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ANALYSIS OF MECHANICAL BEHAVIOR IN AL-SIC METAL MATRIX COMPOSITES FORMED THROUGH STIR CASTING

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Abstract:. Aluminum-Silicon Carbide (Al-SiC) metal matrix composites (MMCs) have gained considerable interest due to their superior mechanical properties, making them suitable for use in industries such as automotive and aerospace. This research focuses on evaluating the mechanical characteristics of Al-SiC composites produced through the stir casting method, a popular technique known for its simplicity and cost efficiency. Various weight fractions of SiC particles were added to the aluminum matrix, followed by a controlled stirring process to achieve uniform distribution of the reinforcement. The resulting composites underwent mechanical testing, including tensile strength, hardness, and impact toughness assessments. Findings reveal that increasing SiC content significantly enhances mechanical performance, particularly in terms of strength, hardness, and wear resistance, compared to unreinforced aluminum. However, challenges such as particle clustering and porosity were observed to influence the overall properties of the composite. This study concludes that the stir casting process is an effective approach for producing Al-SiC composites with improved mechanical properties, ideal for demanding applications.

Index terms: *Al-SiC, MMCs, Stir casting, Mechanical properties, SiC content, Particle clustering.*

I. INTRODUCTION

Composite materials have gained substantial prominence in advanced engineering sectors due to their superior mechanical and physical properties. These materials, formed by the combination of two or more distinct constituents, synergize the beneficial characteristics of each component, resulting in enhanced performance. In particular, metal matrix composites (MMCs) have shown significant potential, especially in high-performance applications, owing to their high stiffness, strength, and wear resistance. Traditionally, continuous-fiber- reinforced composites dominated the landscape; however, their high manufacturing costs and complex processing methods have steered focus toward particulate-reinforced composites, which offer a more cost-effective and efficient alternative.

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Aluminum and its alloys, known for their excellent properties such as low density, high plasticity, ductility, and superior corrosion resistance, are widely used in industries including aerospace, automotive, and high-speed rail systems. Despite these advantages, the inherent low hardness and suboptimal impact resistance of aluminum alloys limit their application in high-stress, heavy-duty environments. The development of aluminum matrix composites (AMCs), particularly those reinforced with ceramic particles, provides a robust solution to these limitations. By incorporating reinforcements such as silicon carbide (SiC), the mechanical properties of aluminum alloys are significantly improved, achieving a tailored balance of strength, stiffness, thermal conductivity, and wear resistance. Silicon carbide (SiC) is a ceramic material characterized by a tetrahedral arrangement of carbon and silicon atoms, leading to an exceptionally hard and thermally stable structure. SiC exhibits excellent resistance to chemical attack, maintaining stability against acids, alkalis, and molten salts up to temperatures of 800°C. Additionally, SiC forms a protective silicon oxide layer in air at temperatures exceeding 1200°C, allowing it to function at extreme temperatures up to 1600°C without significant strength degradation. These properties, coupled with its high thermal conductivity and low coefficient of thermal expansion, make SiC an ideal reinforcement material for metal matrix composites. SiC-reinforced aluminum MMCs exhibit remarkable thermal shock resistance, high wear resistance, and mechanical stability at elevated temperatures, making them suitable for critical applications in aerospace, automotive, and defense industries.

Among the various fabrication methods, stir casting is widely recognized as an effective and economical technique for the production of particulate-reinforced MMCs. The process involves the incorporation of reinforcement particles into a molten metal matrix, followed by vigorous mechanical stirring to achieve uniform distribution of the reinforcement phase. Stir casting offers several advantages, including scalability, cost-efficiency, and the ability to control the volume fraction and size of the reinforcing particles. This study focuses on the fabrication of aluminum-silicon carbide (Al-SiC) metal matrix composites through the stir casting route, with an emphasis on evaluating their mechanical properties, such as tensile strength, hardness, and impact resistance. By systematically investigating the 1 influence of SiC content and distribution on the mechanical behavior of Al-SiC composites, this research aims to provide insights into optimizing the material for high-performance applications.

