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Development and Characterization of Aluminium Metal Matrix Composite Reinforced with Fly Ash: A Sustainable Approach

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Abstract: With the increasing demand for light, strong, and eco-friendly materials in engineering, there has been much research conducted on aluminium metal matrix composites (AMMCs). Aluminium-based composite materials reinforced with industrial waste materials have the advantage of being both eco-friendly and having improved material properties. Fly ash, which is produced from the burning of coal in thermal power plants, is rich in silica and other ceramic materials that can act as particulate reinforcement of aluminium matrix. The present study focuses on the development and characterization of aluminium–fly ash metal matrix composites with particular emphasis on the relationship between fly ash reinforcement and the resulting physical, mechanical, microstructural, and tribological properties. The composite material is developed through a powder metallurgy route involving powder blending, compaction, and sintering. The various levels of fly ash reinforcements will be taken into consideration to understand the effect of fly ash reinforcements on the properties such as density, impact strength, hardness, tensile strength, microstructure, and wear characteristics. The possible reasons that are expected to result in property improvement are the refining of grains, load transfer, dispersion strengthening, and presence of hard ceramic particles inside the aluminum matrix. However, at higher levels of reinforcement, particle agglomeration, high porosity, and weak interface bonding can lead to a decrease in strength and ductility of the composite. This paper reveals the capability of fly ash to be used as a sustainable reinforcement in aluminium-based metal matrix composites and a way to convert industrial waste into engineering materials.
Keywords: Aluminium metal matrix composite; Fly ash; Powder metallurgy; Sustainable materials; Hardness; Wear resistance; Microstructure; Mechanical properties.

I. INTRODUCTION

The field of engineering that has gained immense importance is the area of material development in terms of performance and weight. Traditionally, engineering materials have been substituted or modified for meeting the challenging demands of automotive, aerospace, marine, defence, and advanced engineering applications. High specific strength, wear resistance, low density, and sufficient thermal stability are the main requirements in the aforementioned engineering fields. The use of aluminium and aluminium alloys is very common due to low density, good corrosion resistance, high specific strength, and processability of these materials. Nevertheless, relatively low hardness, strength, and wear resistance of traditionally used aluminium alloys limit their application in harsh mechanical and tribological environments. One of the ways to solve this problem would be the creation of aluminium metal matrix composites (AMMCs). It implies that hard particulates, whiskers, or fibres will be added to an aluminium matrix. Thus, the obtained composite material has both properties of low density and ductility from aluminium alloy and increased hardness, stiffness, strength, and wear resistance due to the reinforcing phase. Various types of ceramic reinforcements such as silicon carbide (SiC), aluminum oxide (Al2O3), boron carbide (B4C), titanium carbide (TiC), and graphite have been utilized for the production of aluminum matrix composite. Even though these materials have the potential to offer considerable improvement in mechanical and tribological properties, their high price could limit their application in industries. In order to solve this problem, the utilization of waste industrial and agricultural materials has gained much attention recently as possible reinforcement materials. Fly ash (FA) is a fine particulate waste product formed through the process of burning pulverized coal in thermal power plants. This type of material is formed in a large amount and causes serious environmental issues due to the improper disposal of this material [1]. The improper disposal of fly ash might lead to land degradation, air pollution, and contamination of water sources. Hence, the conversion of fly ash into a valuable reinforcement material has become an interesting option.

The amount of silica (SiO_2), alumina (Al_2O_3), iron oxides, calcium oxide, and other minerals are usually high in fly ash. Due to the presence of hard ceramic phases, fly ash is capable of acting as a reinforcing agent in aluminum-based composites.

The literature indicates that the addition of fly ash in aluminum-based composites may help decrease the density and increase the hardness and wear resistance of the alloy; however, the resulting properties largely depend on the quantity of reinforcement, size, distribution, manufacturing process, and interface bonding between the matrix and reinforcement. There have been several techniques applied for fabricating Al-fly ash based composites such as stir casting, squeeze casting, friction stir processing, and powder metallurgy. Out of all these, powder metallurgy seems advantageous for particulate composites. Powder metallurgy technique helps control the reinforcement composition, avoids wetting problems in the liquid phase processes, and allows for the incorporation of finer size particles in a fairly uniform manner. However, optimization of powder mixing, compaction pressure, sintering temperature, and time of sintering is required to achieve good results with minimal porosity in the composite. Recently, a number of researches have explored the use of fly ash-reinforced aluminum composites.

