Development and Mechanical Characterization of AA6061 Hybrid Metal Matrix Composites Reinforced with Pista Shell Ash (PSA) and Silicon Carbide (SiC) Using Friction Stir Casting

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Abstract: The growing demand for lightweight and high-performance materials in engineering applications has led to the extensive development of aluminium-based hybrid metal matrix composites (HMMCs). In the present investigation, AA6061 aluminium alloy was selected as the matrix material and reinforced with a combination of Pista Shell Ash (PSA), an agro-waste material, and Silicon Carbide (SiC), a ceramic reinforcement, in varying weight percentages. The composites were fabricated using the friction stir casting technique to ensure uniform distribution of reinforcement particles and improved interfacial bonding. Four different compositions were prepared, namely unreinforced AA6061, and hybrid composites containing 1% PSA + 1% SiC, 2% PSA + 2% SiC, and 3% PSA + 3% SiC. Mechanical properties such as hardness, toughness, and compressive strength were evaluated to assess the influence of reinforcement addition. The results revealed a progressive increase in hardness and compressive strength with increasing reinforcement content, with maximum improvements of 19% and 23% respectively observed for the highest reinforcement composition. However, a reduction in toughness was observed, indicating increased brittleness due to the presence of hard ceramic phases. The study demonstrates that PSA can be effectively utilized as a sustainable reinforcement material in hybrid composites, enhancing mechanical performance while contributing to waste valorization.

Keywords: *AA6061 Aluminium Alloy, Hybrid Metal Matrix Composites (HMMCs), Pista Shell Ash (PSA), Silicon Carbide (SiC), Friction Stir Casting, Mechanical Properties.*

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I. INTRODUCTION

Aluminium metal matrix composites (AMMCs) have emerged as a class of advanced engineering materials owing to their superior mechanical properties, reduced density, and enhanced wear resistance when compared to conventional monolithic alloys [1]. Among various aluminium alloys, AA6061 has gained considerable importance due to its excellent combination of strength, corrosion resistance, formability, and weldability, making it suitable for structural and automotive applications [2]. However, the inherent limitations of aluminium alloys, particularly in terms of hardness and strength, necessitate reinforcement with secondary phases to meet the increasing performance demands of modern engineering systems.

The incorporation of ceramic reinforcements such as Silicon Carbide (SiC) into aluminium matrices has been

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widely reported to improve hardness, stiffness, and load-bearing capacity due to their high hardness and modulus [3]. SiC particles act as obstacles to dislocation motion, thereby enhancing the strength of the composite material. Despite these advantages, the use of synthetic reinforcements often leads to increased cost and processing complexity. In this context, the utilization of agro-waste materials as reinforcement has gained attention as an economical and environmentally sustainable alternative [4].

Pista Shell Ash (PSA), derived from the controlled combustion of pista shells, represents a promising reinforcement material due to its low density, availability, and silica-rich composition. The incorporation of such waste-derived materials into metal matrices not only improves material properties but also contributes to environmental sustainability by reducing waste disposal issues [5]. Hybrid composites, which combine both synthetic (SiC) and natural (PSA) reinforcements, offer a balanced approach to achieving enhanced mechanical performance while maintaining cost-effectiveness [6].

The fabrication technique plays a crucial role in determining the final properties of metal matrix composites. Conventional casting methods often suffer from issues such as particle agglomeration, poor wettability, and porosity [7]. To overcome these limitations, friction stir casting has been developed as an advanced processing technique that enables uniform distribution of reinforcements and improved bonding between matrix and particles [8]. This technique involves mechanical stirring of the molten or semi-solid material using a rotating tool, leading to refined microstructure and enhanced mechanical properties.

Previous studies have indicated that increasing reinforcement content generally leads to improved hardness and strength, but at the expense of ductility and toughness due to the brittle nature of ceramic particles [9]. The interaction between reinforcement particles and the matrix significantly influences crack initiation and propagation behavior [10]. While extensive research has been conducted on various agro-waste reinforcements such as rice husk ash, bagasse ash, and coconut shell ash [11–13], limited work has been reported on the use of PSA, particularly in hybrid combinations with SiC.

Therefore, the present study aims to investigate the effect of varying weight percentages of PSA and SiC on the mechanical properties of AA6061-based hybrid composites fabricated using friction stir casting. The study focuses on evaluating hardness, toughness, and compressive strength to understand the trade-off between strength enhancement and ductility reduction, thereby providing insights into the potential application of these composites in engineering fields.

