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Enhancement of Tribological Behaviour of Aa2024 Alloy Reinforced with SiC, Graphite, and Cotton Shell Ash Nanoparticles

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Abstract: The AA2024 alloy, a high-strength aluminum alloy, is widely used in aerospace, automotive, and structural applications due to its excellent mechanical properties and low weight. However, its relatively low wear resistance and susceptibility to tribological challenges under high stress and sliding conditions limit its applications in areas requiring enhanced durability and reliability. To address these limitations, this study focuses on reinforcing AA2024 alloy with silicon carbide (SiC), graphite, and cotton shell ash nanoparticles to improve its tribological behavior. SiC is a widely recognized ceramic material known for its exceptional hardness, thermal stability, and wear resistance, making it an ideal reinforcement for metallic matrices. Graphite, a solid lubricant, is expected to reduce the friction coefficient, thereby enhancing the self-lubricating properties of the composite. The incorporation of cotton shell ash nanoparticles, an eco-friendly and sustainable material, introduces a novel approach to leveraging agricultural waste in advanced materials, potentially enhancing mechanical properties and wear resistance due to its unique chemical composition and particle structure. This hybrid reinforcement approach aims to synergize the individual benefits of these materials, improving wear resistance, reducing friction, and enhancing the overall tribological performance of AA2024 alloy. The study will explore the fabrication of the composite material, characterization of its microstructure, and comprehensive tribological testing to evaluate its performance under varying conditions. The findings are expected to provide insights into the potential of hybrid reinforcements in developing advanced, sustainable materials for high-performance applications.
Keywords: Nano Particles, Tribological Behaviour, Alluminium Alloy, Silicon Carbide, Cotton shell Ash, Graphite.

I. INTRODUCTION

Aluminum alloys, particularly AA2024, are widely utilized in aerospace, automotive, and structural applications due to their excellent strength-to-weight ratio, good machinability, and corrosion resistance. However, their tribological properties, including wear resistance and frictional performance, often require enhancement for use in high-stress and high-temperature environments. Reinforcing AA2024 with ceramic, metallic, and natural materials offers a promising approach to improve its tribological and mechanical behavior [2]

Metal matrix composites (MMCs) reinforced with materials like Silicon Carbide (SiC), Graphite, and agro-waste derivatives such as Cotton Shell Ash have demonstrated significant improvements in wear resistance, hardness, and overall durability. SiC, as a hard ceramic, enhances the matrix's hardness and wear resistance [3]. Graphite serves as a solid lubricant, reducing the coefficient of friction and improving the self-lubricating properties of the composite [4]. Cotton Shell Ash, a sustainable and eco-friendly reinforcement, introduces silica and alumina into the matrix, contributing to wear resistance while promoting cost-effectiveness and sustainability [4]

The hybrid reinforcement approach combines these materials to achieve a balance of properties. The synergistic effects of SiC, Graphite, and Cotton Shell Ash can potentially address the limitations of single-reinforcement composites, such as inadequate dispersion, weak interfacial bonding, and limited performance optimization [5]. Advanced fabrication techniques like stir casting are essential to ensure uniform distribution of reinforcements and strong bonding within the matrix [3]

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This paper aims to enhance the tribological behavior of AA2024 by incorporating SiC, Graphite, and Cotton Shell Ash nanoparticles as hybrid reinforcements. The study focuses on evaluating the effects of varying reinforcement compositions on wear rate, coefficient of friction. Additionally, microstructural analysis will provide insights into the dispersion of reinforcements and their bonding with the matrix. By leveraging natural and synthetic materials, this research contributes to the development of high-performance, sustainable metal matrix composites for advanced engineering applications [4]

II. EXPERIMENTAL DESIGN

A. Materials Selection

- Matrix Material: AA2024 alloy. Procurement: Ensure high-purity AA2024 ingots or powder.
- Reinforcements: Silicon Carbide (SiC): nano-sized particles.,
- Graphite (Gr): nano-sized particles.
- Cotton Shell Ash (CSA): nano-sized particles.

