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Experimental Investigation on Mechanical Properties of Fly Ash Reinforced Aluminium Alloy (Al 6061) Metal Matrix Composites

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Abstract-*The present research investigates the mechanical properties of Al6061 aluminium matrix composites reinforced with fly ash particles. The composites were fabricated using the stir casting technique with fly ash content varied from 0 wt. % to 12 wt. % in steps of 4%. The mechanical properties of the fabricated composites were evaluated. The experimental results reveal that the ultimate tensile strength and hardness increase with increasing fly ash content, whereas percentage elongation decreases as the fly ash content increases.*

Keywords: aluminum, Al 6061, fly ash, mechanical properties, ultimate tensile strength, hardness, aluminum metal matrix composites.

I. INTRODUCTION

The demand for advanced engineering materials in critical sectors such as automotive, aerospace, defense, and maritime industries is continuously increasing. Modern engineering applications require materials with low weight, high strength, high stiffness, and low cost. These requirements cannot be fully satisfied by conventional monolithic alloys, leading to a growing interest in composite materials with enhanced properties. A composite material is a combination of two materials with different physical and chemical properties. A composite material is made up of a matrix and a reinforcement phase. In recent years, metal-matrix composites (MMCs) have attracted significant attention due to their superior mechanical properties compared to conventional monolithic alloys. Among MMCs, aluminium metal-matrix composites (AMMCs) are considered advanced materials and are widely used in applications such as aircraft structures, race car bodies, buildings, defense systems, electronics, automotive components, power plants, and satellite launch vehicles. Aluminum matrix composites have superior properties such as high modulus of elasticity, high strength, high fatigue resistance, high abrasion resistance, high rigidity, stability at high temperature, high strength to weight ratio, low coefficient of thermal expansion and low density. Various aluminium alloy series, including 1xxx, 2xxx, 5xxx, 6xxx, and 7xxx, are commonly used as matrix materials in AMMC fabrication. Among these, 6xxx series aluminium alloys are widely preferred due to their good machinability, excellent miscibility, and balanced mechanical properties. Aluminium matrix composites can be fabricated using several techniques, including stir casting, infiltration processes, squeeze casting, reactive in-situ methods, powder metallurgy, and friction stir processing. Among these methods, stir casting is one of the most economical and widely used techniques due to its simplicity, cost-effectiveness, and suitability for large-scale production. Figure 1 shows different types of reinforcements commonly used for the fabrication of MMCs. Fly ash, a waste by-product generated during coal combustion in thermal power plants, is abundantly available in the Indian subcontinent and worldwide. Compared to conventional ceramic reinforcements such as carbon nanotubes (CNTs), boron carbide (B_4C), silicon carbide (SiC), aluminium oxide (Al_2O_3), and titanium carbide (TiC), fly ash is significantly cheaper.

In 2024–25, India generated 340.11 million tonnes of fly ash, of which 332.63 million tonnes were successfully utilized. During the year 2024-25, 32% of the total fly ash generated was used in the construction of roads and flyovers, followed by 27% utilized within the cement industry, and 14% in the manufacturing of bricks and tiles. The utilization of fly ash in India during the year 2024–2025 is depicted in figure 2.

