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Mechanical, Microstructural and Tribological Behavior of Stir-Cast Aluminum Hybrid Matrix Composites

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Abstract
Aluminum matrix composites (AMCs) have attracted considerable attention in modern engineering applications due to their excellent strength-to-weight ratio, improved wear resistance, and enhanced mechanical properties. In this study, aluminum hybrid matrix composites reinforced with ceramic particles were fabricated using the stir casting technique. Reinforcement materials such as silicon nitride (Si_3N_4), aluminum nitride (AlN), zirconium boride (ZrB_2), fly ash, titanium diboride (TiB_2), and boron carbide (B_4C) were incorporated into the aluminum matrix to enhance mechanical and tribological properties. Mechanical characterization was performed through hardness, tensile strength, and compressive strength tests, while tribological behavior was evaluated using a pin-on-disc wear testing apparatus. Microstructural analysis was carried out using scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS), and X-ray diffraction (XRD). Furthermore, the Taguchi method and analysis of variance (ANOVA) were applied to determine the most significant parameters affecting wear behavior. The results revealed that the incorporation of ceramic reinforcements significantly improved hardness, tensile strength, and wear resistance due to grain refinement and improved interfacial bonding between the matrix and reinforcement particles. The findings indicate that stir-cast aluminum hybrid composites possess excellent potential for advanced structural and tribological applications.

Keywords: Aluminum matrix composites; Hybrid composites; Stir casting; Mechanical properties; Tribological behavior; Microstructure.

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1. Introduction
Lightweight materials with high strength and improved tribological performance are increasingly demanded in modern engineering applications such as aerospace, automotive, and marine industries. Aluminum alloys are widely used in these sectors because of their low density, high specific strength, excellent corrosion resistance, and good thermal conductivity. However, conventional aluminum alloys often exhibit low hardness and poor wear resistance, which restrict their performance in high-load applications [1].

To address these limitations, researchers have focused on reinforcing aluminum matrices with ceramic particles to form aluminum matrix composites (AMCs). The addition of ceramic reinforcements such as silicon carbide, aluminum oxide, titanium carbide, boron carbide, and titanium diboride has been shown to significantly enhance hardness, stiffness, and wear resistance of aluminum alloys [2]. These reinforcements improve load transfer mechanisms and restrict dislocation motion in the matrix, thereby enhancing the mechanical strength of the composite material.

Hybrid aluminum matrix composites (HAMCs) represent a further advancement in composite technology, where more than one reinforcement material is introduced into the matrix. Hybrid composites allow tailoring of mechanical and tribological properties by combining the beneficial characteristics of different reinforcements. Studies have shown that hybrid reinforcement systems can provide improved hardness, tensile strength, and wear resistance compared with single-reinforcement composites [2].

Several fabrication methods are used to produce aluminum matrix composites, including powder metallurgy, squeeze casting, compo casting, and stir casting. Among these techniques, stir casting is widely considered the most economical and scalable method for manufacturing metal matrix composites. The process involves mechanical stirring of reinforcement particles in molten aluminum followed by casting into molds, resulting in relatively uniform particle distribution [2].

Mathan Kumar et al. investigated Al2618 aluminum alloy reinforced with Si_3N_4, AlN, and ZrB_2 using an in-situ composite fabrication technique. Their results showed significant improvements in hardness, tensile strength, and compressive strength due to grain refinement and strong interfacial bonding between reinforcement particles and the matrix [1].

Similarly, Sathish et al. studied aluminum hybrid matrix composites reinforced with fly ash and titanium diboride using stir casting. Their research revealed that the addition of TiB_2 significantly enhanced tensile strength and hardness due to increased dislocation density and improved particle distribution within the aluminum matrix [2].

Sharath et al. investigated the tribological behavior of Al2618 composites reinforced with boron carbide particles. Their results demonstrated improved wear resistance and hardness due to the presence of hard ceramic particles that resisted plastic deformation and reduced material removal during sliding contact [3].

Fly ash has also emerged as a promising reinforcement material for aluminum composites due to its low density, low cost, and environmental sustainability. When combined with ceramic reinforcements such as TiB_2 or B_4C, fly ash contributes to improved stiffness, wear resistance, and thermal stability of hybrid aluminum composites [2].

The tribological performance of aluminum matrix composites is influenced by several factors, including reinforcement content, applied load, sliding speed, and sliding distance. Experimental studies have shown that wear rate generally increases with increasing load and sliding speed due to higher frictional forces and temperature rise at the contact interface. However, the presence of hard reinforcement particles can reduce wear by acting as load-bearing elements that protect the softer aluminum matrix [3].