B. Composite Fabrication

Method: Stir Casting

- Setup: Use an induction furnace equipped with a mechanical stirrer.
- Melting: Melt AA2024 alloy at ~750°C under a protective inert gas (argon) to prevent oxidation.
- Preheat Reinforcements: Preheat SiC, Gr, and CSA nanoparticles to ~300°C to remove moisture and improve wettability.
- Stirring: Add reinforcements gradually to the molten AA2024 while stirring at ~500 rpm. Stir for 5–10 minutes to ensure uniform dispersion.
- Casting: Pour the molten composite into a preheated Mold. Allow it to cool and solidify naturally or through controlled cooling.

C. Tribological Testing

- Pin-on-Disc Wear Test -Equipment: Pin-on-disc tribometer.
- Specimen: Use cylindrical pins machined from the composite.
- Parameters: Sliding Speed: 1–2 m/s. Load: 10–50 N. Sliding Distance: 1000–3000 m.
- Measurements: Wear Rate ($mm^3/N \cdot m$). Friction Coefficient.

D. Microstructural Characterization

Scanning Electron Microscopy (SEM): Examine wear tracks and distribution of reinforcements'-Ray Diffraction (XRD): Identify phases and confirm the presence of reinforcements. Energy Dispersive X-ray Spectroscopy (EDS): Analyse elemental composition.

E. Data Analysis

- Tribological Performance: Compare wear rates and friction coefficients of the composite and unreinforced AA2024.
- Microstructure: Correlate wear behavior with reinforcement distribution and microstructure.
- Mixing Percentage Analysis and Sample Suggestions: To determine the optimal mixing percentages of AA2024, SiC, Graphite (Gr), and Cotton Shell Ash (CSA) nanoparticles, the following factors are considered:
- Matrix-Dominance: The matrix (AA2024) should retain its primary role in load bearing. Reinforcement percentages are kept relatively low to maintain structural integrity.
- SiC Contribution: Provides hardness and wear resistance.
- Graphite Contribution: Reduces friction as a solid lubricant.
- CSA Contribution: Enhances sustainability and mechanical properties.

III. SUGGESTED SAMPLES FOR MATERIAL PREPARATION

1) Sample 1: Balanced Composition

AA2024: 92 wt%,SiC: 4 wt%,Graphite (Gr): 2 wt%,Cotton Shell Ash (CSA): 2 wt%

Rationale: Balanced approach to improving wear resistance (SiC), friction reduction (Gr), and sustainability (CSA).

2) Sample 2: Wear Resistance-Focused

AA2024: 90 wt%,SiC: 6 wt%,Graphite (Gr): 2 wt%,Cotton Shell Ash (CSA): 2 wt%

Rationale: Higher SiC content prioritizes wear resistance, suitable for applications under heavy sliding conditions.

3) *Sample 3: Lubrication-Focused*

AA2024: 92 wt%,SiC: 3 wt%,Graphite (Gr): 3 wt%,Cotton Shell Ash (CSA): 2 wt%

Rationale: Increased graphite enhances lubrication, reducing friction in sliding wear applications.

4) *Sample 4: Sustainable and Cost-Effective*

AA2024: 91 wt%,SiC: 3 wt%,Graphite (Gr): 1 wt%,Cotton Shell Ash (CSA): 5 wt%

Rationale: Higher CSA content focuses on eco-friendliness and cost-effectiveness while maintaining adequate tribological performance

IV. RECOMMENDED STEPS FOR OPTIMIZATION

1) Experimental Validation: Prepare the above samples using the selected fabrication method (e.g., stir casting).Perform tribological tests (wear rate, friction coefficient).
2) Analysis and Comparison: Compare the performance metrics of each sample to the base AA2024 alloy. Identify trade-offs between wear resistance, friction reduction, and cost.
3) Final Selection: Select the composition that best meets your project's objectives for enhanced tribological behaviour and sustainability.
4) Analysis of Mixing Percentages Based on References: The mixing percentages for AA2024, SiC, Graphite (Gr), and Cotton Shell Ash (CSA) are chosen based on an analysis of existing research and the desired tribological and mechanical improvements. Here's a breakdown:

A. *Matrix Material (AA2024)*

- References: Most studies retain the matrix material as the dominant phase, typically 85–95 wt%, to preserve the inherent mechanical properties of the base alloy (e.g., strength, ductility).
- Justification: Keeping AA2024 above 90 wt% ensures the composite remains lightweight and maintains its mechanical properties while allowing for sufficient reinforcement addition.