II. EXPERIMENTAL

This study focused on the development of aluminum (Al-6061)/silicon carbide (SiC) metal matrix

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composites (MMCs) using the stir casting technique. The stir casting method involves the mechanical dispersion of reinforcement particles (in this case, SiC) into a molten metal matrix (Al-6061). The MMC plates were fabricated with varying weight fractions of SiC reinforcement (5%, 10%, and 15%) to investigate the influence of reinforcement content on the composite's properties. The SiC particles were of a fine size (325 mesh), which can enhance the interfacial bonding between the reinforcement and the matrix. The stirring process was conducted at a rotational speed of 200 revolutions per minute to ensure adequate dispersion of the SiC particles within the molten aluminum.

(a) Composition of samples chosen for the study. Al-SiC composites were synthesized by systematically varying the weight fraction of SiC from 5% to 15%. A base sample mass of 400 grams was utilized, with the SiC content adjusted in proportion to the specified weight percentages.

No.	Al (grams)	SiC (grams)	Remarks
1	385	20	Al-5%SiC
2	365	40	Al-10%SiC
3	345	60	Al-15%SiC

Stir casting method for Al6061/SiC metal matrix composites (MMCs)

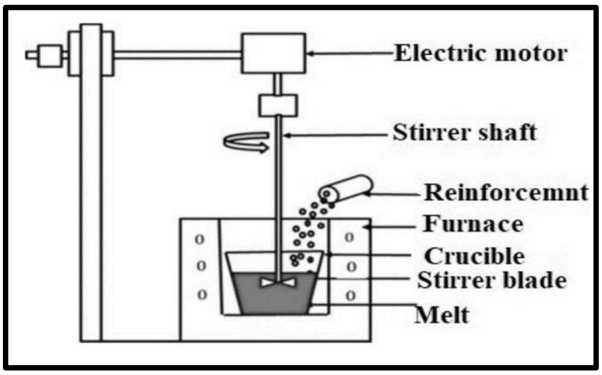

Figure 1: Stir casting apparatus used for the production of Al-SiCp metal matrix composite (MMC)

The stir casting setup used for fabricating Al-SiC particle-reinforced MMCs is illustrated in Figure 1. The system includes a furnace for melting the metal, along with a stirrer and motor for mixing the

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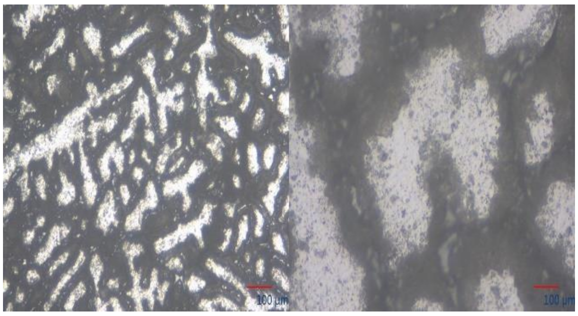
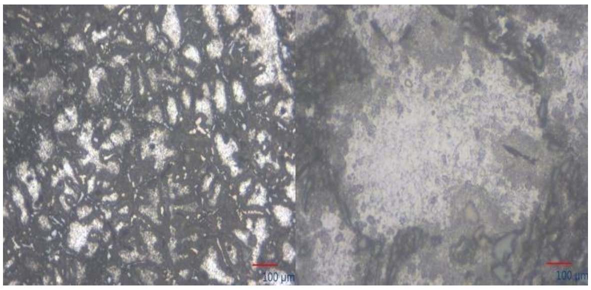
particles. Initially, SiC particles are preheated in a separate muffle furnace at 900°C for 2 hours to remove volatile substances and impurities, and to bring the particle temperature closer to the melting point of the aluminum alloy. This preheating induces the formation of a SiO_2 layer on the particle surface through artificial oxidation, which enhances particle wettability. Subsequently, Al6061 billets are placed in the furnace, and the melting process continues until a uniform temperature of 750°C is reached. Flux is added to the molten aluminum to prevent oxidation. The melt is then cooled to 600°C, slightly below its liquidus temperature, reaching a semi-solid state. At this point, the preheated SiC particles are gradually introduced, and the slurry is manually stirred. A small amount of magnesium, less than 1% of the total weight, is added to further improve wettability between the reinforcement and alloy. After manually stirring for 5 minutes, the remaining SiC is added, along with hexachloroethane tablets to degas the molten metal and minimize porosity in the final cast composite.