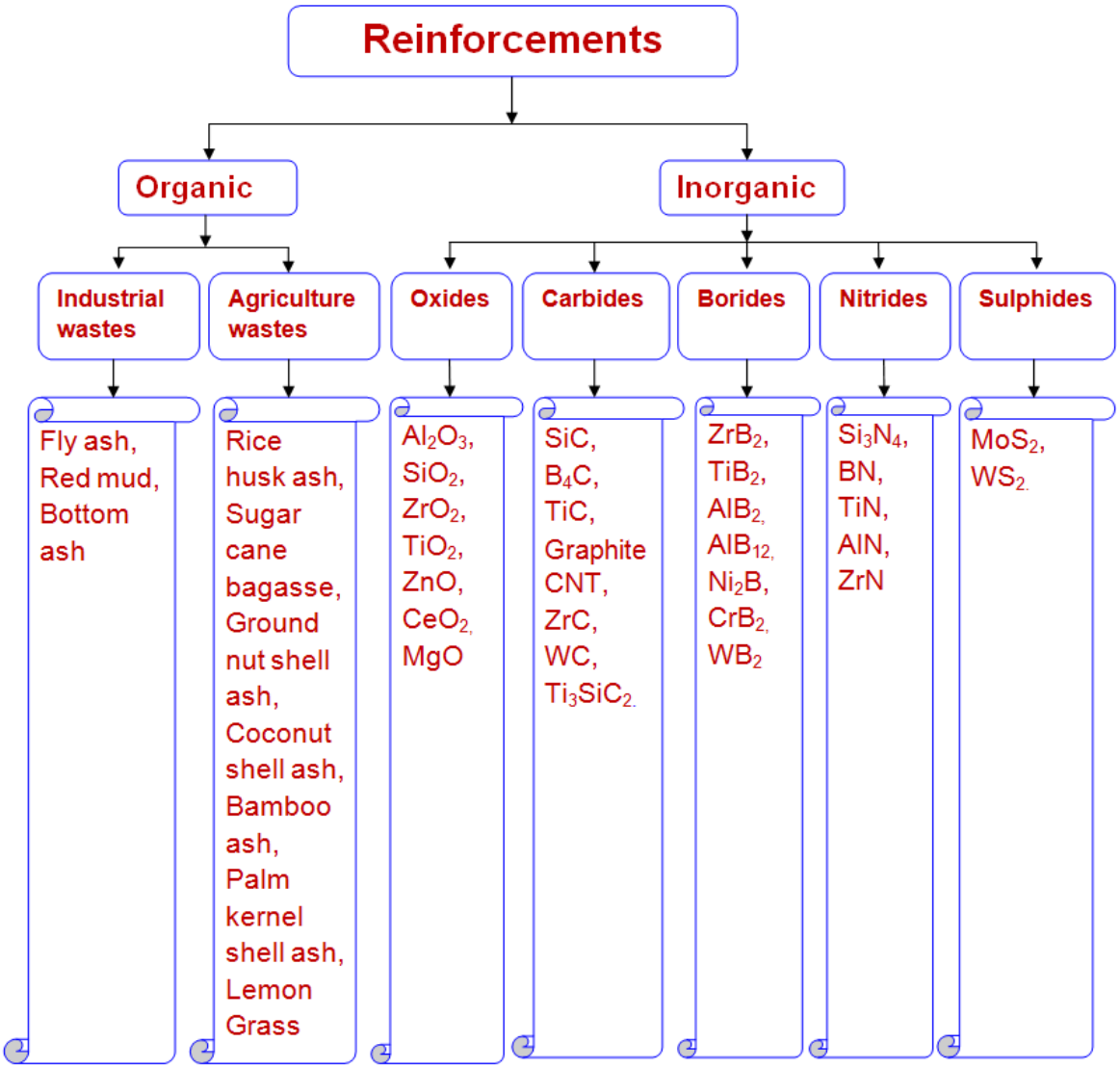

Figure 1: Commonly used reinforcements in MMCs.

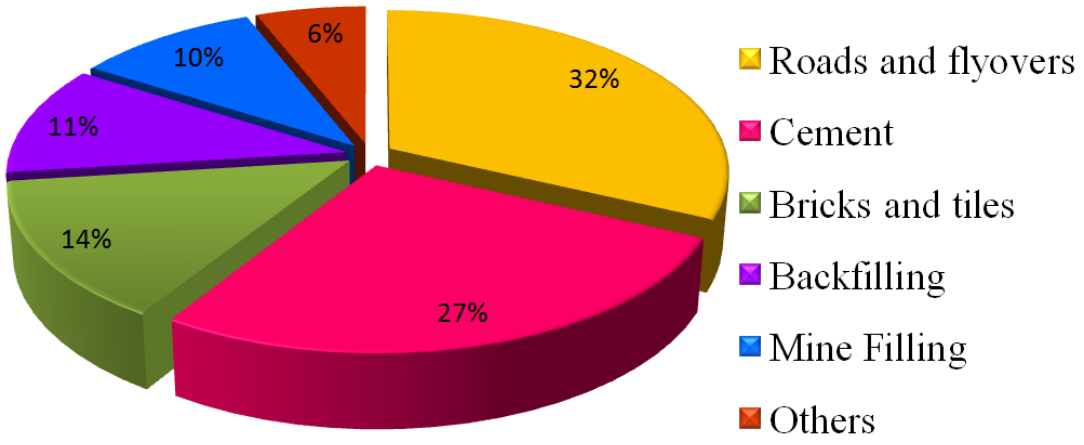

Figure 2: The utilization of fly ash in India during the year 2024–2025.

II. MATERIAL AND METHODS

Al6061 alloy

Al6061 alloy is selected as the matrix material for metal matrix composites because of its excellent combination of properties such as high strength-to-weight ratio and good corrosion resistance. The 6061 alloy mainly consists of aluminum with magnesium and silicon as the principal alloying elements. It is widely used in automotive, marine, aerospace, and structural applications. The composition of aluminium alloy (Al6061) is shown in table-1.

