# Experimental Analysis on the Mechanical and Microstructural Properties of Aluminium-Fly Ash Composite

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ORIGINAL RESEARCH

**Abstract**— An experimental study on the mechanical and microstructural properties of Aluminium - Fly ash composite was carried out using stir casting process. The strengthening of aluminium was achieved by the addition of varying weight percent of fly ash into the aluminium matrix in the following variations 10%, 20%, 30% and 40%. The percentage weight of fly ash was weighed and added to the appropriate volume of molten aluminium. The Mechanical test which include tensile strength test, yield strength, % elongation and young's modulus were carried out on the samples. The outcome showed that at 10% weight of the fly ash, the optimum tensile strength was obtained at 109.41 MPa, the optimum yield strength at 107.76 MPa, and the % elongation at 15.1%. However, the optimum strength of the Young's modulus (2983.21 Joules) was obtained at the 20% weight of fly ash. It can therefore be deduced from this experiment that Aluminium-Fly ash composite attained most of its optimum properties at the 10% weight of fly ash. This experiment was carried out in other to strengthen the aluminium metal, and to determine at what weight percent can this strength be achieved using fly-ash. It then showed that at 10% fly ash, aluminium gave optimum strength. This mean that decrease in the fly ash increases the tensile strength of the composite. This study further gave clarity on the composition of Aluminium-fly ash, which possesses good enough strength for application in automobile industries.

**Keywords**— Aluminium (Al), Fly ash (FA), Composite, Microstructure, Properties, Stir casting.

## 1 INTRODUCTION

Strong materials typically lose impact strength as their strength or stiffness is increased, in addition to being relatively dense. Consequently, it is possible to employ a composite material, which is made up of a mixture of two or more clearly different materials, whose properties are superior to those of the original components in a particular application. When compared to unreinforced alloys, metal matrix composites (MMCs) have far better qualities, such as high specific strength, specific modulus, damping capacity, and strong wear resistance. Particulate-reinforced aluminum metal matrix composites (Al-MMCs) are thought to be a potential way to provide aluminum alloys increased wear resistance. It was discovered that the wear resistance increased with increase of the reinforcement content because of the high hardness and strength of the reinforcement phase. (Babu et al. 2014).

The AMCs, or aluminium matrix composites, are a class of materials with a variety of qualities that can meet the specifications needed for some of the previously listed uses. They can be made using liquid metallurgy processing methods (rheocasting, compocasting, liquid infiltration, stir casting, etc.) or solid metallurgy processing routes (such as powder metallurgy).

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**Section D** - MATERIAL/CHEMICAL ENGINEERING & RELATED SCIENCE
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Stir-casting is still the most often used method despite the technical superiority of other processing techniques because of its affordability, ease of use, adaptability, and commercial viability. Single-reinforced composites have been created over the years primarily for a variety of purposes; nevertheless, it has been noted that they have some limits relating to cost and material properties. Recently, researchers have become interested in hybrid reinforced AMCs. (Alaneme et al. 2016) Ravichandran et al. (2020) reported the mechanical characteristics of fly ash (FA) reinforced aluminium alloy (AA6063) matrix composites utilizing a stir casting technique. With a step of three weight percentages per range, the FA content is applied between 0 and 9 weight percentages. The study focused on the mechanical parameters of the alloy and composite samples, including hardness, tensile strength, and compressive strength. The mechanical properties were improved by adding FA content up to 6wt%, after which it decreased. Nanjayyanamath et al. (2017) investigated the impact of fly ash particle size on the mechanical characteristics of samples of fly ash reinforced aluminium alloy (Al6061) composites that were stir-cast.With fly ash weighing 5, 10, and 15% of the total weight, three composite samples were created, each with 5 to 20 different particle sizes, and also 25 to 30, and 50 to 60 µm. It was discovered that the ultimate tensile strength (UTS), ultimate compression strength (UCS), and hardness increased as the percentage weight of fly ash particles increased and decreased when the reinforcement's particle size increased. On the other hand, UTS slightly decreased for composites containing 15% fly ash.