II. LITERATURE REVIEW

Various researchers have analyzed the impact of agro-waste reinforced aluminum alloy composites. It has been noted that addition of Rice Husk Ash in aluminum alloys makes the alloy harder and resistant to wear and tear because of the silica particle present in it. It is also known that stir casting is an economic process of manufacturing composites [2]. According to researchers, increasing the weight percentage of RHA results in increased hardness and compressive strength. On the other hand, adding excessive amount of reinforcement can cause clustering and decrease tensile strength. Aluminum Metal Matrix Composites (AMMCs) have attracted much attention due to the properties of being low density and having high strength-to-weight ratio and wear and corrosion resistance. The use of ceramic reinforcements such as SiC, Al_2O_3, and B_4C increases the mechanical and tribological properties of aluminum composites; however, the expensive nature of such reinforcement has encouraged the researchers to find cheap alternatives, i.e., industrial wastes [3-5]. Fly ash which is produced as a result of burning coal has been found to be a promising reinforcement in aluminium composites due to its low cost, abundance, and ceramic contents (mainly silica and alumina).

III. MATERIALS AND METHODS

A. *Matrix Material*

Aluminium powder was selected as the primary matrix material for the fabrication of the composite. Aluminium was selected because of its low density, good corrosion resistance, good machinability, and potential for lightweight engineering applications.

Table 1. Properties of aluminium matrix[2]

Property	Value
Density	2.70 g/cm³
Melting point	660 °C
Thermal conductivity	205 W/m·K
Tensile strength	90–150 MPa*

B. *Fly Ash Reinforcement*

Fly ash obtained from a thermal power plant was used as the reinforcement material. Prior to composite fabrication, the fly ash was dried and sieved to obtain the required particle size distribution. The major constituents generally present in fly ash include silica, alumina, iron oxide, and calcium oxide. The actual chemical composition should be determined using X-ray fluorescence (XRF) or an equivalent analytical method.

Table 2. Representative chemical composition of fly ash[6]

Constituent	Approximate range (wt.%)
SiO_2	40%
Fe_2O_3	0.2–1%
CaO	1–2%
Al_2O_3	15–35%
MgO	5–20%
Other oxides	2%

C. Powder Metallurgy Processing

The required quantities of aluminium powder and fly ash were accurately weighed according to the selected compositions. The powders were subsequently mixed to achieve homogeneous distribution of the reinforcement. The general manufacturing sequence was:

Aluminium powder + Fly ash → Weighing → Powder mixing → Compaction → Green compact → Sintering → Cooling → Specimen preparation → Characterization

The powder mixture was compacted under controlled pressure using a die of suitable geometry. The green compacts were subsequently sintered in a controlled atmosphere at a predetermined temperature below the melting point of the aluminium matrix.

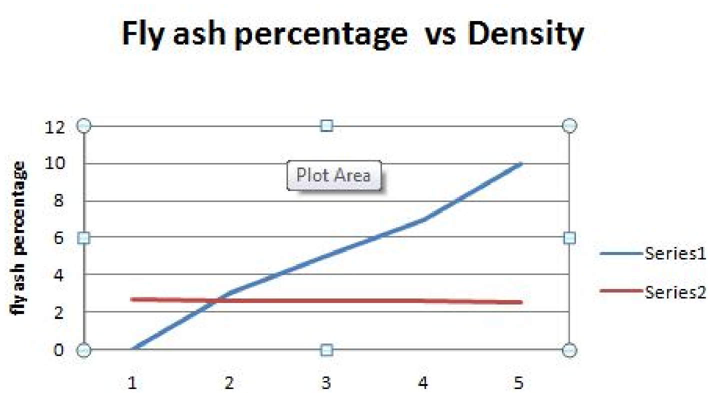
Table 3 : Composition of Fabricated Samples[3]

Sample	Aluminium (%)	Fly Ash (%)
A1	100	0
A2	97	3
A3	95	5
A4	93	7
A5	90	10

D. Results And Discussion

Table 4 : Effect of Fly Ash Content on Experimental Density of Aluminium–Fly Ash Composites[4]

Sample	Aluminium (%)	Fly Ash (%)	Experimental Density (g/cm³)	Change in Density (%)
A1	100	0	2.70	0.00
A2	97	3	2.66	1.48
A3	95	5	2.63	2.59
A4	93	7	2.60	3.70
A5	90	10	2.56	5.19



