Journal of
Polymer & Composites

ISSN: 2321-2810 (Online)
ISSN: 2321-8525 (Print)
Volume 13, Special Issue 6, 2025
DOI (Journal): 10.37591/JoPC

https://journals.stmjournals.com/jopc

Research JoPC

AL6061/Al_2O_3-Ash Reinforced Composites: An Experimental and Statistical Study Using Ultrasonic Stir Casting

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Abstract

This study presents an experimental investigation on the influence of fly ash particle size on the mechanical properties of aluminum alloy (Al6061) composites fabricated through Ultrasonic Assisted Stir Casting. Fly ash, a low-cost and low-density by-product of thermal power plants, has emerged as an effective reinforcement material due to its excellent fluidity, high filling capability, and ease of processing. It has been increasingly utilized in metal, polymer, and rubber composites to enhance mechanical and thermal performance. In this research, Al6061-based composites were developed with fly ash contents of 5%, 10%, and 15% by weight, incorporating particle sizes ranging from 5–20 µm, 25–30 µm, and 50–60 µm. The mechanical behavior of the composites was evaluated in terms of ultimate tensile strength (UTS), ultimate compressive strength (UCS), and hardness. The results revealed that the mechanical properties improved with an increase in fly ash content, owing to enhanced interfacial bonding and particle dispersion within the matrix. However, as the particle size increased, a decline in mechanical performance was observed due to reduced surface area and weaker bonding with the matrix. An optimal fly ash content of around 10% was found to provide the best balance between strength and ductility, whereas a slight reduction in UTS occurred at 15% reinforcement, indicating a saturation threshold for effective load transfer.

Keywords: Ultrasonic-assisted stir casting, Al6061, metal matrix composites, fly ash powder, Al2O3, mechanical properties

INTRODUCTION

A broad range of applications employ aluminum alloys because of its exceptional qualities, which include a high strength-to-weight ratio, outstanding corrosion resistance, and simplicity of manufacture. The demand for enhanced mechanical performance and durability in industries such as aerospace, automotive, and construction has led to the development of advanced materials, including composites. Metal matrix composites (MMCs), which combine a metal matrix with reinforcing phases such as ceramics or natural fibers, are particularly sought after for their superior thermal, mechanical, and wear-resistant properties. Among the various MMCs, aluminum matrix composites (AMCs) are the most popular due to the inherent advantages of aluminum, such as low density, high specific strength, and good formability.

The AI6XXX series is one of the most often utilized alloys for MMCs, particularly AA 6061.

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Received Date: August 27, 2025
Accepted Date: September 26, 2025
Published Date: November 21, 2025

Citation: M Naga Phani Sastry, K. Devaki Devi, Borigorla Venu, PVR Girish Kumar. AL6061/Al_2O_3-Ash Reinforced Composites: An Experimental and Statistical Study Using Ultrasonic Stir Casting. Journal of Polymer & Composites. 2025; 13(Special Issue 6): S1123–S1133p.

It is favoured in the aviation and automotive sectors for its high strength, good weldability, and suitability for a wide range of structural applications. Despite these benefits, AA 6061 suffers from limitations such as low wear resistance and suboptimal performance under high-temperature conditions. To overcome these limitations, researchers have explored the reinforcement of AI6061 with materials such as alumina (Al_2O_3) and other particulate phases like ash powder. These reinforcements are chosen for their superior hardness, thermal stability, and ability to improve mechanical properties such as tensile strength, hardness, and wear resistance [1-3].

Reinforcements such as Al_2O_3 particles offer high thermal stability and excellent abrasion resistance, which can significantly enhance the wear properties of the composite. Ash powder, often sourced from industrial waste, provides an eco-friendly and cost-effective alternative as a reinforcing phase. Ash powder, being lightweight and fine, has shown potential in improving properties like toughness, impact strength, and overall mechanical performance of composites.

The final properties of the composite and the distribution of reinforcement materials are determined in large part by the MMC fabrication process. Stir casting is one of the most commonly used techniques for producing aluminum-based MMCs due to its simplicity, cost-effectiveness, and ability to incorporate a wide range of reinforcements. However, one of the challenges in stir casting is achieving uniform dispersion of the reinforcing particles within the aluminum matrix. Issues such as particle agglomeration, poor wettability between the matrix and reinforcement, and the tendency of particles to settle can limit the overall performance of the composite [4,5].

Ultrasonic vibration-assisted stir casting (UASC) has emerged as an advanced method to address these challenges. The application of ultrasonic vibrations during the stir casting process helps improve the distribution of reinforcing particles by enhancing the fluidity of the molten metal and preventing particle clustering. The ultrasonic vibrations also promote better wetting of the reinforcement material and can refine the microstructure of the composite. As a result, composites produced using UASC exhibit improved mechanical properties, such as enhanced tensile strength, hardness, and uniformity of reinforcement distribution [6,7].