After manual agitation, the composite slurry was reheated and stabilized at 750°C ± 10°C, exceeding the liquidus threshold, before initiating mechanical stirring. The stirring operation was conducted for 10 minutes at an average rotational speed of 150 rpm. A Platinum-Rhodium thermocouple was employed throughout the process to precisely monitor the furnace temperature. Prior to casting, the permanent cast iron mould was preheated to 350°C to ensure optimal thermal conditions. Subsequently, the composite mixture was cast, allowed to solidify, and subjected to drying before being extracted from the mould.

III. Outcomes and Interpretation Metallurgical and microstructure examination





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Figures 2a and 2b: Depict the optical microstructures of the Al-5% SiC composite at magnifications of 100x and 500x, respectively.

Figure 3a & 3b: Shows optical microstructures of Al-10% SiC composite at 100x and 500x magnification respectively.

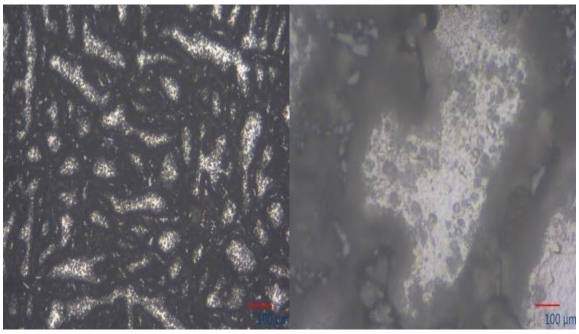

Figure 4a & 4b: Illustrates the optical micrographs of the Al-15% SiC composite at magnifications of 100x and 200x, respectively.

Microstructural evaluation: A detailed microstructural analysis of the stir-cast Al6061 matrix reinforced with varying amounts of SiC particles (5%, 10%, and 15%) was conducted using an optical microscope. The resulting optical micrographs, shown in Figures 2 through 4 at magnifications of 100x and 200x, provide insights into the particle distribution within the composite matrix. The as-cast composites demonstrate a consistent and uniform dispersion of SiC particles throughout the aluminum matrix. Furthermore, the micrographs reveal a noticeable improvement in the uniformity of the SiC particle distribution as the weight percentage of reinforcement increases. This suggests that higher concentrations of SiC lead to more homogeneous incorporation of reinforcement within the matrix, enhancing the overall microstructural integrity of the composite material.

XRD analysis

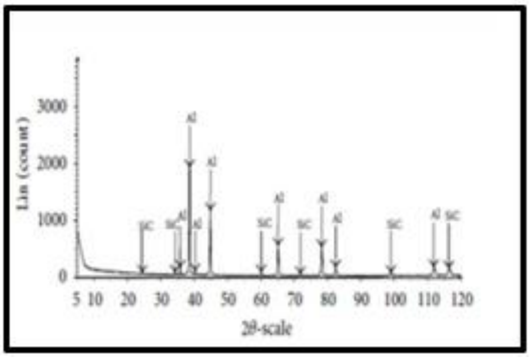

Figure 5a: Al6061/5%SiCp.

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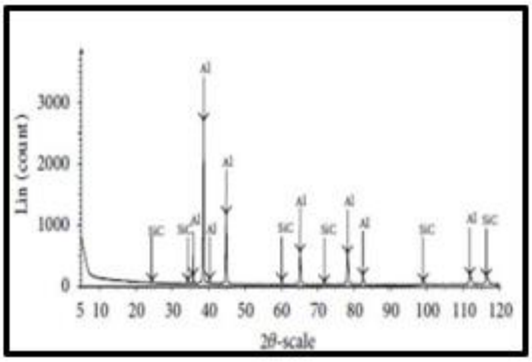

Figure 5b: Al6061/10%SiCp.