Gunawan et al. (2020) showed that adding fly ash to an aluminium alloy melt reduces the composite base's

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ductility, which affects the specimen's surface shape. Nonetheless, the creation of an aluminium matrix composite using the stir casting process and fly ash as reinforcement particles has been crucial in determining the mechanical properties of AMC. Additionally, the fly ash concentration of 8% by weight yields the best results in terms of impact, tensile, and density measurements. Additionally, he saw some porosity in the cross-sectional area, which he believed to be a negative aspect lowering the mechanical abilities of the AMC product.

The mechanical and microstructural characteristics of aluminium alloys (A356 and A7075) with fly ash and basalt was investigated by Sreenatha Reddy & Dhanasekaran, 2016. The test findings showed that the tensile values increased with the addition of fly ash and basalt. The weight proportion of A356 and A7075 with 3% fly ash and 7% basalt yields the maximum strength

Juang & Li, 2022 examined the different fly ash addition ratios of 0, 3, 6, 9, 12, and 15 weight percent that were added by stir casting to the ADC10-2Mg alloy melt in order to make the aluminium-fly ash composite during the chemical reaction that took place at 800 °C for 30 hours. Tests on the microstructure, mechanical properties, and physical attributes were then carried out. The findings demonstrated that stir casting may be used to make an aluminium-fly ash composite with good fly ash debris dispersibility. Over the course of a long reaction process at high temperatures, the fly ash particles gradually broke down small debris. The density of the aluminium/fly-ash composite with 6 weight percent fly-ash dropped by about 2%, but its tensile strength and hardness rose by 49% and 7%, respectively.

Yadav et al. (2023) conducted a study to investigate the effect of varying weight percentages of fly ash (5 wt.%, 10 wt.%, and 15 wt.%) on the tensile properties of aluminium matrix composites fabricated via powder metallurgy. They observed that the tensile strength initially improved with commensuarate increase in fly ash content, reaching a peak at 10 wt.%. Beyond this concentration, a decline in strength was attributed to particle clustering and poor interfacial bonding.

Gupta & Sharma, 2022 explored the influence of weight percent of fly ash on the tensile behavior of AMCs processed through hot pressing. They found that composites containing 10-12 wt.% fly ash exhibited the highest tensile strength due to effective particle dispersion and interfacial bonding. However, excessive fly ash loading (>15 wt.%) resulted in a decrease in strength due to agglomeration and void formation.

Singh et al. (2021) investigated the effect of weight percent of fly ash on the tensile properties of AMCs fabricated by stir casting. They reported an increase in tensile strength with increasing fly ash content up to 20 wt.%, attributed to improved grain refinement and strengthening mechanisms. However, higher fly ash loadings (>20 wt.%) led to a reduction in strength due to particle agglomeration and porosity.

Patel & Patel, 2020 conducted a study on the optimization of fly ash content in aluminium matrix composites using the Taguchi method. They identified an optimum weight percent of fly ash (12 wt.%) that resulted in maximum tensile strength while minimizing defects and improving microstructural homogeneity.

Kumar et al. (2019) investigated the effect of weight percent of fly ash on the fatigue behavior of AMCs under cyclic loading conditions. They found that composites with moderate fly ash content (8-12 wt.%) exhibited superior fatigue strength due to a balanced combination of toughness and elasticity.

Mishra & Das, 2023 conducted a study to analyze the effect of varying weight percentages of fly ash (5 wt.%, 15 wt.%, and 20 wt.%) on the tensile properties of aluminium matrix composites fabricated via powder metallurgy. They observed that the tensile strength increased with increament in fly ash content up to 15 wt.%, beyond which a decline in strength was noted due to agglomeration and poor interfacial bonding.

