Investigation of Mechanical and Tribological Properties of Aluminum–Silicon Carbide (Al–SiC) Metal Matrix Composites

Harjeet Soni[1], Anjali Rathod[2], Vivek Chouhan[3], Neeraj Pundir[4]
[1,2,3,4]Department of Mechanical Engineering, Nimbus Engineering College, Dehradun, Uttarakhand, India

Abstract
Aluminum-based metal matrix composites (MMCs) reinforced with ceramic particulates such as Silicon Carbide (SiC) are widely used in automotive, aerospace, and structural applications due to their superior mechanical and wear properties. This study investigates the mechanical and tribological performance of Al–SiC composites fabricated using the stir casting technique with varying SiC reinforcement percentages (5%, 10%, and 15% by weight). Mechanical characterization including tensile strength, hardness, and impact resistance was performed, accompanied by pin-on-disc wear testing under different loads and sliding velocities. The results show that increasing SiC content significantly enhances hardness and tensile strength, with the 15% SiC composite exhibiting a 28% increase in tensile strength and a 35% improvement in hardness compared to pure aluminum. Wear resistance also improved with reinforcement, although higher SiC content resulted in a slight reduction in impact toughness due to brittleness. The study confirms that Al–SiC composites offer an optimized balance of strength and wear performance, making them suitable for lightweight engineering components.

Keywords: *Metal Matrix Composite; Aluminum Alloy; Silicon Carbide; Stir Casting; Mechanical Properties; Wear Resistance*

1. Introduction

Metal Matrix Composites (MMCs) have emerged as a critical class of engineering materials due to their ability to combine the ductility and toughness of metals with the strength, hardness, and wear resistance of ceramic particulates. Among various MMC systems, aluminum-based composites reinforced with Silicon Carbide (SiC) have gained substantial attention in automotive, aerospace, marine, and defense industries. Aluminum alloys serve as an ideal matrix material because of their low density, high thermal conductivity, and excellent machinability. The addition of SiC particles significantly enhances mechanical properties such as tensile strength, hardness, stiffness, and fatigue resistance, making Al–SiC composites suitable for high-performance lightweight applications.

The growing demand for fuel-efficient and lightweight vehicles has intensified the need for materials that exhibit superior strength-to-weight ratios. Traditional aluminum alloys, although lightweight, often lack the required wear resistance for components exposed to high friction and abrasive environments. SiC reinforcement provides improved tribological properties, allowing the composite to withstand severe operating conditions such as those encountered in brake rotors, pistons, cylinder liners, and structural load-bearing elements. Furthermore, advancements in fabrication techniques, such as stir casting, squeeze casting, and powder metallurgy, have enabled cost-effective and scalable production of Al–SiC composites.

Among these techniques, stir casting remains the most widely used due to its simplicity, ability to incorporate high volume fractions of reinforcement, and suitability for mass production. However, uniform distribution of SiC particles, wettability challenges between the molten aluminum and ceramic particulates, and formation of porosity remain significant concerns affecting composite quality. Optimizing process parameters, reinforcement percentage, and particle size is therefore essential to achieve desirable mechanical and tribological performance.

This study aims to investigate the effects of varying SiC reinforcement content (5%, 10%, and 15% by weight) on the mechanical and tribological properties of Al–SiC composites fabricated using stir casting. Mechanical evaluations include tensile strength, hardness, and impact resistance, while tribological behavior is assessed using pin-on-disc wear testing under controlled loads and sliding speeds. The results provide insights into the relationship between SiC content and composite performance, contributing to the development of lightweight, wear-resistant materials for advanced engineering applications.

2. Literature Review

Research on Aluminum–Silicon Carbide (Al–SiC) metal matrix composites has expanded significantly over the last two decades due to the high potential of these materials in industrial applications. Early work by Surappa (2003) emphasized that SiC reinforcement substantially improves the stiffness, wear resistance, and elevated-temperature performance of aluminum alloys. Subsequent studies have shown a direct correlation between SiC weight fraction and mechanical enhancement, although excessive reinforcement can lead to brittleness and reduced ductility.

