Both basic and complex castings are possible. One of gravity die casting's distinguishing features is its ability to withstand heat treatment of high-strength aluminum alloys, which pressure die casting is still unable to perform. It is ideal for castings requiring short production cycles and precise, sophisticated extraction [16].

Using gravity casting method, this study aims to investigate the effect of adding aluminum nanoparticles and alumina microparticles to the widely used aluminum alloy (6061) on the mechanical and thermal properties of the alloy.

2.Materials and Procedures

2.1. Materials used in the present study

Materials used for the present study were:

1. Commercial grade 6061 aluminum alloy is composed of 96.7% aluminum and trace amounts of iron, silicon, and magnesium, among other impurities. Table (1) displays the aluminum alloy's chemical makeup.

Table 1.
Chemical composition of the used aluminum alloy (6061)

Si %	Fe %	Cu %	Mn %	Mg %	Zn %	Ti%	Cr %	Imp. %	Al %
0.6	0.1	0.2	0.19	1.0	0.24	0.19	0.03	0.75	96.7

2. The parameters of the nano-aluminum used in this study are presented in Table 2. The nano-aluminum was procured from Sigma-Aldrich (Merck).

Table 2.
Properties Of Nano-Aluminum

Property	Nano Aluminum
Particle Size	93 nm (nanoscale)
Specific Surface Area	30.7 m^2/g
Shape	Spherical or Sub-Spherical
Density	2.7 g/cm^3
Chemical composition	≥ 99.9% Al (sometimes with a thin Al_2O_3 oxide layer)
Melting Point	Slightly reduced (~645–655°C)
Appearance	Gray to dark-gray powder

3. (Micro- alumina) particles from the company (**Nippon Light Metal Co., Ltd**) and the table (3) shows their chemical composition.

Table 3.
Chemical Composition Of Al_2O_3

Component	Typical Content (%)
Al_2O_3	98.7
Na_2O	0.6
Fe_2O_3	0.07
SiO_2	0.3
TiO_2	0.06
CaO / MgO	0.07
Loss on Ignition (LOI)	0.2

2.2. Methods and Samples Preparation

In this study, three different kinds of samples were prepared. In an electric furnace, the base alloy was kept at 750°C after being melted in a ceramic crucible (Via P.da Cannobia, 10, 20122 MILANO, Italy). To prevent oxidation or burning upon contact with the molten metal surface, the alumina and nano-aluminum blocks were individually covered with aluminum foil and progressively submerged in the melt.. The components were weighed so that the casting would be samples of the alloy and in proportions that will be mentioned later. A ceramic rod was used to stir the melt. An argon gas shield was used during the stirring procedure. The melt was put into a steel mould with a cylindrical chamber that was 20 mm in diameter and 150 mm in height. The mould had been heated to 300°C. Figure (1) Gravity casting. Table (4) represents the numbers of the prepared samples and the addition ratios of both elements.

Table 4.
Samples with addition ratios

Sample ID	Nano-aluminum	AL_2O_3
S1	0%	0%
S2	1%	2%
S3	2%	4%
S4	3%	6%

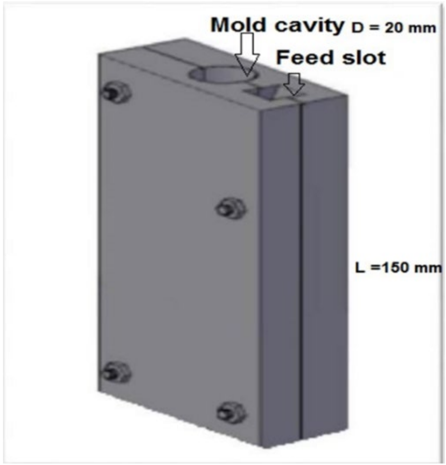

Fig. 1. Steel Mold Casting

3. Samples Tests

3.1. Chemical Composition

Chemical composition analyses were performed to confirm the final chemical composition of the alloy after additions in the prepared samples.