Although significant research has been conducted on aluminum matrix composites, further investigation is required to understand the combined effects of hybrid reinforcements and processing parameters on mechanical and tribological properties.

Therefore, the objectives of the present study are:

1. To fabricate aluminum hybrid matrix composites using the stir casting technique.
2. To investigate the mechanical properties of the fabricated composites.
3. To evaluate the tribological behavior under different operating conditions.
4. To analyze the microstructural characteristics of the composites.
5. To optimize wear parameters using statistical techniques such as Taguchi and ANOVA analysis.

2. Materials and Methodology

2.1 Matrix Material and Reinforcement Selection

Aluminum alloys such as Al2618 and LM25 were selected as matrix materials due to their excellent mechanical strength and lightweight characteristics [1]. These alloys are widely used in aerospace and automotive applications due to their good thermal stability and strength.

The reinforcement materials used in this study include:

- Silicon Nitride (Si_3N_4)
- Aluminum Nitride (AlN)
- Zirconium Boride (ZrB_2)
- Titanium Diboride (TiB_2)
- Boron Carbide (B_4C)
- Fly Ash

These ceramic particles were selected because of their high hardness, good thermal stability, and ability to improve wear resistance of aluminum alloys.

2.2 Fabrication of Composites

The composites were fabricated using the stir casting technique. The aluminum alloy was melted in a graphite crucible at approximately 800 °C. Reinforcement particles were preheated to remove moisture and improve wettability before being introduced into the molten aluminum [2]. Mechanical stirring was carried out using a four-blade stirrer rotating at approximately 500 rpm for about 10 minutes to ensure uniform distribution of reinforcement particles. Magnesium was added in small quantities to improve wettability between the aluminum matrix and reinforcement particles. The molten composite mixture was then poured into cylindrical molds and allowed to solidify at room temperature.

3. Experimental Procedures

3.1 Fabrication of Aluminum Hybrid Matrix Composites

The aluminum hybrid matrix composites were fabricated using the stir casting technique, which is one of the most economical and widely used methods for producing metal matrix composites. In this process, reinforcement particles are introduced into molten aluminum and uniformly dispersed through mechanical stirring before casting into molds. Stir casting is particularly advantageous due to its simplicity, cost-effectiveness, and ability to produce composites with relatively homogeneous particle distribution [4].

Initially, the aluminum alloy ingots were melted in a graphite crucible at temperatures between 750–850 °C. Reinforcement particles such as Si_3N_4, AlN, ZrB_2, TiB_2, B_4C, and fly ash were preheated in a separate furnace to eliminate moisture and improve wettability with the molten aluminum. Preheating of reinforcement particles is an important step because it prevents the formation of gas porosity and ensures better interfacial bonding between the matrix and reinforcement phases [5]. After reaching the molten state, mechanical stirring was carried out using a four-blade stainless steel stirrer rotating at approximately 450–600 rpm for about 10 minutes. The reinforcement particles were gradually introduced into the vortex created by the stirrer to achieve uniform distribution throughout the molten matrix. Magnesium was added in small quantities to enhance the wettability between reinforcement particles and the aluminum matrix. Previous studies have demonstrated that proper stirring parameters significantly influence the dispersion of reinforcement particles and the final mechanical properties of the composite material [6]. The molten composite slurry was then poured into preheated steel molds and allowed to solidify under ambient conditions. The cast specimens were subsequently machined according to ASTM standards for mechanical and tribological testing.

3.2 Mechanical Testing

3.2.1 Hardness Testing

The hardness of the fabricated composites was evaluated using a Vickers hardness testing machine in accordance with ASTM E10 standards. A load of approximately 0.5 kg was applied for 25 seconds, and the indentation diagonal lengths were measured to determine the hardness values. Hardness testing is important for evaluating the resistance of materials to plastic deformation. In aluminum matrix composites, hardness generally increases with the addition of ceramic reinforcement particles due to the presence of hard phases that resist indentation and restrict plastic deformation of the matrix [7].

3.2.2 Tensile Testing

Tensile testing was carried out using a Universal Testing Machine (UTM) following ASTM E8 standards. Specimens were prepared according to standard dimensions and polished to remove machining marks before testing. The tensile test measures the ultimate tensile strength, yield strength, and elongation of the composite material. Reinforcement particles act as load-bearing elements within the matrix and restrict dislocation movement, which improves the tensile strength of aluminum composites [8].

