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Response Evaluation of Fly-Ash on the Hardness and Microstructural Properties of Aluminum Composite

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Abstract

Fly ash has gained the widespread attention of researchers in aluminum matrix composite (AMC) production as reinforcement to enhance the properties of AMCs and reduce the production cost. The response evaluation of fly-ash was carried out in this work, in order to explore its influence on the hardness and microstructural properties of Aluminum composite. In this research, aluminum alloy was reinforced with different amounts (10, 20, 30 and 40 wt. %) of fly ash. The alloy, reinforced with fly ash were fabricated by a stir casting method. Afterwords, the Aluminum composites were characterized based on the hardness and microstructural analysis (phase analysis). The results showed that the hardness gave an optimum property of 74.20N/mm^2 at 40wt%. This showed that the addition of fly-ash improved the properties of the composites. This result were further confirmed through the microstructural analysis which showed a good interfacial bonding between the reinforcement (fly-ash) and the matrix (Aluminum). This composite can be applied in automobile and construction industries.

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Keywords: Hardness, Microstructural, Aluminum, Fly-ash (FA), Response Evaluation

1. Introduction

Aluminum composites have garnered significant attention in the materials science community due to their lightweight, high strength, and superior mechanical properties. The incorporation of various reinforcements into aluminum matrices has been a focal point of research aimed at enhancing these properties. Fly ash, a by-product of coal combustion in thermal power plants, is an attractive reinforcement material due to its low cost, availability, and beneficial properties such as high surface area and pozzolanic activity. (Ahmed *et al*. 2024) [1]. Fly ash has emerged as a promising reinforcement material for aluminum composites. It is primarily composed of alumina, silica, and unburned carbon, which contribute to its pozzolanic characteristics. Previous studies have shown that the incorporation of fly ash into aluminum matrices can significantly enhance the mechanical properties, including hardness and tensile strength, due to the dispersion strengthening mechanism and the formation of a uniform microstructure. The hardness of aluminum composites is a critical property that influences their wear resistance and overall durability. Studies have demonstrated that the addition of fly ash to aluminum composites results in an increase in hardness, attributed to the hard particles of fly ash acting as barriers to dislocation movement within the aluminum matrix.

Microstructural analysis has revealed that fly ash particles are uniformly distributed within the matrix, leading to a refined grain structure and enhanced mechanical properties. The interface between the fly ash particles and the aluminum matrix plays a crucial role in determining the composite's overall performance. (Nordin *et al*. 2024) [2]. Research by Kumar *et al*. (2020) [3] indicated that aluminum composites reinforced with fly ash exhibited superior hardness and wear resistance compared to those reinforced with traditional ceramic materials. Singh and Gupta (2019) [4] focused on the microstructural analysis of fly ash-aluminum composites, revealing the presence of a well-bonded interface and a homogeneous distribution of fly ash particles, which contributed to the improved mechanical properties. Meena *et al*. (2013) [5], explored the microstructural characteristics and mechanical properties of aluminum alloy composites reinforced with fly ash. The results indicate that the addition of fly ash particles enhances the hardness of the composite due to the dispersion strengthening effect. The uniform distribution of fly ash within the matrix also contributes to improved wear resistance. Veeresh Kumar *et al*. (2011) [6] discovered that fly ash significantly improves the hardness of aluminum composites, attributed to the reinforcement effect of hard ceramic particles. The microstructural analysis revealed a refined grain structure, which contributes to the enhanced mechanical performance. Thirumalai Kumaran & Palanikumar, 2013 studied the influence of fly ash on the microstructure and mechanical properties of AA7075 aluminum alloy composites. The inclusion of fly ash resulted in increased hardness and improved tensile strength. Microstructural analysis showed a well-bonded interface between the fly ash particles and the aluminum matrix, contributing to the overall enhancement in mechanical properties. Subramanian *et al*. (2013) [8] in their study revealed that fly ash can be effectively utilized as a reinforcing agent to enhance the hardness and wear resistance of aluminum matrices. They reported a homogenous distribution of fly ash in the aluminum matrix, resulting in an improved microstructure with minimal porosity and defects. Veeresh Kumar *et al*. (2017) [6] investigated the mechanical and tribological properties of AlSi10Mg composites reinforced with fly ash particles demonstrated an improvement in hardness and wear resistance. The presence of fly ash leads to the formation of a more uniform microstructure with finer grains, which enhances the load-bearing capacity and hardness of the composite. Hashim *et al*. (2001) [10] focused on the microstructure and mechanical properties of Al6061 composites reinforced with fly ash. The findings suggest that the hardness of the composite increases with the addition of fly ash due to the formation of a fine-grained microstructure and the presence of hard fly ash particles. The study also observed a reduction in ductility with increasing fly ash content. Amarnath *et al*. (2013) [11] investigated the mechanical properties of aluminum matrix composites reinforced with fly ash. The results indicate an enhancement in hardness and tensile strength, attributed to the effective dispersion of fly ash particles within the aluminum matrix. The study also noted an improvement in the microstructural homogeneity of the composite, contributing to its overall mechanical performance. This study therefore aimed at investigating the response of fly ash on the hardness and microstructural properties of aluminum composites, with the goal of providing insights into how this industrial by-product can enhance the performance of aluminum-based materials in structural applications.