Chatterjee & Mandal, 2022 explored the influence of weight percent of fly ash on the tensile behavior of AMCs processed through hot extrusion. They found that composites containing 8-12 wt.% fly ash exhibited the highest tensile strength due to effective particle dispersion and interfacial bonding. However, excessive fly ash loading (>15 wt.%) resulted in a decrease in strength attributed to microstructural defects.

Banerjee & Roy, 2021 studied the impact of weight percent of fly ash on the tensile properties of AMCs fabricated by stir casting combined with electromagnetic stirring. They reported an increase in tensile strength with increasing fly ash content up to 18 wt.%, attributed to improved grain refinement and strengthening mechanisms. However, higher fly ash loadings (>18 wt.%) led to a reduction in strength due to particle agglomeration and porosity.

Ghosh et al. (2020) conducted a study on the optimization of fly ash content in aluminium matrix composites using response surface methodology. They identified an optimum weight percent of fly ash (10 wt.%) that resulted in maximum tensile strength while minimizing defects and improving microstructural homogeneity.

Sengupta & Gupta, 2019 looked into the effect of weight percent of fly ash on the fatigue behavior of AMCs under cyclic loading conditions. They found that composites with moderate fly ash content (6-10 wt.%) exhibited superior fatigue strength due to a balanced combination of strength and ductility.

From the above works, several researchers showed that between 10 - 20wt.% of fly ash addition, the tensile strength reaches its optimum strength when added to Aluminium matrix. Thus, this work then examined beyond 20wt. % fly ash, to determine if the strength will further improve or decrease. Therefore the mechanical and microstructural properties of the composite were analyzed by varying the weight percent of fly ash using stir casting method.

## 2 Materials And Methods

The materials and equipment used includes; Gloves, Aluminium scraps, Sand Crucible, Furnace, Shovel, Brush, Trowel, Rammer, Riddle, Draw spikes, Clamps, Stirring rod, Crucible, Ladle, Engine oil, Fly ash, Aluminium foil and Ingots.

### 2.1 Preparation of the Mold

Silica sand and Calcium Carbonate ($CaCO_3$), used as

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binding agent, was mixed together with water, to strengthen the sand and enable plasticity which make the aggregate suitable for molding. Sand molding are relatively inexpensive and give accuracy.

### 2.2 Steps in Mold Making

- Place a pattern in the drag, then fill up with sand and compact together with the aid of a Rammer.
- Fill the cope with sand and compact together with the aid of a Rammer.
- Incorporate the pattern and sand in a gating system.
- Remove the Pattern.
- Clamp both the cope and drag and fill the mold cavity with molten metal.
- Let the metal solidify and cool.
- Break apart the mold of the sand and separate it from the metal cast.

### 2.3 Preparation of the Furnace For Melting

- Gathering the Aluminium: The aluminium scraps were gathered and the impurities removed from the body by peeling them off.
- Setting up the Furnace: The furnace were set up by putting charcoal under it and set it lit after heating it up to a suitable temperature.
- Preheating: The crucible were put inside the furnace, with other apparatus used for the melting, in order to preheat.
- Setting up the Blower: The blower was set beside the furnace to blow hot air and condemn oil through the ducts into the furnace.
- Melting and pouring of the Aluminium Mold: The aluminium sheets were poured inside the furnace, and allowed to heat up to 700°C and then scooped from the furnace with a ladle and poured inside the mold through the runner and it came out from the riser.

### 2.4 Heat Treatment Process

Prior to casting, the aluminium sheets were subjected to heat treatment for grain refinement, and optimizing the properties for composite fabrication. Fly Ash as reinforcement underwent a thermal treatment process to reduce carbon content and enhance its pozzolanic reactivity. Mechanical milling was employed to achieve a consistent particle size distribution, promoting uniform dispersion within the matrix.

### 2.4 Stir Casting Process

In this method, the fly ash was mixed with molten metal matrix by means of mechanical stirring. Using stir-casting method (Figure 1), Al-10% Fly-ash composite materials used for this research were produced at the Foundry Workshop of Metallurgical and Materials Engineering of Nnamdi Azikiwe University Awka, Nigeria. 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 metal matrix composite by stir casting, using aluminium as a matrix were further conducted for 20%, 30%, and 40% weight fraction of fly ash with a stirring rod in a crucible soaked at approximately 700 degrees celsius.