Fly Ash (FA)

Fly ash is an inexpensive, low-density material available as a solid waste by-product of coal-fired thermal power plants. The cement industry is the largest consumer of fly ash in the country. Fly ash particles are generally spherical in shape and range in size from 1 µm to 100 µm. FA is composed of silicon oxide (SiO_2), aluminum oxide (Al_2O_3), and iron trioxide (Fe_2O_3) of more than 70%. It has been incorporated into metal matrix composites for the last few decades to reduce their weight and manufacturing cost and enhance selected properties. The composition of fly ash is shown in table-2.

Table-1: Chemical composition of Al6061

Element	Weight %	
	Minimum	Maximum
Mg	0.8	1.2
Si	0.4	0.8
Fe	0.0	0.7
Cu	0.15	0.40
Cr	0.04	0.35
Zn	0.0	0.25
Ti	0.0	0.25
Mn	0.0	0.15
Al	95.85	98.56

Table-2: Chemical composition of Fly ash

Chemicals	Formula	Content (%)
Silicon Dioxide	SiO_2	50.2-59.7
Aluminum Oxide	Al_2O_3	14-32.4
Iron Oxide	Fe_2O_3	2.7-16.6
Magnesium Oxide	MgO	0.1-2.3
Lime	Cao	0.6-9
Titanium dioxide	TiO_2	0.3-2.7
Alakalies	Na_2O	0.2-1.2
Alakalies	K_2O	0.2-4.7
Loss of ignition	LOI	0.5-7.2

Stir casting

Stir casting is widely used to prepare MMCs of low melting point materials because it is economical, simple, flexible and suitable for mass production. In this method, the reinforcement phase is mixed with the molten matrix metal by mechanical stirring. The molten composite slurry is then cast by conventional casting methods. The properties of the metal matrix composites produced using stir casting methods will depend on the processing parameters such as temperature of melt, stirring speed, stirring duration, geometry of the stirrer and size of crucible which will affect the distribution of the reinforcements in the matrix.

Fabrication of Composites

The aluminium alloy (Al6061) is the base material, and fly ash is used as the reinforcement particles. Initially, pure aluminium alloy was cut into small pieces to minimize the melting time and maximize the effective melting. The fly ash particles were initially preheated separately at a temperature of 350-400°C for 30 minutes to remove moisture and to help even distribution within the aluminium alloy. The aluminum alloy was charged into the graphite crucible and heated to 750°C till the entire metal in the crucible was melted. After the metal alloy is completely melted, degassing tablets are added to reduce porosity. Simultaneously, 1% by weight magnesium was added to the melt to enhance the wettability between the matrix and the reinforcements. The preheated fly ash particles were added to the molten metal at a constant rate during the stirring. After the completion of particle feeding, stirring was maintained for a further 20 minutes to ensure uniform dispersion of the reinforcement particles. After 20 minutes of stirring, the complete mixture of reinforcement materials with aluminium alloy metal matrix was made. The mixture was poured into the mold, which was also preheated to 500°C for 20 min to obtain uniform solidification. After solidification, the composite can be cut into different shapes and sizes as per requirements.

III. RESULTS AND DISCUSSION

The prepared aluminium metal matrix composite samples are investigated for their mechanical properties and are compared with the pure aluminium. The mechanical properties of the matrix alloy and the composite specimens are presented in Table 3.

Table-3: Mechanical properties of the matrix alloy and its composites.

Weight % of fly ash	Ultimate Tensile Strength (MPa)	Percentage Elongation	Hardness (BHN)
0	129	18.6	42
4	141	16.7	50
8	149	15.4	56
12	155	14.2	61