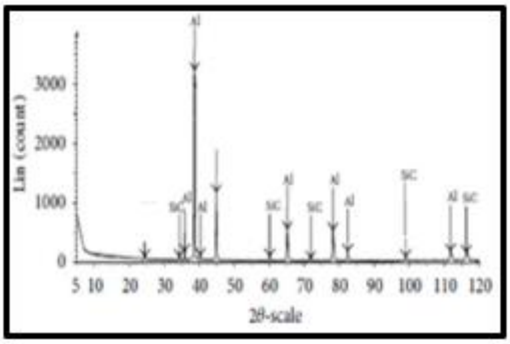

Figure 5c: Al6061/15%SiCp.

X-ray diffraction (XRD) analysis was conducted to verify the phase composition of the Al-SiCp metal matrix composite (MMC). The results indicate the absence of any undesired or secondary phases, confirming that only aluminum (Al) and silicon carbide (SiC) are present in the composite structure. The XRD patterns, as shown in Figures 5a through 5c, were recorded on a 2-theta (2θ) scale, which provides critical information about the crystallographic structure of the materials. For precise characterization, the diffraction angle (2θ) was varied between 5° and 120°. This wide scanning range ensures a comprehensive evaluation of the material's phase composition, reinforcing the purity and successful incorporation of SiC particles within the Al matrix without the formation of unwanted by- products.

X-Ray fluoroscence spectroscopy (XRF)

A WD-XRF Spectrometer Model-S8, Make TIGER Bruke has been used for analyzing the elemental composition and spectrum of Al-SiC MMC. Circular samples of 34mm diameter are prepared for XRF analysis. It has been concluded that the SiC is uniformly dispersed throughout the matrix. Moreover, compositional analysis reveals the presence of Silicon and carbon.

Hardness Hardness is defined as a material's ability to resist deformation, such as indentation or

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scratching. Various techniques are employed to measure hardness, with Brinell, Rockwell, and Vickers hardness tests being among the most commonly used methods. In this study, the hardness of the Al-SiC metal matrix composites (MMCs) was assessed using the Vickers hardness test. A diamond micro-indenter was employed to apply a controlled load of 10 kgf with a dwell time of 10 seconds to ensure accurate measurement. The resulting Vickers hardness values provide insight into the material's resistance to deformation and are listed in Table 2, with graphical representations shown in Figures 7 and

8. These results highlight the mechanical strength of the composites under specified test conditions, offering a clear understanding of how the SiC reinforcement impacts the hardness of the Al matrix.

Table 2: Vickers hardness measurement of Al-SiC metal matrix composites (MMCs).

Sr. No.	**Samples**	**Hardness (HV10)**
1	Al-5%SiC	38
2	Al-10%SiC	47
3	Al-15%SiC	52

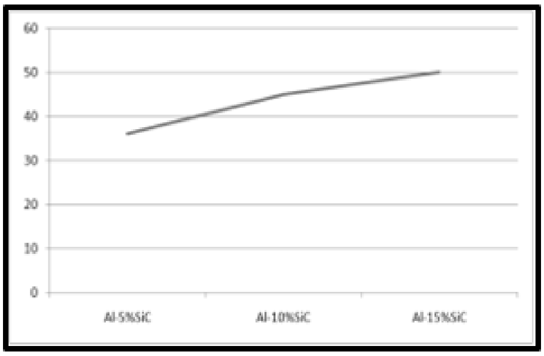

Figure 6: Illustrates the relationship between hardness values and the SiC content percentage."