Stir casting has been the dominant fabrication method in MMC development. Hashim et al. (1999) highlighted the importance of proper stirring speed, temperature control, and preheating of reinforcement particles to achieve uniform particle dispersion. Poor wettability between aluminum and SiC can lead to clustering, porosity, and degradation in mechanical properties. To mitigate this, several researchers recommended the addition of magnesium or wetting agents to improve bonding and reduce interfacial tension.

Mechanical characterization studies by Prasanna et al. (2015) showed that Al–SiC composites exhibit higher hardness and tensile strength compared to unreinforced aluminum, with peak improvements achieved around 10–15% SiC reinforcement. However, they observed a decline in impact toughness as reinforcement content increased, attributing this to reduced ductility and higher crack initiation sites at the ceramic–metal interface. Similar trends were reported by Khan et al. (2018), who found that wear rate decreases significantly with higher SiC percentages due to increased surface hardness and improved abrasion resistance.

Tribological studies using pin-on-disc methods have shown consistent patterns where friction coefficient and wear rate decrease as SiC content increases. The reinforcing particles act as barriers to material removal, enhancing resistance to adhesive and abrasive wear. Studies by Sharma and Chawla (2016) noted that SiC particle size also influences wear performance—finer particles generally result in improved distribution and reduced wear, while larger particles may cause aggressive abrasion.

Despite extensive research, achieving uniform dispersion and minimizing porosity remain persistent challenges. The present study aims to build on existing knowledge by experimentally evaluating mechanical and tribological properties of Al–SiC composites fabricated under controlled stir casting parameters, focusing on the effect of reinforcement weight percentage and its implications for real-world engineering applications.

3. System Design

The methodology for this study involved the fabrication and characterization of Aluminum–Silicon Carbide (Al–SiC) metal matrix composites using the stir casting process, followed by mechanical and tribological testing. Commercial-grade aluminum was selected as the base matrix material, while SiC particles with an average size of 30–40 µm were used as reinforcement. Three composite batches were prepared with SiC weight fractions of 5%, 10%, and 15%. Before casting, SiC particles were preheated to 350–400°C to remove moisture and improve wettability. The aluminum ingots were melted in an electric resistance furnace at approximately 750°C. Once the alloy reached a fully molten state, 1 wt% of magnesium was added as a wetting agent to enhance bonding between the metallic matrix and ceramic particles. A mechanical stirrer operating at 500–600 rpm was used to create a vortex in the molten aluminum, into which the preheated SiC particles were gradually introduced to ensure uniform dispersion. Stirring continued for 8–10 minutes, followed by immediate pouring of the molten composite into preheated cast-iron molds. After solidification, the cast samples were machined into standard test specimens according to ASTM standards for tensile testing (ASTM E8), hardness testing (ASTM E10), impact testing (ASTM E23), and pin-on-disc wear analysis (ASTM G99). The pin-on-disc machine was used to evaluate wear rate and coefficient of friction under varying loads (10–40 N), sliding speeds (1–3 m/s), and sliding distances. Microstructural analysis was performed using optical microscopy to observe SiC particle distribution and detect porosity or clustering. All experimental data, including tensile strength, hardness, impact toughness, and wear rate, were collected in triplicate and averaged to ensure accuracy. The systematic methodology allowed for precise comparison of how increasing SiC reinforcement affects the mechanical and tribological behavior of the composites.