2. Materials and Methods

2.1. Materials

The materials and equipment used includes; Laddle, Engine oil, Fly ash, Aluminum foil and Ingots, Silica Sand, Binder, Rammer, Riddle, Draw spikes, Clamps, Stirring rod, Crucible, Ruler, Weighing balance, Airtight container, Vernier-caliper, Calcium carbonate powder, Water, Gloves, Aluminum scrap, Sand Crucible, Furnace, Shovel, Brush, Trowel. The microstructural observation were conducted with these materials: 95ml distilled water, the beaker, 2.5ml Nitric acid (HNO_3), 1.5ml Hydrochloric acid (HCl), 1ml Hydrogen fluoride (HF), the gloves, eye google, and the Applicator or brush.

2.2. Methods

2.2.1. Preparation of the mold

In order to make the aggregate acceptable for molding, silica sand and calcium carbonate ($CaCO_3$), which is used as a binding agent, were combined with water. This strengthened the sand and allowed for plasticity. Sand molding provides accuracy and is reasonably priced.

2.2.2. Steps in mold making

The method of mold making consists of six steps:

- To make a mold, draw a pattern on the sand.
- Use sand and the pattern in a gating system; otherwise, remove the pattern.
- Pour molten material into the mold cavity.
- Permit the substance to cool.
- Take out the casting and break off the sand mold.

2.2.3. Preparation of the furnace for melting

- Collecting the Aluminum: The leftover aluminum was collected, and the contaminants were extracted from the body by peeling them off.
- Furnace setup: After heating the furnace to the proper temperature, charcoal was placed underneath it and it was ignited.
- Preheating: The crucible was placed inside the furnace along with additional melting equipment.
- Assembling the Blower: The blower was positioned next to the furnace to force heated air and oil into the furnace through the ducts.
- Setting up the Blower: A blower was placed next to the furnace to force hot air and condemn oil through the ducts into the furnace.
- Melting and Pouring the Aluminum Mold: After the aluminum sheets were heated to 700 degrees Celsius, they were taken out of the furnace using a ladle and poured into the mold through the runner, which allowed the oil to emerge from the riser.

2.2.4. Heat treatment process

In order to optimize the properties for the fabrication of composites, the aluminum sheets were heat-treated before being cast. The fly-ash reinforcement was thermally treated to lower its carbon content and increase its pozzolanic reactivity. The particle size distribution was uniformly achieved through mechanical milling, which helped to promote dispersion in the aluminum matrix. (Emekwisia *et al*. 2024) [12].