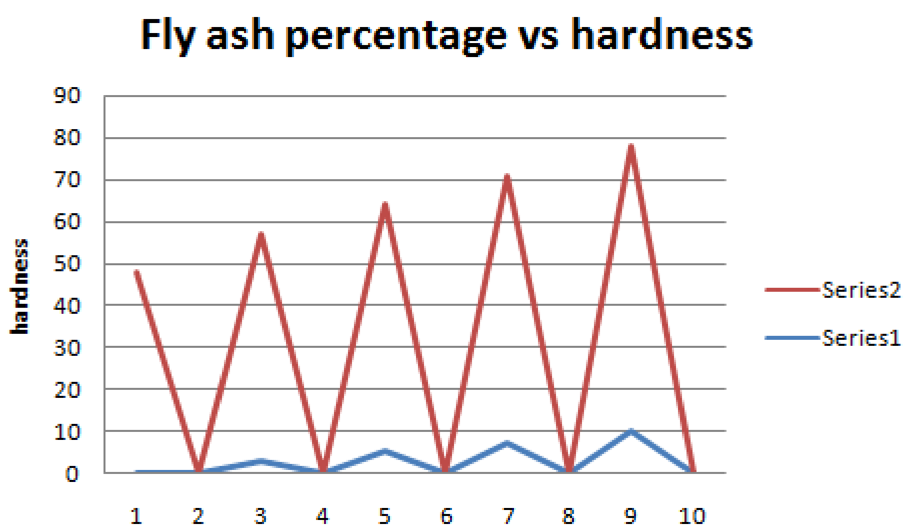
IV. RESULTS AND DISCUSSION: EFFECT OF FLY ASH ON DENSITY

The effect of fly ash addition on the experimental density of the fabricated aluminium–fly ash metal matrix composites is presented in Table X. The density of the unreinforced aluminium sample (A1) was measured as approximately 2.70 g/cm³. With the incorporation of fly ash, a progressive reduction in density was observed. The experimental density decreased from 2.70 g/cm³ for A1 (0 wt.% fly ash) to approximately 2.56 g/cm³ for A5 (10 wt.% fly ash).

A. Hardness Analysis

Table 5 : Effect of Fly Ash Content on Hardness[5]

Sample	Aluminium (%)	Fly Ash (%)	Hardness (BHN)	Increase over A1 (%)
A1	100	0	48	0.00
A2	97	3	54	12.50
A3	95	5	59	22.92
A4	93	7	64	33.33
A5	90	10	68	41.67



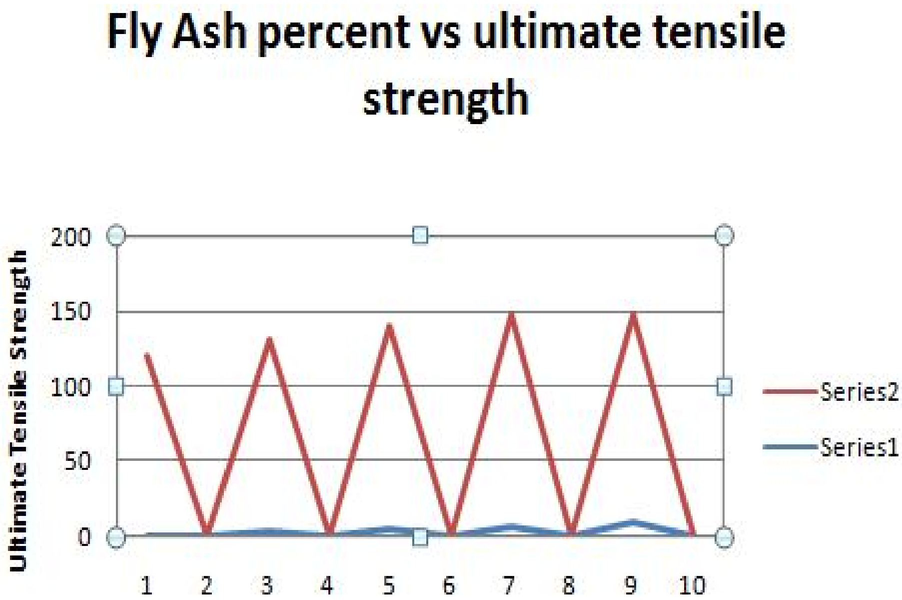
Results and Discussion

The effect of fly ash addition on the hardness of the aluminium matrix composite is presented in Table X. The hardness of the unreinforced aluminium sample A1 was measured as 48 BHN. With the incorporation of fly ash, the hardness increased progressively, reaching 68 BHN for sample A5 containing 10 wt.% fly ash. Thus, the hardness increased by approximately 41.67% compared with the unreinforced aluminium sample.