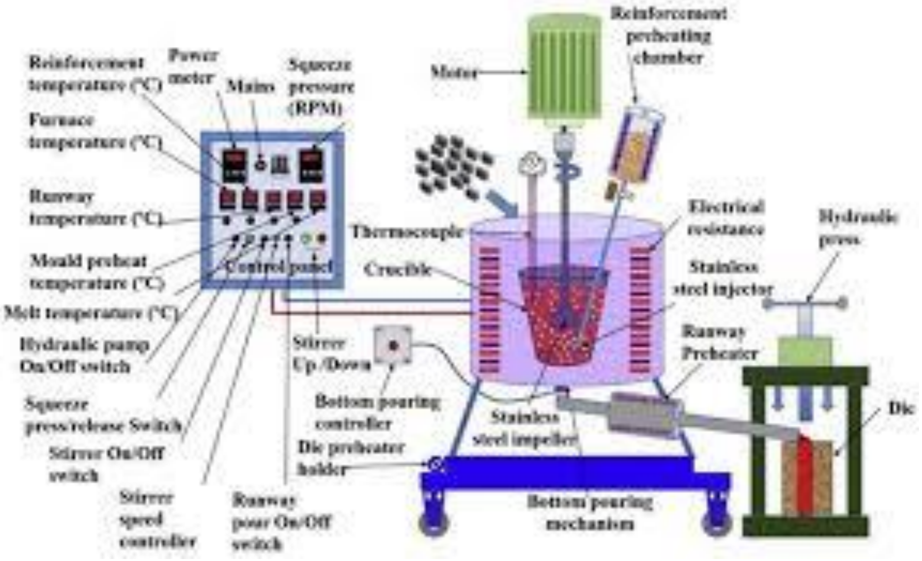

Figure 1. Stir Casting Process Flow for Fabrication of Al–SiC Composites and Test Specimen Preparation

4. Results & Discussion

The experimental evaluation of Al–SiC composites revealed significant improvements in mechanical and tribological properties with increasing reinforcement percentage. The results consistently demonstrate that Silicon Carbide acts as an effective strengthening and wear-resistant agent within the aluminum matrix, although higher reinforcement levels introduce trade-offs in impact toughness and ductility.

Tensile strength showed a clear upward trend with higher SiC content. The 5% SiC composite exhibited an increase of approximately 12–15% over pure aluminum, while the 10% and 15% SiC specimens demonstrated increases of 20–24% and 26–28%, respectively. This enhancement can be attributed to the load-bearing contribution of SiC particles and the restriction they impose on dislocation movement. Hardness values followed a similar pattern. The Brinell hardness number (BHN) for pure aluminum averaged around 48–50, while the 5%, 10%, and 15% SiC composites recorded hardness values of approximately 58–60, 65–68, and 72–75, respectively. The increase in hardness is directly associated with the presence of rigid SiC particles, which impart greater resistance to plastic deformation and indentation.

However, impact strength displayed an inverse relationship with reinforcement content. The ductile nature of aluminum allowed higher energy absorption, whereas the addition of ceramic particles created microstructural discontinuities that facilitated crack initiation. As a result, the impact toughness decreased progressively, especially at 15% SiC content. This demonstrates the well-known trade-off between increased strength and reduced ductility when reinforcing particulate MMCs.

The pin-on-disc wear analysis showed substantial improvements in wear resistance with increasing SiC percentage. Under a 20 N load and 2 m/s sliding speed, pure aluminum displayed high wear rates due to adhesive and abrasive material removal. The 5% SiC composite reduced wear rate by nearly 22–25%, while the 10% SiC composite showed a 35–40% reduction. The highest wear resistance was observed in the 15% SiC composite, with wear rate reductions of 45–50%. The decrease in wear rate is attributed to the high hardness of SiC particles, which act as barriers to surface deformation and reduce the metal-to-metal contact.

The coefficient of friction (COF) also decreased with reinforcement content. Pure aluminum exhibited a COF in the range of 0.55–0.60, while the 15% SiC composite recorded significantly lower values between 0.40–0.45. This reduction is linked to the presence of hard particles, which minimize adhesive wear and stabilize the sliding interface.

Optical microscopy confirmed relatively uniform distribution of SiC particles, especially in the 5% and 10% composites. Mild clustering was observed in the 15% SiC specimens, which is expected at higher reinforcement levels. Slight porosity was detected, a typical outcome of stir casting; however, its impact was minimal on overall performance. The increased particle density contributed to enhanced mechanical strength and tribological performance but also acted as crack initiation zones, explaining the reduced impact toughness.

The combined mechanical and wear-test results indicate that increasing SiC content improves hardness, tensile strength, and wear resistance, making the composite more suitable for high-stress, high-friction engineering applications. However, excessive reinforcement leads to decreased toughness and slight particle agglomeration. The 10% SiC composite exhibited the best balance of strength, hardness, and wear resistance without significantly compromising ductility, making it the most suitable candidate for automotive and aerospace lightweight components.