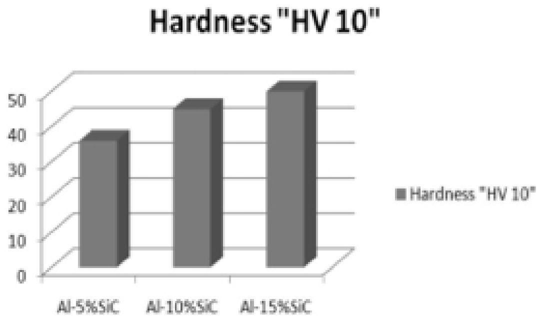

Figure 7: Depicts a bar chart demonstrating the trend of increasing hardness with the rise in SiC

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content

Tensile Testing: Tensile testing was performed using a universal testing machine to evaluate the mechanical properties of the Al6061 matrix composites reinforced with varying SiC content. The results are detailed in Table 4, which outlines the percentage elongation, yield strength at 0.2% offset, and ultimate tensile strength (UTS) for Al6061 with 5%, 10%, and 15% SiC particles. The analysis reveals a clear trend where the percentage elongation, a measure of ductility, decreases progressively with increasing SiC content, indicating a reduction in the material's ability to undergo plastic deformation. On the other hand, the yield strength and UTS exhibit a more complex behavior: both properties initially decline as the SiC content rises to 10%, likely due to a threshold in reinforcement effectiveness or matrix interaction. However, beyond this point, with the addition of 15% SiC, both yield strength and UTS begin to increase, suggesting enhanced load-bearing capability and overall strength as the SiC reinforcement reaches a higher concentration. This trend highlights the balancing effect of SiC content on the composite's mechanical performance.

Samples	%Elongation	0.2% Y.S (Mpa)	UTS (Mpa)
Al-5%SiC	2.1	53.9	53.1
Al-10%SiC	14	41.2	40.4
Al-15%SiC	0.6	52	56.1

CONCLUSION

Al-SiC metal matrix composites (MMCs) were successfully fabricated using the stir casting technique, which is recognized for its efficiency in integrating ceramic reinforcements into metallic matrices. In this method, the composite slurry is stirred while in a semi-solid state, allowing for the effective incorporation of silicon carbide (SiC) particles into the aluminum alloy matrix. This semi- solid stirring process is crucial as it prevents the settling of SiC particles; they become entrapped between the dendritic arms formed during solidification, ensuring a homogeneous distribution throughout the matrix.

Several critical processing parameters influence the quality and mechanical properties of the cast MMCs. These include the holding temperature, stirring speed, impeller size, and the position of

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the impeller in the molten alloy. Each of these factors must be carefully optimized to achieve the desired mechanical performance of the final composite material.

Comprehensive microstructural investigations, complemented by X-ray diffraction (XRD) analysis, revealed a uniform distribution of SiC particles within the aluminum matrix, which is essential for achieving enhanced mechanical properties. Furthermore, X-ray fluorescence (XRF) analysis provided detailed information regarding the chemical composition and spectrum of the fabricated composites. Although accurately determining the precise percentage of SiC in the matrix can be challenging, this was successfully achieved through meticulous adjustments to the processing parameters based on multiple rounds of XRF testing. This iterative process ensured that a consistent and uniform distribution of SiC reinforcement was maintained throughout the alloy matrix.

The addition of SiC particles significantly contributes to improving the mechanical properties of the aluminum matrix, notably enhancing hardness and tensile strength. These improvements are attributed to the reinforcing effect of the SiC particles, which enhance the load-bearing capacity of the composite. Interestingly, the wear rate of the composites decreased as the percentage of SiC increased from 5% to 15%. This reduction in wear rate indicates that SiC is highly effective in minimizing wear, making it advantageous for applications where abrasion resistance is critical. Additionally, the resulting Al-SiC MMCs exhibit high-temperature stability, making them suitable for use in environments subjected to elevated thermal conditions. The incorporation of SiC not only improves wear resistance but also enhances corrosion resistance, thus broadening the application range of these composites in various industries, including automotive, aerospace, and other fields where enhanced durability and performance are paramount. This combination of properties highlights the potential of Al-SiC MMCs as advanced materials for high-performance applications.

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