3.2.3 Compression Testing

Compression tests were performed to determine the compressive strength of the composites using a universal testing machine. The compressive strength of aluminum composites is often higher than that of the base alloy due to the presence of reinforcement particles that impede deformation and improve load distribution within the matrix.

3.3 Tribological Testing

The tribological performance of the composites was evaluated using a pin-on-disc wear testing apparatus under dry sliding conditions according to ASTM G99 standards.

The parameters considered during the wear test include:

Applied load (10–50 N)

Sliding speed (1–5 m/s)

Sliding distance (up to 3000 m)

Before and after each test, the specimen weight was measured using an electronic balance with high precision. The wear rate was calculated using the weight loss method.

Wear behavior of aluminum matrix composites is strongly influenced by reinforcement type, particle size, applied load, and sliding speed. Ceramic particles such as SiC, B_4C, and TiB_2 improve wear resistance by acting as load-bearing elements and preventing severe deformation of the aluminum matrix during sliding contact [9].

3.4 Microstructural Characterization

Microstructural analysis was carried out using the following techniques:

- Optical microscopy
- Scanning Electron Microscopy (SEM)
- Energy Dispersive Spectroscopy (EDS)
- X-Ray Diffraction (XRD)

SEM analysis was used to observe the distribution of reinforcement particles and the bonding between the matrix and reinforcement phases. EDS analysis provided information about the elemental composition of the composites, while XRD analysis was used to identify the phases present in the material.

Microstructural analysis plays a crucial role in understanding the relationship between processing parameters and the resulting mechanical properties of composite materials.

4. Results and Discussion

4.1 Microstructural Characteristics

SEM images of the fabricated composites revealed a relatively uniform distribution of reinforcement particles within the aluminum matrix. The presence of ceramic particles such as Si_3N_4, TiB_2, and B_4C contributed to grain refinement during solidification. Grain refinement occurs because reinforcement particles act as nucleation sites during the solidification process, leading to the formation of smaller grains in the aluminum matrix. Smaller grain size improves the mechanical strength of the composite through the Hall–Petch strengthening mechanism [10]. Similar observations have been reported in previous studies where the addition of SiC and TiB_2 reinforcement particles resulted in uniform particle distribution and improved mechanical properties of aluminum composites [11].

XRD analysis confirmed the presence of reinforcement phases such as B_4C and TiB_2 along with the aluminum matrix phase. The absence of unwanted phases indicates successful incorporation of reinforcement particles into the matrix.

4.2 Hardness Behavior

The hardness values of the composites increased with increasing reinforcement content. This increase in hardness can be attributed to several factors:

- Presence of hard ceramic particles in the matrix
- Grain refinement during solidification
- Increased dislocation density around reinforcement particles

The improvement in hardness is mainly due to the resistance of reinforcement particles to localized plastic deformation. Hard particles such as TiB_2 and B_4C act as obstacles to dislocation motion, which enhances the overall hardness of the composite material [12]. Several researchers have reported similar results where aluminum composites reinforced with ceramic particles exhibited higher hardness compared with the base alloy [13].

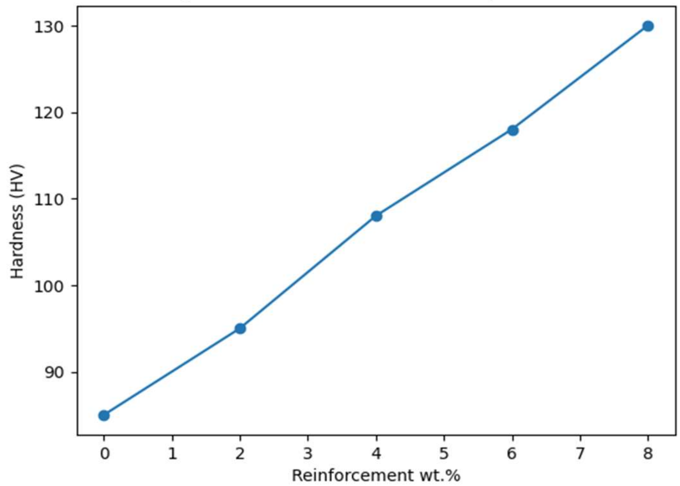

Figure 1: Hardness vs Reinforcement Weight %

4.3 Tensile Strength

The tensile strength of the composites increased significantly with the addition of reinforcement particles. This improvement is primarily attributed to the load transfer mechanism between the aluminum matrix and the reinforcement particles. During tensile loading, stress is transferred from the softer aluminum matrix to the harder reinforcement particles. The strong interfacial bonding between the matrix and reinforcement ensures efficient load transfer, resulting in higher tensile strength. Previous studies have shown that the addition of TiB_2 and SiC particles to aluminum alloys significantly enhances tensile strength and wear resistance [11]. However, excessive reinforcement content may lead to particle clustering, which can reduce ductility.