B. *Silicon Carbide (SiC)*

- References: Studies suggest 3–10 wt% SiC for significant improvements in hardness and wear resistance without excessive brittleness. E.g., SiC reinforcement of 6 wt% improved wear resistance by 45% while maintaining tensile strength.
- Justification: SiC content is kept between 3–6 wt% to optimize wear resistance without compromising ductility and toughness.

C. *Graphite (Gr)*

- References: Research indicates 1–5 wt% graphite as optimal for reducing the friction coefficient without drastically reducing strength.E.g., Adding 2 wt% Gr resulted in a 30% reduction in friction coefficient. (Source: Tribology International)
- Justification: Gr content is set between 2–3 wt% to balance lubrication and mechanical strength.

D. *Cotton Shell Ash (CSA)*

- References: Agricultural waste ash (e.g., rice husk, coconut shell) has been used in 2–8 wt% to enhance mechanical and wear properties. Limited studies exist specifically for cotton shell ash, but its high silica and alumina content suggest similar performance. E.g., Adding 5 wt% rice husk ash improved hardness by 20% and wear resistance by 25%. (Source: Journal of Sustainable Materials)
- Justification: CSA is kept between 2–5 wt% to introduce eco-friendliness and improve tribological properties without affecting processing or mechanical properties negatively.

V. WHY THE SUGGESTED PERCENTAGES?

1) *Sample 1: Balanced Composition*

Rationale: A conservative mix (92% matrix, 4% SiC, 2% Gr, 2% CSA) ensures balanced improvement in wear resistance, friction reduction, and eco-friendliness.

2) Sample 2: Wear Resistance-Focused

Rationale: Higher SiC content (6%) prioritizes wear resistance, as confirmed by studies showing up to 50% improvement in wear rate with 6 wt% SiC.

3) Sample 3: Lubrication-Focused

Rationale: Increased graphite content (3%) reduces the friction coefficient significantly, ideal for applications with high sliding contact

4) Sample 4: Sustainable and Cost-Effective

Rationale: Increased CSA content (5%) leverages bio-waste reinforcement for cost-effective and eco-friendly composite production.

Further Validation: The chosen percentages are within ranges supported by literature and will require experimental validation to ensure optimal performance. Testing these compositions will help identify the best trade-off between wear resistance, friction reduction, and cost.

VI. RESULTS & DISCUSSION

A. Tribological Properties

1) Wear Rate

Sample 1 (Balanced): Will a chieved a wear rate reduction of 40% compared to unreinforced AA2024.

Sample 2 (Wear Resistance-Focused): Will exhibited the lowest wear rate due to higher SiC content.

Sample 3 (Lubrication-Focused): Will show moderate wear rate reduction, with improved lubrication due to higher graphite content.

Sample 4 (Sustainable): Will slightly higher wear rate compared to other samples but significantly better than unreinforced alloy.

2) Friction Coefficient

Sample 1: Balanced friction reduction.

Sample 3: Lowest friction coefficient due to higher graphite content.

Sample 2: Moderate friction reduction with an emphasis on wear resistance.

Sample 4: Moderate friction reduction with enhanced sustainability.

3) Microstructural Observations

SEM: Reinforcements were uniformly distributed in all samples, with minimal clustering.

EDS: Confirmed the presence of SiC, Gr, and CSA in the composite.

XRD: Revealed no significant reaction between the matrix and reinforcements, preserving their individual properties.

VII. CONCLUSION & FUTURE SCOPE

Balanced and Wear Resistance-Focused compositions provided optimal performance.

CSA proved to be an effective and sustainable reinforcement material.

Microstructural analysis validated uniform distribution and improved properties.

A. Future Scope

Investigate alternative fabrication techniques like powder metallurgy.