Ultimate Tensile Strength

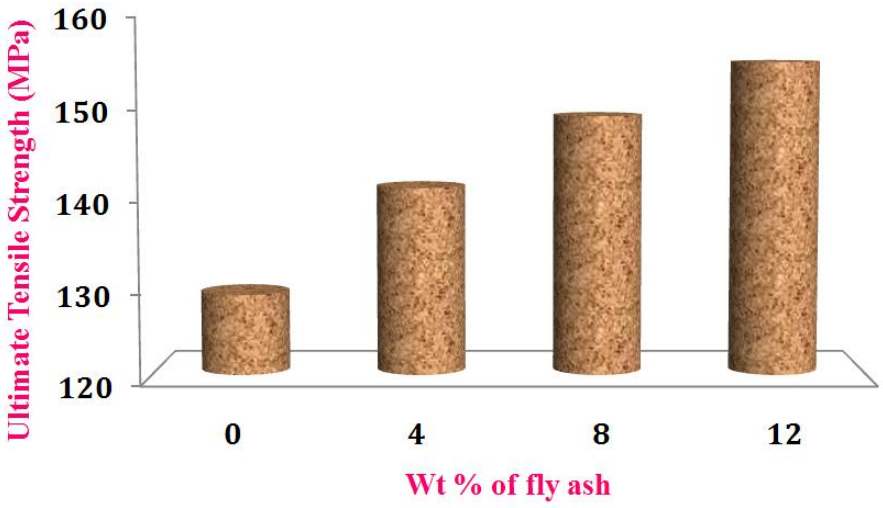

Figure 3: Ultimate tensile strength of composites

The graph plotted between ultimate tensile strength versus different weight percentages of fly ash particulates is shown in figure-3. From figure-3 it can be observed that, with the inclusion of fly ash particles, the ultimate tensile strength of composites increased than the matrix material. Furthermore, increment in the reinforcement weight percentage increases the ultimate tensile strength. The ultimate tensile strength of Al6061- 12% fly ash composite is 155N/mm^2, which is 20.15% higher than that for Al6061 alloy. The incorporation of fly ash as a reinforcement in Al6061-based metal matrix composites enhances the ultimate tensile strength due to the presence of hard and rigid particles, which promote efficient load transfer from the matrix to the reinforcement and restrict dislocation movement within the matrix. K.V. Mahendra et al [1] fabricated aluminium - fly ash composite and investigated the effect of reinforcement on the mechanical properties of aluminium metal matrix composite. The reinforcing particles in the Al–4.5% Cu alloy were varied from 0% to 15% by weight. Results indicated that the tensile strength of the composites is higher than the unreinforced matrix metal and tensile strength of the composites increased with increasing the amount of the fly ash in the matrix phase. S. Rajesh et al [2] fabricated and analysed the mechanical properties of fly ash reinforced aluminium composites. Aluminium metal matrix composites were fabricated by considering aluminium alloy 7075 reinforced with various weight percentage (0, 5, and 10) of fly ash through stir casting technique. The researchers observed that the tensile strength of the composites is higher than the unreinforced matrix metal and the tensile strength of the composites increases with increasing the weight fraction of fly ash.