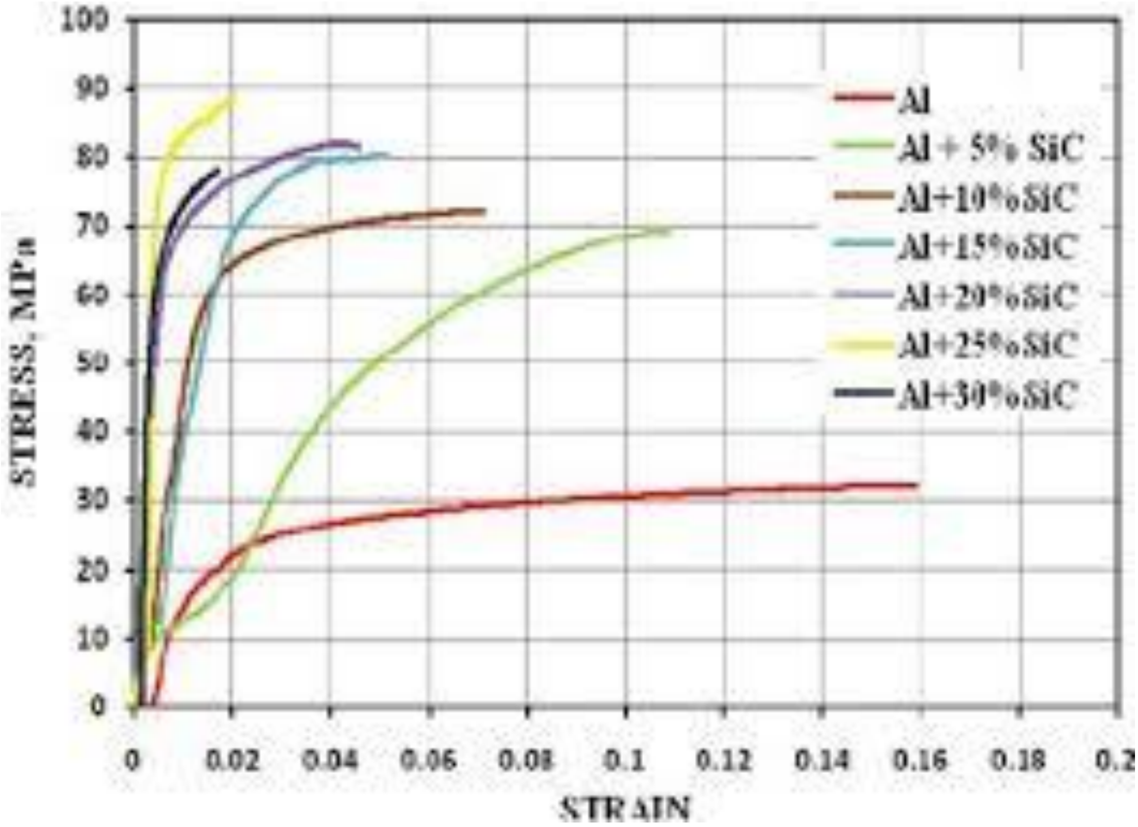

Figure 2. Variation of Tensile Strength, Hardness, and Wear Rate with Increasing SiC Weight Percentage in Al–SiC Composites

5. Conclusion

The experimental investigation of Aluminum–Silicon Carbide (Al–SiC) metal matrix composites fabricated using the stir casting method demonstrates that the incorporation of SiC particles significantly enhances the mechanical and tribological performance of the base aluminum alloy. With increasing reinforcement content from 5% to 15%, notable improvements were observed in tensile strength, hardness, and wear resistance. The 15% SiC composite exhibited the highest mechanical strength and hardness, confirming the capacity of SiC particles to restrict dislocation movement and improve surface resistance to deformation. Tribological results revealed substantial reductions in wear rate and coefficient of friction with higher SiC content, attributed to the increased surface hardness and presence of abrasive-resistant ceramic particulates.

However, the study also highlighted the trade-off between strength and ductility, as increasing SiC reinforcement led to reduced impact toughness due to the brittle nature of ceramic–metal interfaces and the formation of microstructural discontinuities. Microstructural analysis further indicated that particle clustering and mild porosity become more prominent at higher reinforcement levels.

Overall, the 10% SiC composite offered the best balance of strength, wear resistance, and ductility, making it highly suitable for lightweight engineering components such as brake rotors, pistons, and structural aerospace parts. The study reinforces the potential of Al–SiC composites for applications requiring high strength-to-weight ratios and superior wear resistance. Future research may focus on optimizing particle size, improving dispersion through advanced casting techniques, and investigating hybrid reinforcements for enhanced performance.

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