The suitability of aluminum Matrix Composites (AA-MMCs) for a range of industrial applications is largely determined by their mechanical characteristics. These properties, including yield strength and ultimate tensile strength, are largely influenced by the choice of reinforcement materials and the fabrication processes used. The crystal structure, physical characteristics, and properties of the reinforcement particles play a vital role in tailoring the overall mechanical behavior of the composite. Researchers have noted that the type, size, shape, and volume fraction of reinforcements, as well as the processing methods, significantly affect the mechanical properties of AA-MMCs.

The reinforcement particles in AA-MMCs enhance their mechanical properties through improved interface bonding and the superior attributes of the reinforcements themselves. Common reinforcements include ceramic particles such as SiC, Al2O3, TiC, B4C, and others, which have been extensively studied for their effects on the mechanical performance of AA-MMCs. Because of its exceptional mechanical qualities, such as high strength, hardness, and wear resistance, silicon carbide (SiCp) is one of the most commonly used reinforcements among these. Studies have shown that SiCp-reinforced aluminum composites exhibit improved yield strength and ultimate tensile strength, as well as a refined microstructure, thanks to the addition of SiCp particles. For instance, research by David Raja Selvam et al. [8] and Bharath V et al. [9] has demonstrated that the addition of SiCp particles reduces the grain size and increases both yield strength and ultimate tensile strength of the composites. Moreover, hybrid composites, which combine SiCp with other reinforcements such as graphene or carbon nanotubes (CNTs), show even further improvements in mechanical properties due to enhanced interfacial bonding and the synergistic effect of multiple reinforcements [10,11].

The mechanical properties of AA-MMCs are largely determined by the size and volume fraction of the reinforcement particles. Research indicates that finer reinforcement particles, such as nano-sized SiCp, lead to improved mechanical performance compared to their micron-sized counterparts. For example, studies by Donanta Dhanswara et al. [12] and Satyashankara Sharma et al. [13] found that smaller reinforcement particles contribute to increased yield strength and tensile strength due to the reduced dislocation movement and the creation of more nucleation sites during solidification. Furthermore, increasing the volume fraction of reinforcement particles generally enhances the strength of the composites, although it may reduce ductility. For instance, Donanta Dhanswara et al. [12] found that the addition of nano-sized B4C particles significantly increased the yield and tensile strength without significantly affecting ductility, whereas larger particles caused a decrease in ductility. Additionally, composites with higher volume fractions of reinforcement particles tend to show better mechanical performance due to the increased load-bearing capacity of the reinforcement phase.

The hardness of AA-MMNCs is significantly influenced by the size, volume fraction, and hardness of the reinforcement particles. The composite material becomes harder when hard ceramic particles like SiCp, Al2O3, or B4C are added. Studies by Uppada Ramakanth et al. [14] and Donanta Dhanswara et al. [12] have demonstrated that the hardness of aluminum alloys increases with the addition of reinforcement particles, particularly when the size of the reinforcement particles is small. This is due to the high surface-to-volume ratio of nanoparticles, which provide a greater barrier to dislocation movement and enhance the material's resistance to localized indentation. Moreover, as the volume fraction of the reinforcement increases, the hardness of the composite also increases, a trend that has been observed in several studies[11-13] and optimization techniques[21]. However, the hardness of the composite is also greatly influenced by the crystal structure and the interfacial bonding between the reinforcement and the matrix.

Through this experimental study, aims to explore the potential of utilizing cost-effective and sustainable reinforcement materials like ash powder, alongside the more conventional Al_2O_3, to improve the mechanical properties of AA 6061 aluminum alloy. The findings of this research could contribute to the development of high-performance materials that are not only cost-effective but also environmentally friendly, opening new opportunities for their use in various industrial sectors, including automotive, aerospace, and construction.

This study focuses on the fabrication of AA 6061-based MMCs reinforced with Al_2O_3 and ash powder using the UASC technique. The primary objective is to systematically investigate the effects of different weight percentages of Al_2O_3 and ash powder on the mechanical properties and microstructure of the composites. The study aims to identify the optimal processing conditions for enhancing the performance of AA 6061 composites, with a particular focus on improving their tensile strength, yield strength, impact toughness, and microhardness. Additionally, the microstructural evolution of the composites is analyzed to better understand the relationship between reinforcement content, processing parameters, and mechanical properties.

METHODOLOGY

Material Composition

Table 1 and 2 present the chemical compositions of Al6061 (known for its strength and casting properties), and fly ash collected from Raichur thermal power plant collected (highlighting its suitability as a reinforcing material) respectively.

Fly ash composition: The fly ash had the composition detailed in Table 1&2.

