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# Enhancing Mechanical and Wear Properties of Aluminum-Coconut Fly Ash Composites through Microwave Sintering

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***Abstract***— ***Aluminium composites are widely employed in the manufacture of various components for the automotive, marine, aerospace, and nuclear industries. Silica is the most abundant component in coconut fly ash, followed by potassium, calcium, and magnesium in smaller amounts. Silica content typically varies from 80% to 95%. Coconut ash has other advantages besides its high silica concentration, such as great porosity and relatively moderate heat conductivity. Aluminium is added in varying ratios to improve the strength of coconut fly ash composites, often at 3%, 6%, and 9%. The samples underwent microwave sintering at 550°C with a tolerance of ±5°C. Mechanical testing involved both pure aluminium specimens and aluminium composites. The results show a favourable association between CFA concentration and both density and porosity. When compared to pure aluminium, composites reinforced with 3%, 6%, and 9% showed considerable increases in hardness, ultimate tensile strength (UTS), and yield strength (YS). However, it is worth mentioning that the elongation of the composites decreased rapidly. The observed gains in both ultimate tensile strength (UTS) and yield strength (YS) may be attributed to particle size reduction, which is controlled by a variety of processes including dislocation density, grain refinement, and lower porosity. Incorporating CFA reinforcement into composites reduced wear rates and increased wear resistance.***

***Index Terms***— ***Aluminum, Coconut Fly Ash Composites, Microwave Sintering, Wear Properties***

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## I. INTRODUCTION

The mechanical properties of reinforced composites are governed by a variety of factors, including reinforcement parameters (size, shape, and weight percentage), matrix material, and interface reaction. Achieving a homogeneous dispersion of reinforced material is critical for optimising mechanical parameters such as microhardness and tensile strength. Several studies have shown that particle size and shape influence the microstructural integrity and mechanical performance of the optimal compact. Ceramic composites containing coconut fly ash (CFA) have received interest in a variety of disciplines due to its favourable properties, which include reduced apparent density, higher melting temperatures, increased hardness, higher Young's modulus, and corrosion resistance.

Metal matrix composites (MMCs) are sophisticated materials created by mixing two or more components. They have improved properties such as strength, stiffness, and resistance to wear. The use of aluminium metal matrix composites (AMMCs) offers great promise due to their superior specific strength, wear resistance, and ability to sustain high temperatures. Considerable study has been conducted to investigate the mechanical properties of ceramic composites, such as their capacity to tolerate wear, deform under tension, resist fractures, and withstand cyclic stresses. Many reinforcement materials, such as silicon carbide, coconut fly ash, graphene, boron carbide, and carbon nanotubes, have been widely studied and used to improve the efficacy of matrices.

To perform optimally, Al/CFA composites must have increased strength, thermal properties, and resistance to wear and corrosion. Spark Plasma Sintering (SPS) at exact temperatures has been shown to achieve enough densification while minimising defects in Al/CFA composites. Powder metallurgy (P/M) technologies provide various advantages, including constant particle dispersion and precise control over contact kinetics, which results in enhanced mechanical properties. The introduction of SiC nanoparticles in an aluminium matrix, followed by sintering using the hot isostatic press (HIP) process, has resulted in significant strength gains.

Microwave sintering is a highly efficient process for producing composites due to its rapid heating rate, reduced production time, and equal distribution of morphology. Microwave sintering offers benefits such as uniform heating, reduced environmental risk, and enhanced density, resulting in better microstructures and superior physical and mechanical qualities. Economic study has shown that microwave-aided sintering (MAS) may create components with high accuracy while minimising errors and lowering processing times. Nonetheless, academics have showed little interest in the microwave processing of metal composites in powder metallurgy.

The major goal of this study is to investigate the effects of varied sliding speeds on dry sliding wear in metal matrix composites. CFA reinforcements have been shown to improve composite durability while creating a less substantial volume drop when compared to composites reinforced with silicon carbide particles. The sliding speed is the primary predictor of wear behaviour, with the applied load and sliding distance playing secondary roles. The presence of CFA in unalloyed aluminium significantly improves its wear resistance, resulting in a drop in coefficients of friction as the quantity of reinforcement increases. This study aims to compare the mechanical and wear properties of Al-CFA composites to pure aluminium.