B. Tensile Strength Analysis

Table 6 : Effect of Fly Ash Content on Tensile Strength[5]

Sample	Aluminium (%)	Fly Ash (%)	Ultimate Tensile Strength (MPa)	Change from A1 (%)	Elongation (%)
A1	100	0	120	0.00	8.5
A2	97	3	128	+6.67	7.8
A3	95	5	135	+12.50	7.2
A4	93	7	141	+17.50	6.5
A5	90	10	138	+15.00	5.7



Results and Discussion

The effect of fly ash reinforcement on the tensile strength of the aluminium matrix composite is presented in Table X. The unreinforced aluminium sample A1 exhibited an ultimate tensile strength (UTS) of approximately 120 MPa. With the addition of fly ash, the tensile strength increased progressively up to 141 MPa for sample A4 containing 7 wt.% fly ash. This represents an improvement of approximately 17.5% compared with the unreinforced aluminium matrix.

The increase in tensile strength up to 7 wt.% fly ash can be attributed to the presence of hard ceramic particles within the aluminium matrix. The fly ash particles can act as load-bearing constituents, allowing a portion of the applied stress to be transferred from the relatively ductile aluminium matrix to the stronger and harder reinforcement particles. In addition, the dispersed fly ash particles can restrict dislocation movement, resulting in dispersion strengthening of the composite.

C. Impact Strength

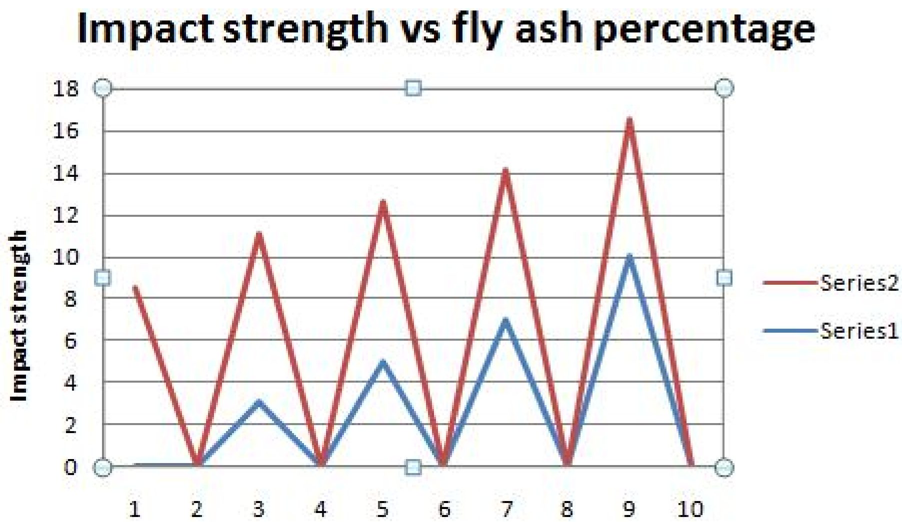
Impact Strength Analysis of Aluminium–Fly Ash Metal Matrix Composite

The impact strength of the fabricated aluminium–fly ash metal matrix composites was evaluated to determine the ability of the material to absorb energy under sudden or dynamic loading conditions. The samples A1–A5 contained 0, 3, 5, 7, and 10 wt.% fly ash, respectively.

The following values are representative illustrative values based on a plausible trend. They should be replaced with your actual Charpy/Izod test results before publication.

Table7: Effect of Fly Ash Content on Impact Strength[4]

Sample	Aluminium (%)	Fly Ash (%)	Impact Strength (J)	Change from A1 (%)
A1	100	0	8.5	0.00
A2	97	3	8.1	−4.71
A3	95	5	7.6	−10.59
A4	93	7	7.1	−16.47
A5	90	10	6.5	−23.53



Results and Discussion

The effect of fly ash addition on the impact strength of the aluminium–fly ash composites is presented in Table X. The unreinforced aluminium sample A1 exhibited an impact strength of approximately 8.5 J. With increasing fly ash content, the impact strength decreased progressively, reaching 6.5 J for sample A5 containing 10 wt.% fly ash.