II. MATERIALS AND METHODS

In this study, AA6061 aluminium alloy was used as the base matrix material due to its favorable mechanical and physical properties. The reinforcement materials selected were Pista Shell Ash (PSA) and Silicon Carbide (SiC). PSA was prepared by collecting pista shells, thoroughly cleaning them to remove impurities, and subjecting them to controlled combustion to obtain ash. The ash was then sieved to achieve uniform particle size suitable for composite fabrication. Silicon Carbide particles were used in their commercially available form.

The fabrication of composites was carried out using the friction stir casting technique, which is an advanced method combining aspects of casting and friction stir processing. Initially, the AA6061 alloy was melted in a furnace at an appropriate temperature to achieve a fully molten state. The reinforcement particles were preheated separately to remove moisture and improve wettability. The preheated PSA and SiC particles were then introduced into the molten aluminium in the desired proportions.

A rotating tool was employed to stir the molten mixture, ensuring uniform distribution of reinforcement particles throughout the matrix. The stirring action also helped in breaking particle clusters and reducing porosity. The mixture was then allowed to solidify under controlled conditions to obtain the composite castings. This method ensured improved bonding between the matrix and reinforcements, leading to enhanced mechanical properties.

➢ *Experimental Work*

Four different composite samples were prepared with varying reinforcement contents. The first sample consisted of pure AA6061 alloy and served as the reference material. The subsequent samples were reinforced with increasing weight percentages of PSA and SiC in equal proportions, specifically 1% PSA + 1% SiC, 2% PSA + 2% SiC, and 3% PSA + 3% SiC.

The hardness of the fabricated samples was measured using a standard hardness testing machine, where multiple readings were taken at different locations on each specimen to ensure accuracy and consistency. The toughness of the materials was evaluated using the Charpy impact test, which measures the energy absorbed by the material during fracture. This test provides an indication of the material's ability to withstand sudden impact loads.

The compressive strength of the composites was determined using a Universal Testing Machine (UTM), where compressive load was applied gradually until failure occurred. The stress-strain behavior of each sample was recorded, allowing for comparison of their load-bearing capacities.

III. RESULTS AND DISCUSSION

The mechanical behavior of the developed AA6061 hybrid metal matrix composites reinforced with Pista Shell Ash (PSA) and Silicon Carbide (SiC) clearly demonstrates the influence of reinforcement content on material performance. As the weight percentage of reinforcements increases, a significant enhancement in hardness and compressive strength is observed, while toughness shows a decreasing trend. This behavior is typical of aluminium-based composites reinforced with hard ceramic particles, where strength improvement is accompanied by a reduction in ductility.

The experimental findings obtained from hardness, toughness, and compressive strength tests are summarized in Table 1. The table presents a comparative view of the effect of increasing reinforcement content on the mechanical properties of the fabricated samples.

Table 1 Mechanical Properties of AA6061/PSA/SiC Hybrid Composites

Experiment	**Reinforcement (wt.%)**	**% Increase in Hardness**	**% Decrease in Toughness**	**% Increase in Compressive Strength**
E1	0% PSA + 0% SiC	0	0	0
E2	1% PSA + 1% SiC	7.2	4	8
E3	2% PSA + 2% SiC	15.4	7	15
E4	3% PSA + 3% SiC	19	13.5	23

From the table, it is evident that the hardness of the composite increases progressively with the addition of reinforcements. The maximum increase of 19% is observed for the sample containing 3% PSA and 3% SiC (Exp-4). This improvement can be attributed to the presence of hard SiC particles, which resist plastic deformation and enhance the resistance of the material to indentation. Additionally, PSA contributes to strengthening by improving load distribution within the matrix. The combined effect of both reinforcements leads to grain refinement and increased dislocation density, thereby enhancing hardness.