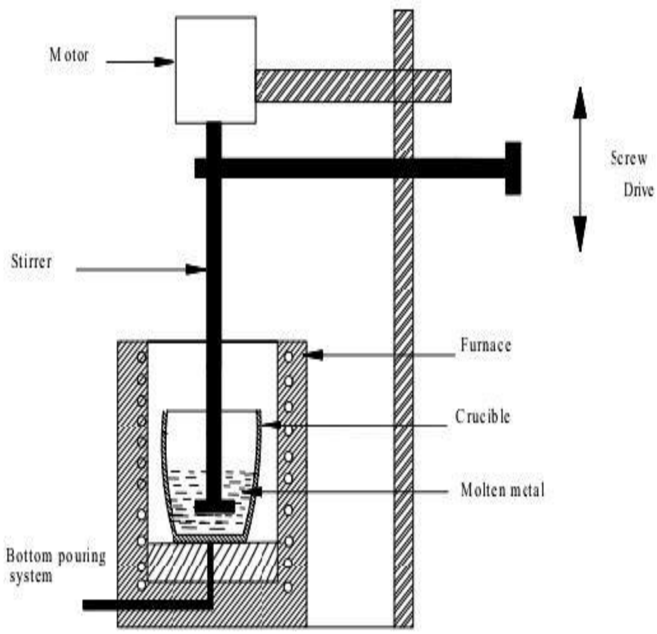


Fig. 1. Stircasting Process (Abdulfatai et al. 2023)

## 3 Results and Discussion

Table 1: Mechanical properties test results.

| Percentage Weight of fly ash (%) | Tensile Strength (MPa) | Yield Strength (MPa) | Percentage Elongation (%) | Young Modulus (N/mm²) |
|---|---|---|---|---|
| 0 (control) | 84.16 | 83.5 | 13.13 | 1022.58 |
| 10 | 109.41 | 107.76 | 15.1 | 1319.02 |
| 20 | 98.78 | 96.08 | 8.3 | 2983.21 |
| 30 | 97.16 | 96.92 | 15 | 1163.56 |
| 40 | 101.16 | 99.31 | 9.8 | 2199.29 |

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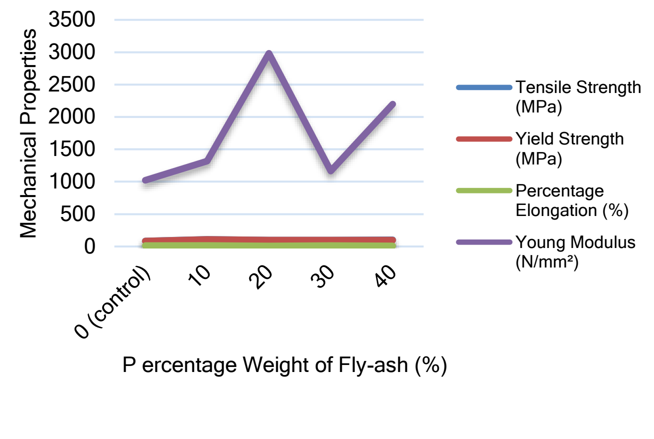


Fig.2. A graph of the mechanical property test results.

### 3.1 Tensile Strength

Tensile strength test was carried out on composites using universal testing machine (Emekwisia et al. 2020). With the results obtained, the aluminium composite recorded a maximum tensile strength on the addition of 10% wt. of fly ash (109.41MPa) as compared to the aluminium with no reinforcement (84.16MPa). The tensile strength took to a decline on the addition of 20% wt. of fly ash. This decline in the tensile strength value was as a result of excess reinforcement particles in the aluminium metal composite. The excess particles caused the development of pores in the composite leading to the development of a crack propagation thereby making the material more brittle than ductile. At the optimum tensile strength of 109.41MPa, the aluminium matrix and the fly ash reinforcement achieved an optimum bond with low porosity level on the addition of 3g wt. of fly ash.