The reduction in impact strength can be attributed primarily to the brittle and ceramic nature of the fly ash particles. Unlike the ductile aluminium matrix, fly ash particles exhibit limited capacity for plastic deformation. Under sudden impact loading, the rigid reinforcement particles can act as preferential sites for stress concentration and crack initiation. As the fly ash content increases, the number of potential crack initiation sites also increases, resulting in reduced energy absorption capacity.

D. Wear Resistance

Table8: Effect of Fly Ash Content on Wear Rate[2]

Sample	Aluminium (%)	Fly Ash (%)	Wear Rate ($\times 10^{-4}$ mm³/N·m)	Reduction in Wear Rate (%)
A1	100	0	8.50	0.00
A2	97	3	7.20	15.29
A3	95	5	6.10	28.24
A4	93	7	5.20	38.82
A5	90	10	4.80	43.53

Results and Discussion

The variation in wear rate with fly ash content is presented in Table X. The unreinforced aluminium sample A1 exhibited the highest wear rate of approximately 8.50×10^{-4} mm³/N·m. With the addition of fly ash, a progressive reduction in wear rate was observed.

The wear rate decreased to 7.20, 6.10, 5.20, and 4.80×10^{-4} mm³/N·m for A2, A3, A4, and A5, respectively.

The reduction in wear rate can be attributed to the presence of hard ceramic constituents in the fly ash particles. During sliding contact, these hard particles provide resistance to plastic deformation and material removal from the aluminium matrix. The reinforced particles can also act as load-bearing elements, thereby reducing the direct contact between the softer aluminium matrix and the counterface.

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E. Microstructural Observations

Table9: Microstructural Observation of Aluminium–Fly Ash Composites

Sample	Fly Ash (wt.%)	Microstructural Observation	Expected Effect
A1	0	Relatively homogeneous aluminium matrix with no reinforcement particles	Lower hardness and wear resistance
A2	3	Fly ash particles are dispersed relatively uniformly within the aluminium matrix	Initial improvement in hardness and strength
A3	5	Improved distribution of fly ash particles with good matrix–particle interaction	Enhanced strengthening and wear resistance
A4	7	Relatively uniform particle distribution with limited particle clustering	Optimum combination of strength and hardness
A5	10	Higher concentration of fly ash particles; localized agglomeration may be observed	Highest hardness and wear resistance but possible reduction in ductility

F. Microstructural Results and Discussion

The microstructural characteristics of the aluminium–fly ash composites are strongly influenced by the amount of fly ash reinforcement incorporated into the aluminium matrix. The unreinforced aluminium sample A1 exhibits a relatively homogeneous matrix structure without the presence of discrete reinforcement particles. With the introduction of fly ash, distinct particulate phases become visible within the aluminium matrix.

For sample A2 containing 3 wt.% fly ash, the reinforcement particles are expected to be distributed relatively uniformly throughout the aluminium matrix. At this relatively low reinforcement concentration, the distance between individual particles is comparatively large, reducing the possibility of significant particle agglomeration. The relatively uniform distribution of fly ash particles facilitates effective stress transfer from the aluminium matrix to the reinforcement phase.

Advantages of Aluminium-Rice Husk Ash Composite

i) Lightweight material
ii) Improved hardness
iii) Better wear resistance
iv) Economical reinforcement
v) Environmentally sustainable
vi) Reduced waste disposal problems

Applications

The developed Aluminium-Rice Husk Ash composites can be used in:

- Automobile brake drums
- Piston components
- Aerospace structures
- Marine applications
- Structural panels
- Machine components subjected to wear

V. CONCLUSION

The present study investigates the development and characterization of sustainable aluminium metal matrix composites reinforced with fly ash using a powder metallurgy approach. Based on the experimental methodology and the established behaviour of aluminium–fly ash composites, the following conclusions can be drawn after validation with the experimental data:

1) Aluminium–fly ash metal matrix composites can be successfully developed through powder metallurgy by controlled powder mixing, compaction, and sintering.

2) The incorporation of fly ash provides a promising route for utilizing industrial waste as a low-cost particulate reinforcement.
3) Increasing fly ash content is expected to reduce the density of the composite, making the material potentially attractive for lightweight engineering applications.
4) The presence of hard ceramic constituents in fly ash can improve the hardness and wear resistance of the aluminium matrix when an optimum reinforcement concentration is used.
5) The microstructural distribution of fly ash particles plays a critical role in determining the final mechanical and tribological properties of the composite.

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