2.2.5. Stir casting process
Using mechanical stirring, the fly ash was combined with the molten metal matrix in this process. This is a process where large sized composites can be manufactured in a highly economical way. The key process parameters during this process include a number of variables such the distribution of the reinforcement material, wettability, porosity of the cast composites, and the chemical reaction between the matrix and the reinforcement material. Fabrication of MMC using this process involved the use of aluminum as a matrix along with the combination of 10%, 20%, 30%, and 40% weight fraction of fly ash, which was done with a stirring rod in crucible still soaking at approximately 700ºC. Emekwisia C.C. *et al*., 2024 [12].

2.2.6. Hardness Property
The Hardness test was conducted with the use of the Rockwell hardness tester machine, model 150A. The samples were prepared by cutting to its proper dimensions. Afterwhich they were cleaned and smoothened for the testing apparatus. The tester was powered on, and the Rockwell B scale (HRB) with a 1/16-inch steel ball indenter was selected. The anvil was placed on the sample, and a 10 kgf preliminary load applied on it to stabilize the indenter. Then the 100 kgf major load was also applied. It was allowed to dwell for a few seconds before releasing the load. The hardness value was displayed on the machine. The test was repeated at multiple points for accuracy and the average hardness value was recorded.

2.2.7. Mass Fraction Expression
The mass fraction is the amount of mass of one substance, divided by the mass of the total mixture. It can also be expressed, with a denominator of 100, as percentage by mass. (In commercial contexts often called percentage by weight, abbreviated wt %).

Mass fraction (wt %) was determined with this expression;

$$\text{Wt\%} = \frac{m}{m\ total} \times 100 \quad (1)$$

$$\text{For 3g}(W_1)\text{; Wt\%} = \frac{W_1}{W_1 + W_2 + W_3 + W_4} \times 100 \quad (2)$$

$$\text{For 6g}(W_1)\text{; Wt\%} = \frac{W_2}{W_1 + W_2 + W_3 + W_4} \times 100 \quad (3)$$

$$\text{For 9g}(W_1)\text{; Wt\%} = \frac{W_3}{W_1 + W_2 + W_3 + W_4} \times 100 \quad (4)$$

$$\text{For 12g}(W_1)\text{; Wt\%} = \frac{W_4}{W_1 + W_2 + W_3 + W_4} \times 100 \quad (5)$$

2.2.8. Microstructural/Optical Analysis
Following the casting process, the microstructural observations was conducted to study the internal structure of the cast specimens. Metallographic analysis techniques were employed, involving sample preparation, grinding, polishing, etching, and microscopic examination using a metallurgical microscope. The prepared specimens were mounted and ground to achieve a smooth surface. Polishing was performed meticulously to remove any surface imperfections that could interfere with the microstructural observations. Etching was carried out using suitable chemical reagents to reveal the microstructure clearly. The specimens were then examined under a metallurgical microscope to study the grain structure, grain boundaries, and other microstructural features. This analysis were employed to gain a comprehensive understanding of the cast specimens. It was utilized to determine the percentage purity of aluminum and Fly Ash, as well as trace elements. This information is crucial for accurately calculating the charge composition and alloying process.

3. Results and Discussions
3.1 Determination of mass fraction (%) of fly-ash composites
From the Equations 1 to 4 above, the mass fraction values were determined as follows;

$$\text{For 3g}(W_1)\text{; Wt\%} = \frac{3}{3+6+9+12} \times 100 = 10\%$$

$$\text{For 6g}(W_1)\text{; Wt\%} = \frac{6}{3+6+9+12} \times 100 = 20\%$$

$$\text{For 9g}(W_1)\text{; Wt\%} = \frac{9}{3+6+9+12} \times 100 = 30\%$$

$$\text{For 12g}(W_1)\text{; Wt\%} = \frac{12}{3+6+9+12} \times 100 = 40\%$$

Table 1: Mass Fraction of Each Al-FA Composite

Aluminum- Fly Ash Composites (g)	Mass Fraction of AL-FA Composites (%)
3g	10%
6g	20%
9g	30%
12g	40%