### 3.2 Yield Strength

Using extensometer to measure the maximum stress the composite can withstand before it begins to permanently change shape, it was recorded that the optimum yield strength value was on the addition of the 10% wt. of fly ash resulting to a 107.76 MPa value. The yield strength took to a decline on the addition of 20% wt. of fly ash resulting to a 96.08 MPa value. The decline came as a result of a weak or inadequate interfacial bonding between the aluminium matrix and the excessive addition of the fly ash reinforcement. The bond weakness reduced the load transfer and led to reduced yield strength. The optimized interfacial bond on the addition of 10% wt of fly ash was adequate to enhance stress transfer and improve the composite's resistance to deformation. This contributed to the increase in the yield strength.

### 3.3 Percentage Elongation

The percentage elongation results showed an optimum strength of 15.1% on the addition of 10% wt of fly ash. It decreased to 8.3% on the addition of 20% wt. of fly ash. Since fly ash is a less dense reinforcement with low ductility compared to the aluminium matrix, a wt. % increase in the fly ash added got to form a less dense brittle composite with weak interface that hinder the transfer of stress and strain between the phases thereby leading to a reduced percentage elongation. At the 15.1% optimum strength, there was proper dispersion and distribution of the reinforcement within the aluminium matrix improving the ductility of the composite thereby resulting to increased percentage elongation.

### 3.4 Young's Modulus / Elastic Modulus

Young's modulus is all about the stiffness of the composite. And the stiffer a material is the more brittle it gets. The aluminium - fly ash composite Young's modulus test results recorded an optimum Young's modulus value of 2983.21 Joules on the addition of 20%wt. of fly ash. Other properties declined on the addition of 20%wt. of fly ash because of the high young's modulus recorded. Those properties prefer a relationship with ductility than with brittleness. The phase interaction between the reinforcement (fly ash) and the matrix (aluminum) showed an effective transfer of stress thereby increasing load transfer between the phases causing an increased stiffness or Young's modulus in the composite. The Young's modulus declined on the addition of 30% wt. of fly ash to 1163.56 Joules value. This was as a result of a disruption in the previous optimum structure of the composite. A lesser uniformity in the micro-structure and grain boundaries of the composite thereby causing lesser stiffness.

### 3.5 Microstructural Test

The microstructural analysis of the composite was conducted with L2003A metallurgical optical microscope. This process were done in three stages: The grinding, the polishing, and the etching.

#### 3.5.1 Grinding

The composite samples were cut into small sections with dimensions of 3mm using a low-speed angle grinder. Then, utilizing Emery papers in grades 220, 500, 800, 1200, and 2200 (from coarse to fine), a moderate and fine grinding was applied.

#### 3.5.2 Polishing

After grinding, the samples were polished with aluminium oxide, which was placed on a lint cloth and each samples was rubbed on the paste (aluminium oxide mixed with little water). After which, the samples were rinsed in water and dried.

#### 3.5.3 Etching

The samples were etched by dipping the surface into the Keller's reagent (2.5ml $HNO_3$, 1.5ml HCL, 1ml HF, 95ml of distilled water) for about 20 seconds and dried. Immediately after etching with Keller's reagent, then, the microstructures of the samples were viewed using a metallurgical microscope at different magnifications. The photographs were taken with digital camera.

### 3.6 Stress-Strain Curve

A stress-strain curve illustrates a material's response to an applied load graphically. A stress strain curve indicates key properties of a material including its elastic region, plastic region, yield point, and ultimate tensile strength. This was obtained by gradually applying load to a test piece and measuring the deformation, from which the stress and strain was determined.