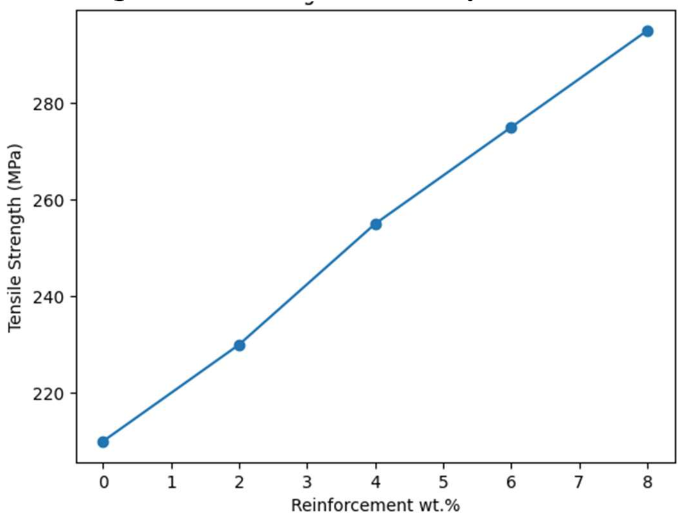

Figure 2: Tensile Strength vs Reinforcement Weight %

4.4 Wear Behavior

Wear tests indicated that the wear rate of the composites increased with increasing applied load and sliding speed. This is due to the higher frictional forces and temperature rise at the contact interface. However, the presence of ceramic reinforcement particles significantly reduced the wear rate compared with the base aluminum alloy. Hard particles such as B_4C and TiB_2 act as protective barriers that prevent severe plastic deformation and material removal from the matrix surface. Research studies have demonstrated that aluminum composites reinforced with B_4C exhibit significantly improved wear resistance due to the high hardness of the reinforcement particles [14]. Similarly, hybrid composites reinforced with SiC and TiB_2 have shown reduced wear rate and improved tribological performance under dry sliding conditions [11]. Statistical analysis using the Taguchi method and ANOVA revealed that sliding speed had the most significant influence on wear rate, followed by sliding distance and applied load. This observation is consistent with earlier studies on aluminum matrix composites, where sliding speed was identified as the dominant factor influencing wear behavior [15].

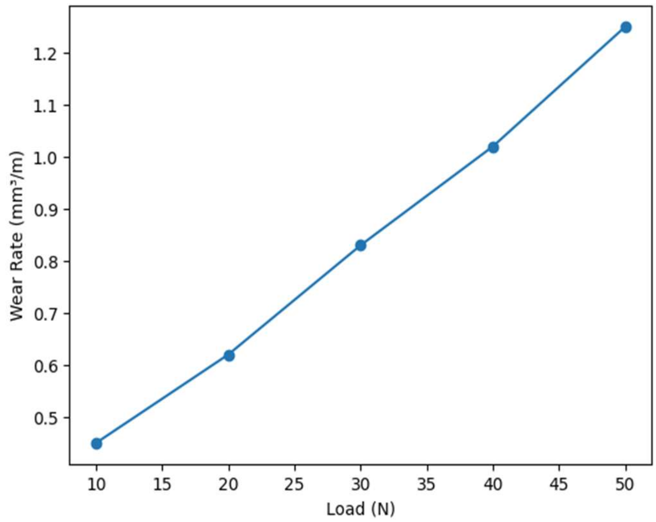

Figure 3: Wear Behaviour vs Load

5. Conclusion

This study investigated the fabrication and characterization of aluminum hybrid matrix composites produced via the stir casting technique. The following conclusions can be drawn:

1. Stir casting is an effective and economical method for producing aluminum hybrid matrix composites.
2. The addition of ceramic reinforcements significantly improves hardness, tensile strength, and compressive strength.
3. Grain refinement and improved interfacial bonding contribute to enhanced mechanical performance.
4. Reinforcement particles significantly improve wear resistance by reducing material loss during sliding.
5. Statistical analysis revealed that sliding speed is the most significant parameter affecting wear behavior.

The developed hybrid composites show promising potential for advanced engineering applications requiring lightweight and wear-resistant materials.

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