## II. EXPERIMENTATION

For this study, we got 99.5% pure aluminium powder and 99.5% pure CFA from Otto Chemie Pvt Ltd. Ltd uses the initial ingredients. The allotment of resources will be limited and used as the primary inputs. The powders are combined in a ball mill, specifically without the addition of balls, at weight ratios of 3%, 6%, and 9%. Following that, the powder is placed in a hydraulic press with a capacity of 20 tonnes and a pressure of 120 bar [16]. The compressed green specimens were then sintered in a microwave heating furnace at 550 °C for 90 minutes. The sintering process was carried out in a controlled nitrogen gas environment.

The density of the samples is determined using Archimedes' approach [17]. The porosity of a composite can be estimated by comparing its actual and theoretical densities. The hardness of aluminium samples subjected to microwave sintering was measured with a Rockwell Hardness tester. The Rockwell hardness number of the specimens was determined by applying a 500-gram force to the samples for 15 seconds and then measuring the indentation diameter at five particular sites. Tensile tests on sintered materials were performed using servohydraulic testing equipment. The crosshead speed was 0.254 mm/min, with a starting strain rate of 1.69 10ℒ4 sℒ1. The flat tension test samples measured 15 mm broad and 30 mm in gauge length.

**Fig. 1 (a)** Planetary Ball Mill

**Fig. 1 (b)** Microwave Furnace

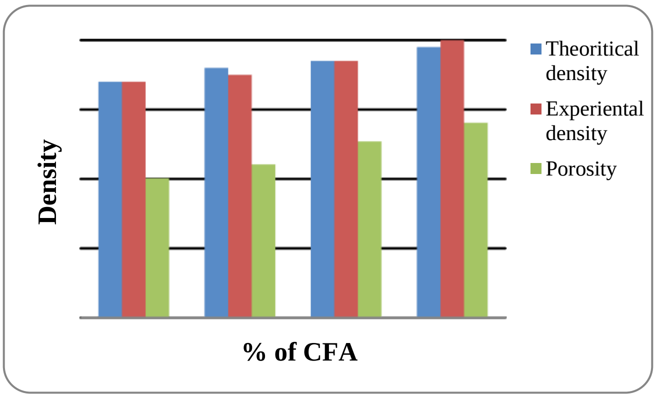
**Fig. 1 (c)** Hydraulic Press

## III. RESULTS AND DISCUSSIONS

### Density and Porosity

Density measurements were used to determine the porosity of the resulting composites and the effect of reinforced ceramic content on density. Following previous research [18], the density and porosity of composites with various quantities of CFA particles were assessed. Figure 5 depicts the observed density and porosity changes in the composite material. Incorporating denser CFA particles into aluminium resulted in an increase in composite density at varying CFA concentrations. Specifically, composites containing 3%, 6%, and 9% CFA particles showed density improvements of 6.28%, 10.75%, and 16.66%, respectively, above pure aluminium. Porosity was determined using both theoretical and experimental densities. The porosity of composites increased marginally with increasing CFA content, reaching a maximum of 2.1760% for the Al/9%CFA composite material, as shown in Figure 2. The maximum permissible porosity during AMMC manufacture is 3%, hence the resulting composites have a porosity level below this threshold. These data show that a porosity level of 2.1760%

or below is considered normal and acceptable in this inquiry.



## HARDNESS

A material's hardness is determined by its sensitivity to surface indentation, which can be modified with additional reinforcement. The addition of stiff CFA particles increases the hardness of the aluminium matrix. Figure 6 shows the relative hardness of pure aluminium and various mixtures. Pure aluminium has a Vickers hardness of 90.6 VHN. However, when combined with 9% CFA and sintered, the resulting composite hardness increases to 118.5 VHN with increasing CFA concentration. Coconut fly ash (CFA) particles increase the hardness of aluminium matrix metal composites (AMMCs) by limiting dislocation mobility. This observed increase in hardness is attributed to the reinforcement provided by implanted particles. The addition of reinforcing particles with a higher hardness than the matrix material contributes to composite hardness. Furthermore, the reduced grain size of the composite material promotes hardness in sintered composites with reinforcement. The Hall-Petch connection [19] demonstrates a clear link between particle size reduction and hardness enhancement.