3.2. Microstructure Test (FESEM)

Field emission scanning electron microscopy (FESEM), which has a nearly limitless depth of field, provides information on components and topography at magnifications ranging from 10x to 300,000x. Compared to traditional scanning electron microscopy (SEM), field emission images (FESEM) have a spatial resolution of 11/2 nanometers, are three to six times sharper, and are less electrostatically distorted. Additionally, energy dispersive spectroscopy (EDS) linked to the FESEM apparatus was employed. The conducted the FESEM test using the TESCAN Mira3 FESEM device; the EDAX is identical to the FESEM device with the exception of the DETECTOR modifications (SE). Before being polished with diamond solution containing 0.2 µm of diamond powder, the cast samples (17 mm in diameter and 12 mm in height) were finely ground and polished using papers of various grit sizes (180, 400, 600, 800, 1000, 1200, and 2000).

3.3. Hardness Test

In this test, specimens measuring 17 mm in diameter by 12 mm in height were employed. Before testing, proper polishing and grinding were done. The test was performed with a load of 31.25 kg for 20 seconds using a digital micro Brinell hardness testing equipment type [Hardness measurements were performed using a digital micro Brinell hardness tester (Model: TH-717), Brand: [Beijing TIME High Technology Ltd]. For each sample specimen, the hardness was measured as the average of three hardness readings.

3.4 Tensile Test

The cast alloy samples were used to create tensile test specimens. ASTM (B557m-15) [11] states. A computerised universal testing machine was used for all tensile tests, which were performed at room temperature with a tensile speed rate of 0.1 mm/min. Figure (2) displays the specimens both before and after testing. All tensile test were conducted at room temperature using a computerized universal testing machine type (Gunt / Hamburg).


Fig. 2. Tensile Test Samples Before And After Fracture

3.5. Thermal Conductivity Test

This test was carried out using a device (NETZSCH LFA 467 HyperFlash / LFA 457 MicroFlash) where a laser pulse was directed at the surface of the sample and then the heat transfer was measured over time at a temperature of up to 1000 °C, Using equation (1) :

$$K = \frac{Q \cdot L}{\Delta T \cdot A} \qquad (1)$$

Where: - L: Sample thickness (m), A: Sample area (m^2), Q: Heat transfer rate (W), K: Thermal conductivity (W/m•K), and ΔT: Temperature differential (K)

4. Results and Discussion

4.1. Chemical Composition

Table (5) shows the chemical composition of one of the prepared samples. The test included verifying the presence of the added elements within the alloy structure.

Table 5.
Chemical composition of the alloy samples prepared in this study

Si %	Cu %	Mn %	Mg %	Zn %	Ti %	Al_2O_3 %	Nano -Al	Al%
0.3	0.1	0.2	0.1	0.1	0.1	5.1	2.6	91.4

4.2. Microstructure results (FESEM and Edax)

Figure (3) shows the FESEM and Figure (4) Edax surface morphologies of the cast alloy. a uniform scale was prepared. Due to the presence of nano-aluminum, the porosity decreased and the grain size was small with it [2]. With the continued presence of aluminum substrate, nano-aluminum leads to a reduction in the grain size of the aluminum alloy. This refinement increases the surface area of the grains, which hinders dislocation movement (transitions in the crystal structure) and improves strength and hardness [8]. We also notice the presence of micronized alumina particles that are distributed on the surface of the sample as a strengthening element, very similar to composite metals.