Table 1. Chemical composition of Al6061 alloy (weight percentage).

Mg	Si	Fe	Cu	Ti	Cr	Zn	Mn	Al
0.91	0.76	0.24	0.21	0.08	0.11	0.05	0.04	Balance

Table 2. Chemical composition of Fly ash used in present study (weight percentage).

Al_2O_3	SiO_2	Fe_2O_3	TiO_2	Loss of ignition
29.56	59.8	4.99	3.1	1.44

Experimental Procedure

In this study, aluminum alloy (Al6061) composites reinforced with fly ash were produced using the stir casting technique. Three types of composites with fly ash particle sizes of 5–20 µm, 25–30 µm, and 50–60 µm were selected after sieve analysis. Fly ash was incorporated into Al6061 at weight percentages of 5%, 10%, and 15%. This process aimed to create a homogeneous distribution of fly ash within the Al6061 matrix, enabling a systematic study of the effects of fly ash content and particle size on the mechanical properties of the composite.

Materials Preparation:

- *Fly ash preheating:* Fly ash particles were preheated to 400°C and maintained at this temperature for approximately 15 minutes. Preheating helps remove moisture and contaminants from the fly ash, enhancing its bonding with the matrix.
- *Matrix preparation*: A measured quantity of Al6061 alloy was taken from the ingot and melted in a crucible at 775°C, which is above its melting point of 675°C. Al6061 was chosen as the matrix material due to its favorable casting properties and strength.
- *Stir casting process:* The molten Al6061 was stirred using a mechanical stirrer to create a vortex, which facilitates uniform mixing. Preheated fly ash particles were slowly introduced into the molten metal. A small amount of magnesium (0.5–0.6 wt.%) was added to improve the wettability of fly ash particles, enhancing their dispersion within the molten alloy, and to reduce oxidation.

The stir casting equipment must be thoroughly cleaned before initiating a new casting process. If the equipment is not cleaned, any residual material from previous castings could mix with the new batch, leading to contamination. The entire stir casting process is controlled using the Secure Controls Framework (SCF) Live Screen software, which not only manages the equipment but also allows for the input of commands and displays real-time outputs. This software interfaces with various sensors, such as the Resistance Temperature Detector (RTD) sensor, to monitor key parameters like temperature and stirring speed.

After that, the furnace is heated to the melting point needed for the aluminum alloy (AL6061) matrix material. The SCF Live Screen software is used to monitor and adjust the furnace temperature, and once the material reaches the target temperature, the molten matrix is poured into the furnace using tongs. Any slag or impurities formed during the melting process are removed from the surface of the molten metal to ensure a clean pour. After this, the furnace is closed, and the stirrer is activated via the SCF Live Screen software to begin the stirring process.

Preheated reinforcement materials (such as Al_2O_3 particles and ash powder) are then added to the molten matrix during the stirring phase, with the addition controlled through the SCF Live Screen software. The die is preheated to remove any moisture or vapor, ensuring a clean die surface for the casting and solidification process.

Next, ultrasonic vibrations are applied to the molten composite to eliminate any trapped air bubbles or pores [15]. This step enhances the material's properties, improving its structural integrity. After the ultrasonic treatment, the molten composite is poured into the preheated die, ensuring the die is properly aligned with the furnace outlet for a smooth, efficient pour. The composite is left to cool naturally in the die under ambient air conditions, completing the solidification process. The schematic representation of process is shown in Figure 1.

Figure 1. Schematic representation of ultrasonic vibration-assisted stir casting process

To observe the microstructure, specimens were cut from the welds and prepared following standard metallographic procedures. To reveal the microstructure, the samples were polished and etched for 30 to 60 seconds using a solution of 2 ml of HF, 3 milliliters of HCl, 5 milliliters of HNO3, and 190 milliliters of distilled water.

Testing for mechanical properties: The mechanical testing of the Al6061-fly ash composites was conducted following ASTM standards for consistency and reliability in evaluating tensile strength, compressive strength and hardness properties.

Tensile tests were performed using a universal testing machine at room temperature in accordance with ASTM E8 standards. The test specimens had a nominal diameter of 12.5 mm and a gauge length of 62.5 mm, with the gauge section aligned along the casting's longitudinal axis.

Compressive strength tests were performed per ASTM E9 standards. The specimens were machined from ingot composites and had a nominal diameter of 15 mm and a height of 20 mm.

Hardness was measured following ASTM E10 standards. This test assessed the composite's resistance to deformation, which provides insights into its suitability for applications requiring high wear resistance.

Experimental Results and Discussion

After testing the specimen under went SEM analysis as discussed below.

Micro-Structural Study:

The microstructure of base metal was shown in Figure 2.