Percentage Elongation

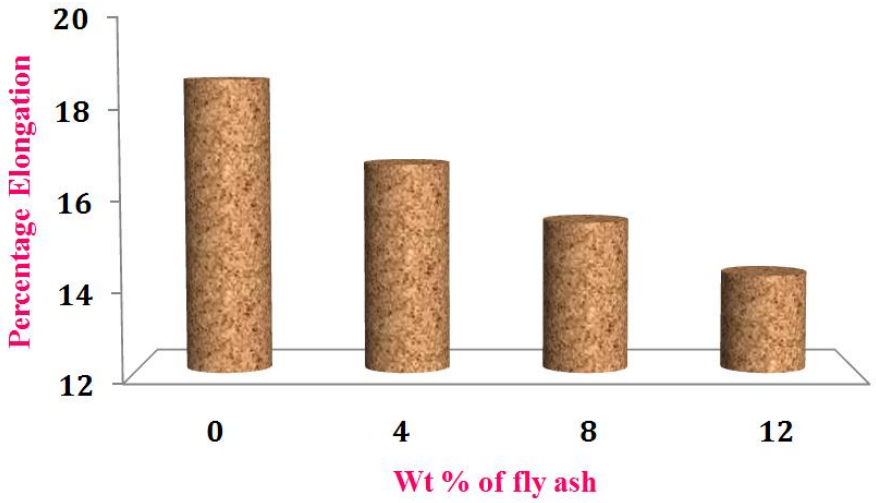

Figure 4: Percentage elongation of composites

Figure-4 shows the graph between the percentage elongations versus the fly ash weight percent. From the figure, it is clearly evident that the percentage elongation of the developed aluminium matrix composites is lower than that of the unreinforced aluminium alloy. Furthermore, the graph indicates a decreasing trend in percentage elongation with increasing fly ash content in the composites. A maximum decrease of 23.65% in elongation was observed for the Al6061–12 wt.% fly ash composite when compared to the base alloy.Fly ash contains ceramic particles such as silica and alumina, which are inherently hard and brittle, thereby reducing the ductility of the composite compared to unreinforced Al6061. Mahendra Boopathi. M et al [3] created aluminum- fly ash composite and researched its mechanical properties. Aluminum alloy (AA 2024) is selected as the matrix material and fly ash as reinforced particles are mixed in different weight percentages (0, 5, and 10 wt %). The authors have revealed that the elongation of composites decreased with an increase in weight percentage of fly ash in the matrix material. The elongation of composites is lower than that of un-reinforced Al-alloy. Pankaj Kr. Sharma et al [4] fabricated and investigated the effect of reinforcement on the mechanical properties of aluminium metal matrix composite. In the present case, the fly ash content is varying in composition of (0, 6, 8 and 10 wt %) in aluminum matrix, fabricated by stir casting technique. The results indicated that the elongation of the composites decreased with increasing weight percentage of fly ash in the matrix.

Hardness

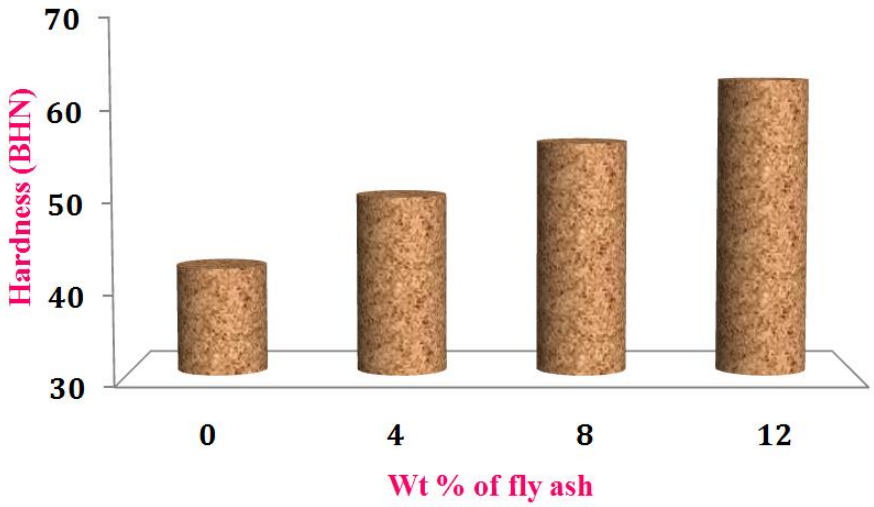

Figure 5: Hardness of composites

The hardness values of Al6061 and its composites are presented in figure 5. It is evident from the figure that the developed composites exhibit higher hardness compared to the Al6061 matrix alloy. Moreover, the hardness increases progressively with an increase in the weight percentage of fly ash reinforcement. Fly ash mainly consists of hard oxides (SiO_2, Al_2O_3, and Fe_2O_3), and its addition as a reinforcement increases the hardness of the composite material. G. N. Lokesh et al [5] created aluminum-fly ash composite and researched its mechanical properties. Aluminum alloy (Al-4.5wt%Cu alloy) is selected as the matrix material and fly ash as reinforced particles are mixed in different weight percentages (0, 3, 6, 9, and 12 wt %). The results show that increasing the weight percentage of fly ash reinforcement increases the hardness of the composites. Alaa Mohammed Razzaq et al [6] investigated the effect of fly ash particles on mechanical properties of aluminum metal matrix composites. The fabrication of aluminum composites with different weight percentage of fly ash particles up to 0-12% was processed by stir casting process. The result shows that the hardness of the composites is higher than the unreinforced matrix metal and the hardness of the composites increases with increasing the weight percentage of fly ash.

IV.CONCLUSION

In the present research work, Al 6061–fly ash metal matrix composites were successfully fabricated by varying the weight percentage of fly ash particles. Four different compositions were prepared, and their mechanical properties such as ultimate tensile strength, percentage elongation, and hardness were evaluated. Based on the experimental results, the following conclusions are drawn:

- Stir casting was found to be an effective and economical technique for the fabrication of aluminium matrix composites reinforced with fly ash particles.
- The Al 6061–fly ash composites exhibited higher ultimate tensile strength compared to the unreinforced Al 6061 alloy. Furthermore, the ultimate tensile strength increased with an increase in the weight percentage of fly ash reinforcement.
- The percentage elongation of the composites is lower than that of the unreinforced aluminium alloy, and it decreases with increasing fly ash content in the matrix material.
- The hardness of the composites is higher than that of the unreinforced matrix metal, and the hardness increases with an increase in fly ash content.

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