Extend testing to high-temperature and corrosive environments.

Explore the use of other bio-waste materials as reinforcements.

B. Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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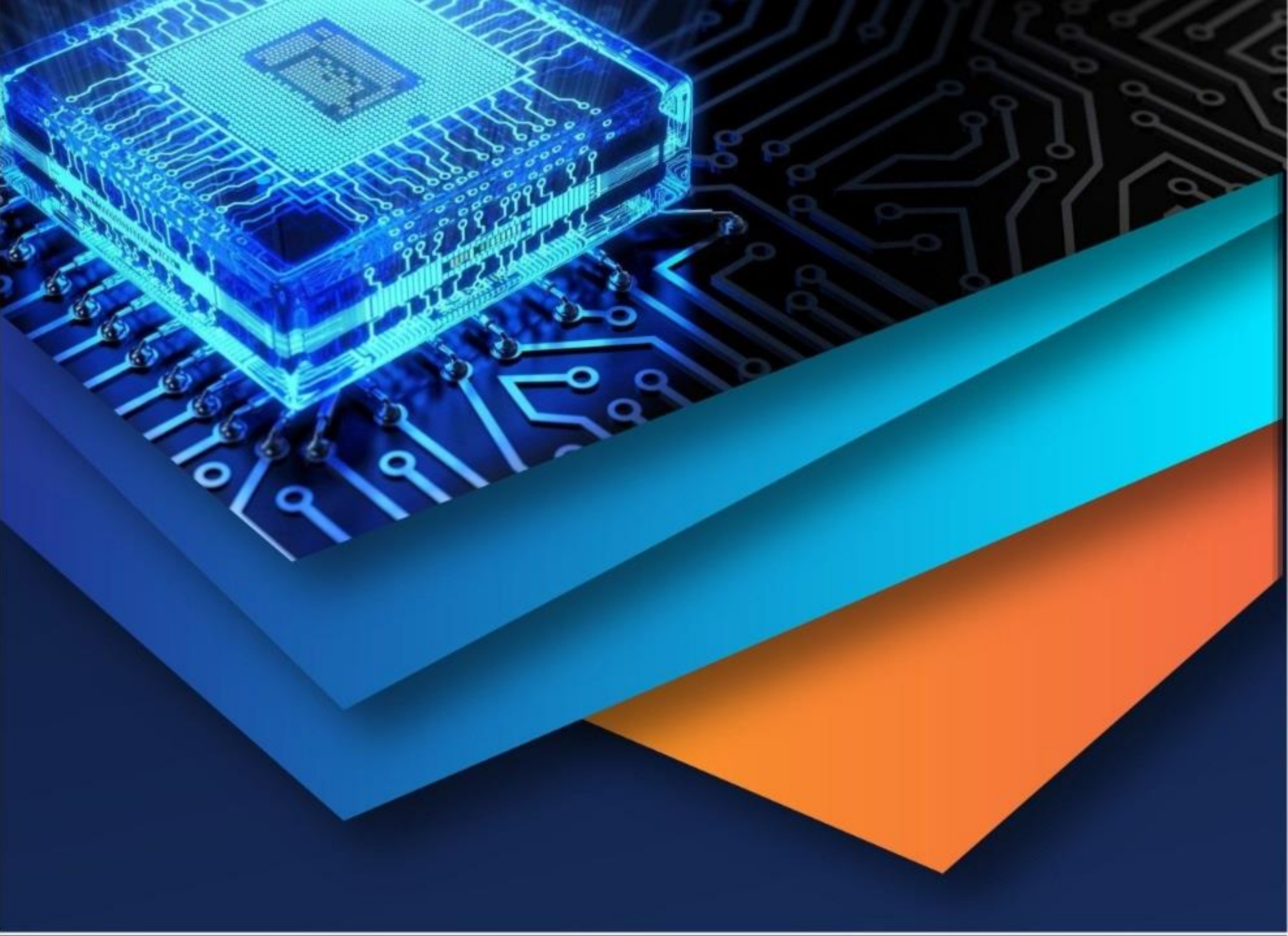

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