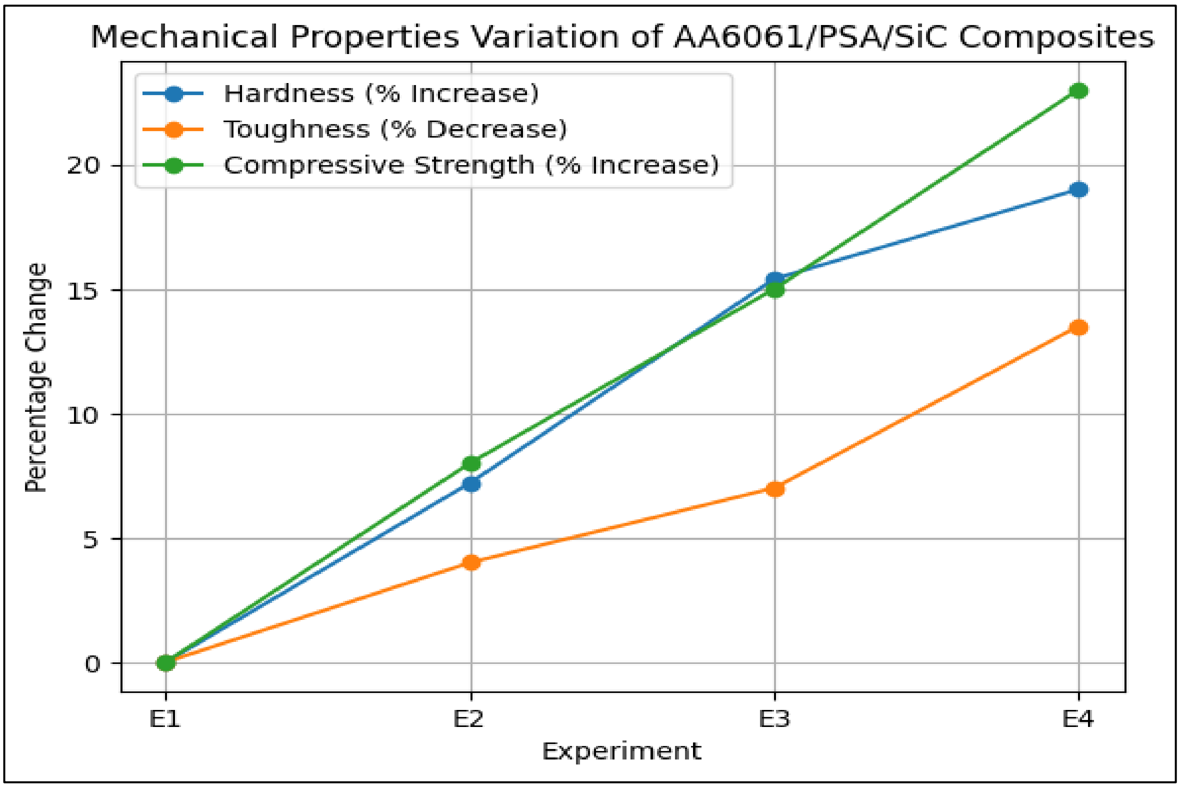

Fig 1 Mechanical Properties Variation AA601/PSA/SiC Composites

In contrast, the toughness of the composites decreases with increasing reinforcement content. The reduction is relatively moderate at lower reinforcement levels but becomes more pronounced at higher percentages, with a maximum decrease of 13.5% observed in Exp-4. This decline in toughness is primarily due to the brittle nature of the reinforcement particles. The presence of hard and brittle phases introduces stress concentration sites within the matrix, which facilitate crack initiation and propagation under impact loading. As a result, the ability of the material to absorb energy before fracture is reduced.

The compressive strength of the composites exhibits a significant increase with increasing reinforcement content, reaching a maximum improvement of 23% for Exp-4. This enhancement can be explained by the effective load transfer from the ductile aluminium matrix to the rigid reinforcement particles. The presence of PSA and SiC restricts dislocation motion and plastic deformation, thereby increasing the load-bearing capacity of the composite. Furthermore, the uniform distribution of reinforcements achieved through the friction stir casting process ensures better interfacial bonding, which plays a crucial role in improving compressive strength.

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Overall, the results indicate that the hybrid reinforcement of PSA and SiC effectively enhances the mechanical properties of AA6061 composites. However, a trade-off between strength and toughness is observed, which must be carefully considered depending on the intended application. The developed composites are particularly suitable for applications where high hardness and compressive strength are required, while moderate toughness is acceptable.

IV. CONCLUSION

The present study successfully demonstrated the fabrication of AA6061-based hybrid metal matrix composites reinforced with Pista Shell Ash and Silicon Carbide using the friction stir casting technique. The results clearly indicate that the incorporation of hybrid reinforcements leads to significant improvements in hardness and compressive strength, with maximum enhancements observed at higher reinforcement levels. However, a reduction in toughness was also observed, highlighting the increased brittleness of the composites. The use of PSA as a reinforcement material offers a sustainable and cost-effective approach to composite development, making it a viable alternative for engineering applications requiring high strength and wear resistance. The study provides valuable insights into the development of eco-friendly hybrid composites and their potential applications in structural and automotive industries.

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