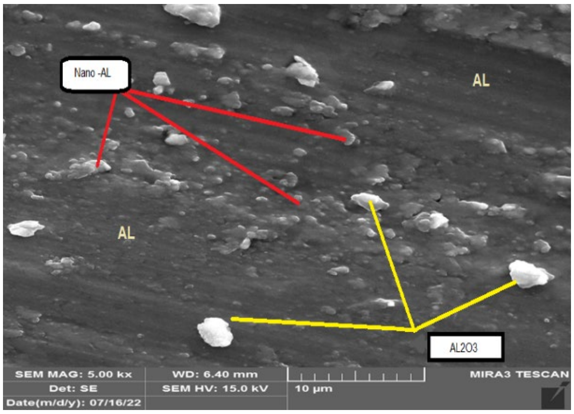

Fig. 3. Shows The FESEM

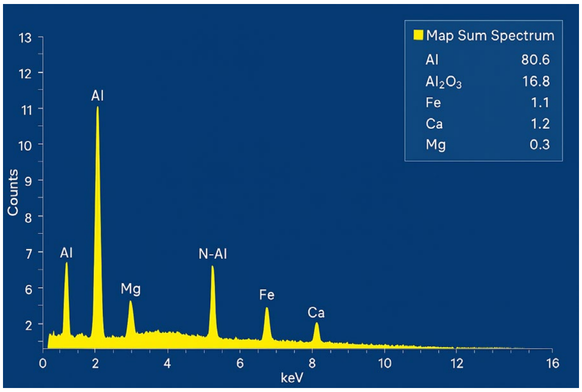

Fig.4. Edax surface morphologies of the cast alloy

4.3. Result of Thermal Conductivity, Hardness, and Tensile Tests

The results showed a significant improvement in hardness and tensile strength as the addition ratios of micronized aluminium oxide and aluminium nanoparticles increased. This indicates that the particles are effective in strengthening the metal structure by preventing slippage and grain refining. On the other hand, the presence of hard particles was shown to reduce ductility, which influences the alloy's vulnerability to plastic deformation. Because aluminum oxide is insulating and increases phonon scattering at particle boundaries, thermal conductivity gradually dropped as addition ratios rose. If enhancing mechanical qualities is the main goal, this is okay. Overall, the findings table (6) show a balance between lower ductility and heat conductivity and higher toughness. This method works well for structural uses where great strength and hardness are required and Fig.5. Effect of additives on mechanical and thermal properties.

Table. 6.
Results of Hardness, Tensile Strength, Elongation, Thermal Conductivity Tests

Sample ID	Hardness (HV)	UTS (MPa)	E (%)	Thermal Conductivity (W/m·K)
S1	63	278	11	168
S2	76	305	9	159
S3	85	323	6	150
S4	94	344	5	138

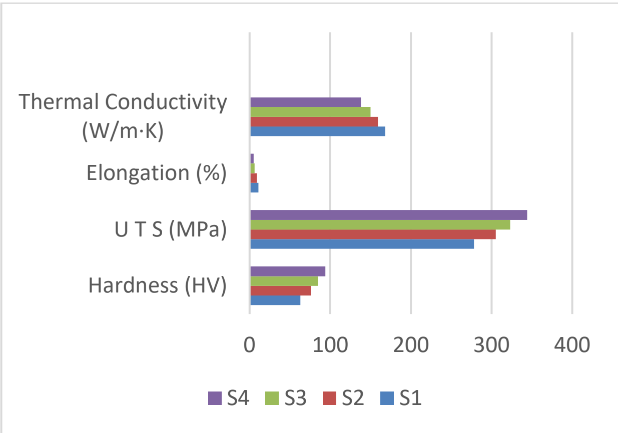

Fig. 5. Effect of additives on mechanical and thermal properties

5. Conclusions

This study explored the effects of incorporating nano-aluminum and alumina particles into 6061 aluminum alloy using gravity die-casting. The results led to several key findings:

1. The addition of nano-Al and Al_2O_3 significantly improved the alloy's mechanical performance, particularly in terms of hardness and tensile strength. This improvement highlights the effectiveness of hard particle reinforcement in strengthening the metal matrix.
2. As the percentage of reinforcing particles increased, ductility decreased. This was expected, given the reduced capacity of the alloy to undergo plastic deformation when rigid particles are present.
3. Thermal conductivity dropped gradually with higher reinforcement levels due to the insulating nature of alumina and the scattering of heat across particle boundaries. This is acceptable for applications that prioritize strength over heat transfer.
4. Among the tested compositions, the sample containing 3% nano-aluminum and 6% alumina offered the best overall performance, balancing improved strength with acceptable levels of ductility and thermal conductivity.

These findings suggest that the developed composite alloys are well-suited for structural applications requiring high strength and moderate heat resistance.

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