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Optimization of Tribological Behaviour of Metal Matrix Composites by Response Surface Methodology

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ABSTRACT

Reducing vehicle emissions and fuel consumption remains a primary challenge for the automotive industry. Using lightweight materials such as Aluminum Metal Matrix Composites (AMMCs) reinforced with Coconut Shell Ash (CSA) offers an eco-friendly and cost-effective solution. This study investigates the optimization of tribological properties, including wear resistance and hardness, of AMMCs using the Response Surface Methodology (RSM). Various composite samples containing 10% and 20% CSA by weight were prepared using powder metallurgy, and tribological tests were performed using a pin-on-disc wear testing machine. The results demonstrate a significant improvement in wear resistance and hardness with increasing CSA content. The wear parameters were optimized, achieving a minimum wear loss of 0.001113 g. This research contributes to the development of sustainable, lightweight materials suitable for automotive and aerospace applications.

KEYWORDS: *Vehicle emissions, Fuel consumption, Aluminum Metal Matrix Composites (AMMCs), Coconut Shell Ash (CSA), Tribological properties, Wear resistance, Hardness, Powder metallurgy, Response Surface Methodology (RSM), ANOVA*

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1. INTRODUCTION

Reducing vehicle emissions and fuel consumption is a critical goal for automotive manufacturers. Aluminum, due to its light weight and corrosion resistance, has emerged as a preferred alternative to heavier materials like cast iron and steel in automotive engine parts. However, pure aluminum lacks adequate wear resistance for high-friction components. The solution lies in developing Aluminum Metal Matrix Composites (AMMCs), which incorporate reinforcement materials to enhance aluminum's tribological properties.

Coconut Shell Ash (CSA), a readily available agricultural waste product, has shown potential as an environmentally friendly reinforcement. Rich in SiO_2 and Al_2O_3, CSA can significantly improve the wear resistance and hardness of AMMCs. This study investigates the tribological behaviour of AMMCs reinforced with CSA, using powder metallurgy to fabricate the composite and Response Surface Methodology (RSM) to optimize wear parameters.

2. Literature Review

AMMCs are widely used in the automotive and aerospace industries due to their high strength-to-weight ratio and excellent wear properties. Conventional reinforcements like SiC and Al_2O_3 have been used in metal matrix composites to improve tribological properties. However, the focus has shifted toward using sustainable, cost-effective materials like agricultural waste products, including fly ash and coconut shell ash (CSA) .

Several studies have explored the mechanical and tribological performance of AMMCs reinforced with natural reinforcements. Kumar et al. and Ononivu et al. highlighted the significant improvements in wear resistance, hardness, and tensile strength when CSA was incorporated into aluminum composites. Mangalore et al. showed that CSA-reinforced composites offer improved hardness and reduced density, making them ideal for lightweight applications in the automotive industry.

3. Methodology

3.1. Material Selection

Table 1 Some important properties of aluminum

S. No.	properties	Aluminium(Al)
1	Atomic number	13
2	phase	Solid
3	Density	2.70 gm/cm^3
4	Melting point	660.32^{0}C
5	Boiling point	2470^{0}C
6	Crystal structure	FCC
7	Thermal conductivity	237 w-m^{-1}k^{-1}
8	Young's modulus	70 GPa
9	Shear modulus	26 GPa
10	Bulk modulus	76 Gpa
11	Brinell Hardness	160-550 MPa

The matrix material used in this study was pure aluminum. CSA, an abundant and eco-friendly waste material, was selected as the reinforcement. The chemical composition of CSA includes SiO2, Al2O3, MgO, and Fe2O3, which contribute to its high wear resistance and hardness.

3.2. Sample Preparation

The AMMC samples were prepared using powder metallurgy. Three sets of samples were synthesized with the following CSA contents:

0% CSA (pure aluminum)
10% CSA by weight
20% CSA by weight

The powders were mixed in an electric mortar and pestle for 2 hours and compacted at 400 MPa. The samples were sintered at 745–800 K in an Electrical Muffle Furnace.

3.3. Tribological and Mechanical Testing

Tribological testing was performed using a pin-on-disc wear testing machine under varying conditions of sliding velocity, sliding distance, and normal load. Rockwell hardness tests were conducted to assess the hardness of each composite. Scanning Electron Microscopy (SEM) was used to examine the distribution of CSA particles in the aluminum matrix and to evaluate the microstructural integrity.

3.4. Response Surface Methodology (RSM)

Response Surface Methodology (RSM) was applied to optimize wear parameters, including sliding velocity, sliding distance, normal load, and CSA weight percentage. A Central Composite Design (CCD) was used to evaluate the effects of these factors on wear loss, and ANOVA analysis was conducted to determine the statistical significance of the model.

4. Results and Discussion

4.1. Microstructural Analysis

SEM images revealed that the CSA particles were uniformly distributed in the aluminum matrix, with minimal porosity. The sample containing 20% CSA showed the highest densification and bonding between the particles and matrix, indicating improved wear resistance.

4.2. Hardness and Wear Resistance

The results of the Rockwell hardness tests showed a significant increase in hardness with increasing CSA content:

Pure Aluminum: 39.1 HR
10% CSA: 44.26 HR
20% CSA: 46.9 HR

Tribological tests demonstrated that wear resistance improved with higher CSA content. The lowest wear loss (0.001113 g) was observed for the sample containing 20% CSA under a normal load of 10 N, sliding velocity of 2 m/s, and sliding distance of 2000 m.

4.3. RSM and ANOVA Analysis

ANOVA analysis revealed that normal load was the most significant factor affecting wear loss, followed by sliding distance and CSA weight percentage. The quadratic model developed using RSM showed a prediction error of ±10%, demonstrating the model's reliability in optimizing wear parameters.

5. Conclusion

This study successfully demonstrated the use of Coconut Shell Ash (CSA) as an effective reinforcement for Aluminum Metal Matrix Composites (AMMCs). The incorporation of CSA improved the hardness and wear resistance of the composite, making it suitable for automotive applications where lightweight and durability are critical. The use of Response Surface Methodology

(RSM) allowed for the optimization of wear parameters, achieving minimal wear loss under optimal conditions. Future research could explore the use of other agricultural waste materials as reinforcements in AMMCs.

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