3.2. Hardness Test
The Hardness test of the composite samples were conducted with variations in wt% of fly-ash, and tested in the Universal Testing Machine (UTM). The Hardness Test versus fly-ash wt% graph were generated as presented in Table 2 and Figure 1 below,

Table 2: Flexural Strength of AL-FA Composites

Samples of AL-FA Composite (wt %)	Hardness Test (N/mm^2)
0%	52.67
10%	59.40
20%	65.73
30%	70.00
40%	74.20

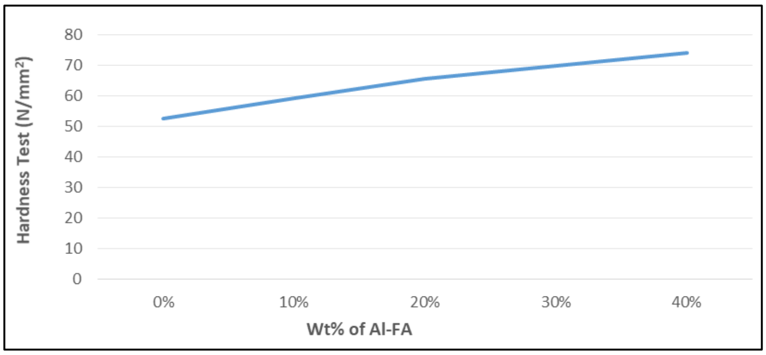

Fig 1: Graph of Hardness Test of Al-FA Composite

The results for the Hardness Test (N/Mm2) of the Al-FA composite as in Figure 1 were analyzed. The test was carried out by subjecting the sample to various forms of loads to see the limits of the sample before deformation. This was done by noting down the the strength of the material of each wt% of the Al-FA from (0 to 40 wt%). The optimum hardness property for the composite was obtained at 40wt%, while at 0%, the minimum property was obtained. This gradual increase up to 40wt%, can be attributed to the increase in the addition of the reinforcement particles (Fly ash) in the aluminium metal composite. At the optimum property of 74.20N/Mm^2, the aluminium matrix and the fly ash reinforcement achieved an optimum bond with low porosity level. This made the composites to become more prominent and gives way for in different industry.

3.3. Microstructural Analysis

As seen in Figures 2–6, the microstructural examination of the composite was examined and interpreted. The composite samples' photo-micrographic components underwent analysis and interpretation. The fly ash particles' distribution and morphology, as well as the composite's structural features, particle size distribution, and interfacial bonding, were all disclosed by the microstructure of the materials. The primary reinforcement (FA) partially formed intermetallic phases with aluminum and partially dissolved in the aluminum solution, strengthening it.

Fig 2: Al - 0%wt of fly ash

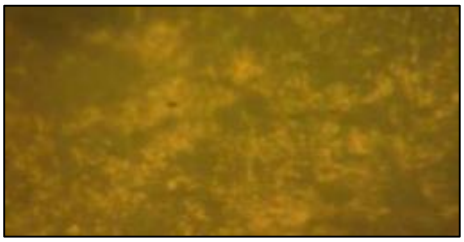

Fig 3: Al – 10%wt of fly ash

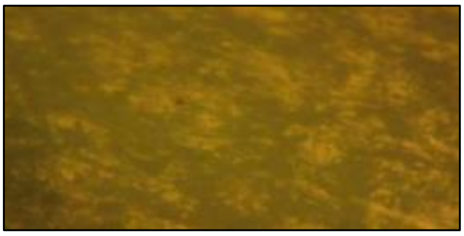

Fig 4: Al – 20%wt of fly ash

Fig 5: Al - 30%wt of fly ash

Fig 6: Al – 40%wt of fly ash

4. Conclusion

This research was done to analyse the response of fly ash on the Hardness properties of Aluminium composite. From the observations, the following conclusions were drawn; the aluminium composite showed optimum hardness property on the addition of 30%wt. of fly ash. This showed that at this point, the fly ash aluminium composite possesses ultimate strength. These observations were further revealed through the microstructural analysis.

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