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Table 2: The Stress-Strain Results with Varying Fly Ash

| Percentage Weight of Fly Ash (%) | Stress value (N/mm²) | Strain Value (%) |
|---|---|---|
| 0 (control) | 84.16 | 11.26 |
| 10 | 109.41 | 14.95 |
| 20 | 98.78 | 8.18 |
| 30 | 97.16 | 15.08 |
| 40 | 101.16 | 9.81 |

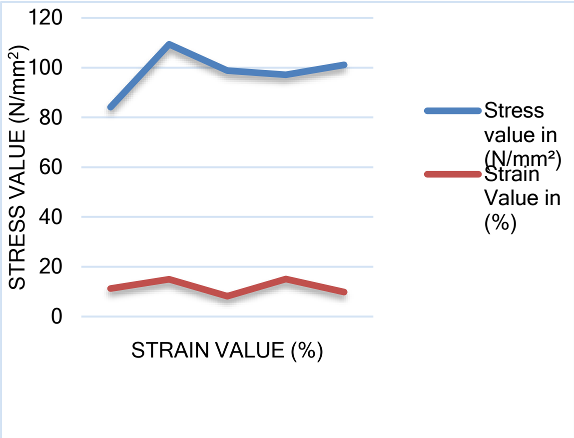


Fig.3. The Stress-Strain Graph.

### 3.7 Microstructural Analysis

The microstructural analysis of the composite were studied and interpreted as shown in Figures 4-8. The photo-micrographic parts of the composite samples were studied and interpreted. The microstructure of the composites revealed the distribution and morphology of the matrix within the fly ash particles, and provided insights into the composite's structural characteristics, particle size distribution, and interfacial bonding.The main reinforcement (FA) partially dissolved in the Aluminium solution, strengthening it by the solution, and partially formed intermetallic phases with aluminium.

Fig. 4. Al - 0%wt of fly ash

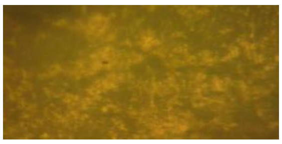

Fig. 5. Al - 10%wt of fly ash

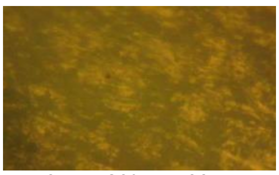

Fig. 6. Al - 20%wt of fly ash

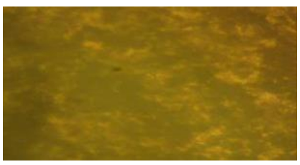

Fig. 7. Al - 30%wt of fly ash

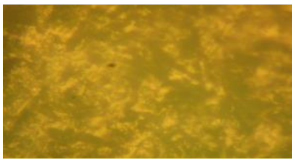

Fig. 8. Al - 40%wt of fly ash

## 4 Conclusion

This research was done to find out the impact of fly ash composite in the mechanical properties, particularly the tensile property, of Aluminium fly-ash composite. Thus there is no need doing any further tests as the scope of the work has been covered. From the evidence gathered here, the following conclusions were drawn; the aluminium composite showed optimum tensile strength and yield strength on the addition of 10%wt. of fly ash and then experiences a declined at the addition of 20%wt. of fly-ash followed by another linear incline as weight of fly ash increase. This entails that 10%wt. fly ash aluminium composite possesses ultimate tensile strength, after which it experienced a decline from 20 - 40%wt. It is still visible with the stress-strain graph that the composite reached its ultimate strength at the addition of 10%wt. of fly ash, and was also revealed through the microstructural analysis.

### 4.1 Recommendation

The authors hereby recommends this composite (aluminium 10%wt. of fly ash) for applications in various industries where lightweight, high-strength materials are required. Such industries include; the automotive industry for production of engine blocks, pistons, cylinder heads, and suspension parts; In aerospace industry for fuselage panels, interior fittings, and structural parts manufacturing; In building and construction industry for production of roofing panels, wall cladding, window frames, and structural beams; and in the electronics industry for laptop casings, smartphone frames, and consumer electronics housings production.

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