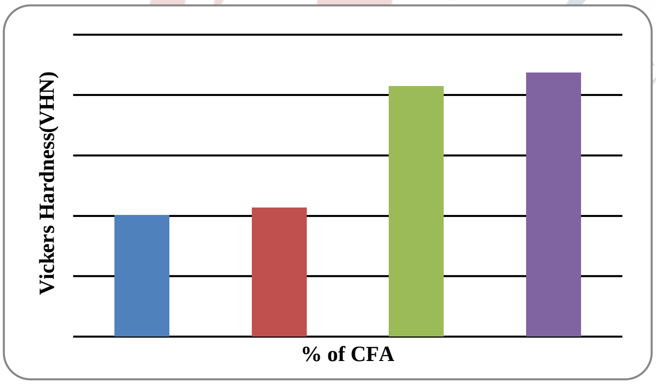


**Fig. 3** Variation in hardness with different CFA content in the composites

## TENSILE BEHAVIOR

The experiment results show that reinforced composites have higher tensile strength than pure aluminium. Stress-strain graphs show that incorporating coconut fly ash (CFA) into composites increases their ultimate tensile strength (UTS). The three sample concentrations (3%, 6%, and 9%) displayed yield strengths (YS) of 21.16%, 49.36%, and 61.06%, respectively, when compared to pure aluminum, as illustrated in Figure 4. Various scholars have offered alternative strengthening approaches based on their observations of aluminum matrix metal composites (AMMCs). However, the mechanical strength of composites is determined by a number of factors, some of which may operate simultaneously. Strengthening methods for MMCs include Hall-Petch strengthening, Orowan strengthening, thermal mismatch strengthening, and load transfer from matrix to reinforcements [19, 20]. This study attempts to elucidate the reinforcing mechanism discovered in the research.

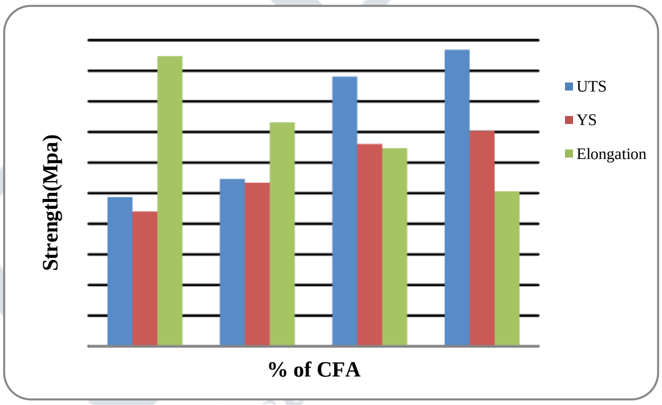


**Fig. 4** Variation in ultimate tensile and yield strength of composite with varying CFA content in the composites

## DISLOCATIONS BASED STRENGTHENING MECHANISM

When compared to aluminum, which has a coefficient of thermal expansion (CTE) of around 23 x $10^{-6}$/°C, reactive hot-pressed alumina (CFA) exhibits a substantially reduced CTE of roughly 5 x $10^{-6}$/°C. The difference in CTE values results in the production of dislocations at the interfaces. The presence of a limited number of dislocations at the interface junction, generated by the CTE mismatch between the matrix alloy and the reinforcement, bolsters the strength of the matrix alloy. The contribution of ceramic particles, specifically CFA in this work, to the total tensile strength of the composite can be attributed to a larger density of dislocations inside the composite matrix. This heightened dislocation density occurs from temperature mismatch during the production process, followed by sintering between the ceramic particles and the aluminum matrix. Numerous investigations have consistently proven a correlation between the coefficient of thermal expansion (CTE) of CFA and aluminum, and their respective impacts on thermal strain. An increasing number of dislocations within an alloy boosts its mechanical strength [21]. The equation provided above elucidates the relationship between thermal mismatch happening throughout the production process and the development of dislocations or dislocation density (ρ).

Delta $\sigma_y$ ¼ $Gb^{pffi}\rho^{ffi}$

Where, G is Shear modulus.

It has been discovered that the strength of a composite material has a quadratic relationship with the quantity of dislocations present. It is projected that there will be a corresponding growth in the quantity of relocations as the concentration of CFA increases. The presence of dislocations in Al/9%CFA composites is obvious, particularly at the contact surfaces, and their occurrence appears to be frequent, resulting in improved mechanical strengths.

## WEAR PROPERTIES

### DRY SLIDING WEAR TEST PROCEDURE

The composite specimen (pin) measures 8mm in diameter, 30mm in height, and has a track radius of 120mm. ASTM G99-95 pin-on-disc equipment is utilized to analyze dry sliding wear characteristics. Testing involves measurements of weights, sliding lengths, and sliding speeds as integral components. After washing with acetone, the specimen's original weight is properly determined using electronic weighing equipment with a precision of 0.0001g before securely affixing it to the steel disk. Wear and frictional force measurements are undertaken by submitting each specimen to various combinations of loads and velocities, with acetone employed for cleaning and material drying. The specimen's final mass is recorded, and wear rate is determined using a specified formula. The Origin software is applied for constructing the ultimate graph.

### Effect of Sliding Distance, Load & Sliding velocity on wear rate

The graphical representation in Figure 5 depicts the link between wear rate and sliding distance. The experiment comprises multiple levels of reinforcement given to pure aluminum samples at distances of 500m, 1000m, 1500m, 2000m, and 2500m. As illustrated in Chart-1 of the current study, the presence of reinforcing material, quantified by weight percentage, leads to a reduction in the overall wear rate when substituting pure aluminum with CFA reinforcement. Initially, if CFA particles lack predicted asperities, the wear rate tends to be higher. Under uniform pressure, the matrix material's asperities yield, allowing CFA particles to plow the counterface and pin surface. As sliding distance increases, crushed CFA particles act as a protective barrier between the pin and counterface surface, effectively lowering the wear rate.

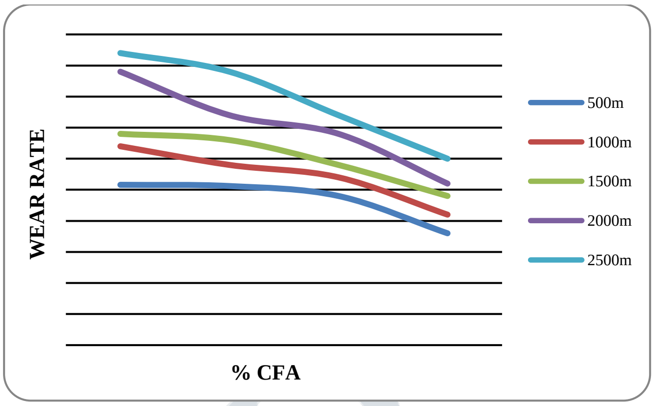


**Fig-5:** The wear rate's variation with the weight percentage of reinforcement is observed across different sliding distances, maintaining a constant sliding velocity of 3.77 m/s.

In this experiment, we evaluated the influence of integrating weight percentage (wt%) reinforcement into an aluminum alloy on wear rate. Specifically, we studied wear rate changes under loads ranging from 10N to 50N across ten unique experimental situations as shown in Fig 6. Our findings demonstrate that adding wt% reinforcement consistently reduces wear rate across all loads, while increasing load leads to increased wear rates across the board. As the applied load increases, there is a proportionate rise in pressure at the pin-disc interface. However, the increased hardness of CFA particles boosts resistance against this pressure. Moreover, bonding at the aluminum-CFA contact minimizes wear rate in abrasive mechanisms, consequently extending the life of pure aluminum.

Figure 7 depicts the relationship between wear rate and weight percentage of reinforcement in an aluminum alloy at various sliding velocities (-1.256m/s, 2.513m/s, 3.77m/s, 5.027m/s, and 6.294m/s). It is obvious that raising the amount of reinforcing weight leads to lower wear across all sliding speeds. Generally, wear rate reduces as sliding velocity increases from 1.256 m/s to 6.294 m/s. This effect can be linked to the creation of a thin protective coating on the pin surface, principally constituted of a specific percentage of CFA particles.

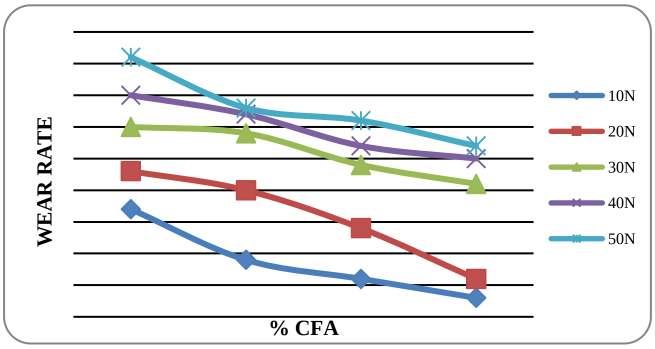


**Fig-6:** The wear rate changes with the weight percentage of reinforcement and various loads while keeping a constant sliding velocity of 3.77 m/s and a sliding distance of 1

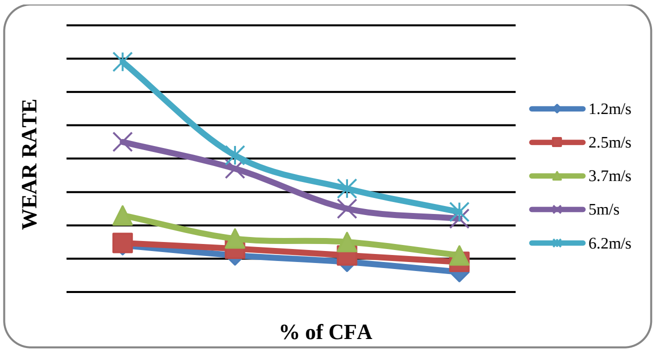


**Fig-7:** The wear rate varies with the weight percentage of reinforcement and different sliding velocities while maintaining a constant load of 30N and sliding distance of 1500m.

## IV. CONCLUSIONS

- The inquiry into the preparation of composites for mechanical and wear behavior qualities by the powder metallurgy approach yielded successful findings, resulting to the following conclusions:
- Microwave sintering in powder metallurgy has been effective in achieving proper dispersion of reinforced coconut fly ash (CFA) particles within the aluminum matrix.
- Incorporating increased density CFA particles into aluminum boosted the density of composites with varying CFA particle concentrations. Specifically, composites containing 3%, 6%, and 9% CFA particles displayed density gains of 6.28%, 10.75%, and 16.66%, respectively, compared to pure aluminum.
- The Vickers hardness value of pure aluminum (Al) measured at 90.6 Vickers Hardness Number (VHN). However, adding reactive hot-pressed alumina (CFA) into the composite material resulted in improved hardness. Notably, the Al/9%CFA sintered composite demonstrated the maximum possible hardness value, measuring 118.5 VHN.
- Engineering stress-strain graphs (Figure 4) reveal a good connection between the presence of recycled high-density polyethylene (CFA) and the ultimate tensile strength (UTS) of composites. All tests, encompassing 3%, 6%, and 9% additions, revealed improvements in UTS of 29.64%, 71.5%, and 103.2%, respectively, compared to pure aluminum. Additionally, yield strength (YS) exhibited increases of 21.16%, 49.36%, and 61.06% for the same samples.
- Initial wear is anticipated to be higher in the absence of asperities on CFA particles. As sliding distance and velocity increase, CFA particles demonstrate a wear-reducing effect by establishing a protective barrier between the pin and counterface surfaces. The increased hardness of the CFA (Reactive Hot-Pressed Alumina) particles provides protection for the comparatively softer aluminum (Al) material against external loads. Additionally, bonding at the interface between these materials performs a vital function in minimising wear in abrasive wear mechanisms.

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