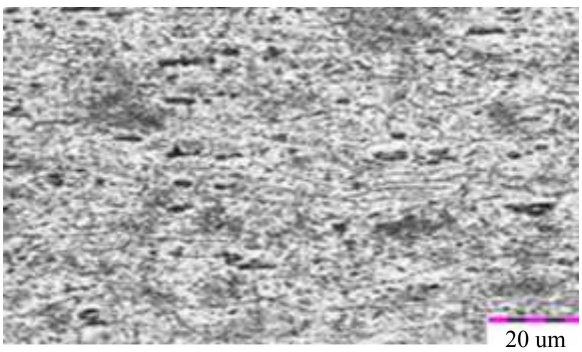

Figure 2. Microstructure of Al6061.

The microstructural analysis was conducted using a metallurgical microscope to evaluate the dispersion and distribution of reinforcement particles in the matrix. The images of the prepared composites with varying reinforcement contents revealed a typical dendritic structure. Notably, the reinforcement particles were uniformly distributed within the matrix, with no significant agglomeration observed, which is a common issue in metal matrix composites (MMCs) [16]. The addition of Al_2O_3 particles (2–5μm) into the molten alloy during composite fabrication facilitated the formation of a transient interfacial layer between the matrix and the reinforcement. This layer significantly improves the wettability of the particles, which is crucial for the uniform distribution of reinforcements [18]. Better adhesion between the matrix and the particles is promoted by the transient layer's low wetting angle, which lowers the liquid matrix's surface tension. This leads to a more homogeneous particle distribution, which is vital for the enhanced mechanical properties of the composite. In MMCs, particle agglomeration can often lead to localized stress concentrations, which negatively affect toughness and mechanical performance [19]. However, such agglomeration was not observed in the stir-cast composites of this study, indicating that the fabrication process effectively avoided this defect.

Additionally, the viscosity of the melt increased when the preheated reinforcement particles were added to the molten alloy all at once, making it more challenging to properly stir the molten metal. This increase in viscosity could hinder the uniform dispersion of particles. However, a bi-stage addition of the reinforcement particles was employed in this study, which alleviated the stirring difficulties by allowing better control over the viscosity of the melt. This method ensured that the reinforcement particles were effectively dispersed in the AL6061 matrix, resulting in a well-distributed composite material with improved structural integrity and enhanced properties. The microstructures are presented in Figure 3a,3b and 3c.

Mechanical Properties

Tensile strength

The results of the tensile strength tests, performed according to ASTM E8-95, for all the MMCs under investigation are presented in Figure 4. The percentage improvements for various weight fractions of reinforcements are also provided.

The tensile strength of the Al6061/fly ash composites increased with higher fly ash content, though the rate of improvement slowed at higher reinforcement levels. This suggests that fly ash particles strengthen the matrix by acting as barriers to dislocation motion. However, larger fly ash particles led to a decrease in tensile strength, likely due to poorer bonding with the matrix compared to smaller particles. Additionally, a drop in tensile strength was observed when fly ash content exceeded 10%, possibly due to poor wettability and ineffective bonding between the reinforcement and matrix.

Compressive strength

Figure 5 displays the findings of the ASTM E9-95-compliant compression strength test for each of the MMCs under investigation. It is evident that as the weight % of fly ash particles grew, so did the compressive strength. This improvement might be explained by the fly ash particles' hardening action on the base alloy, which increases its resistance to compressive stresses.

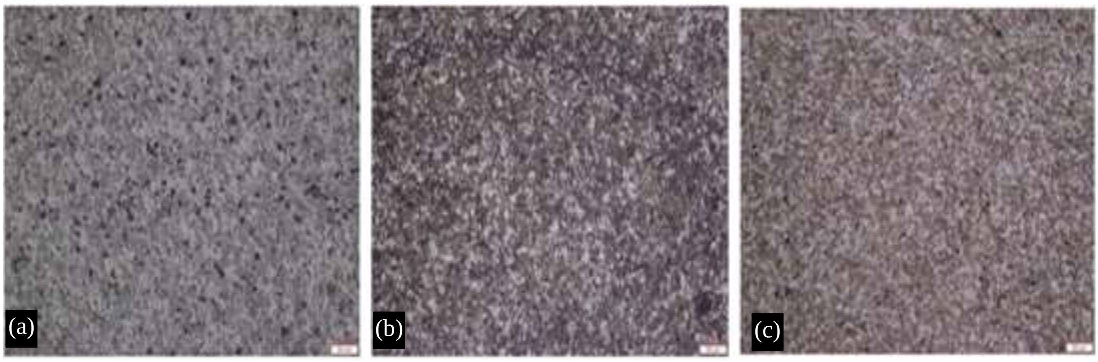

Figure 3. Microstructure of Al6061 with fly ash weight % a) 5% b) 10% c) 15%.

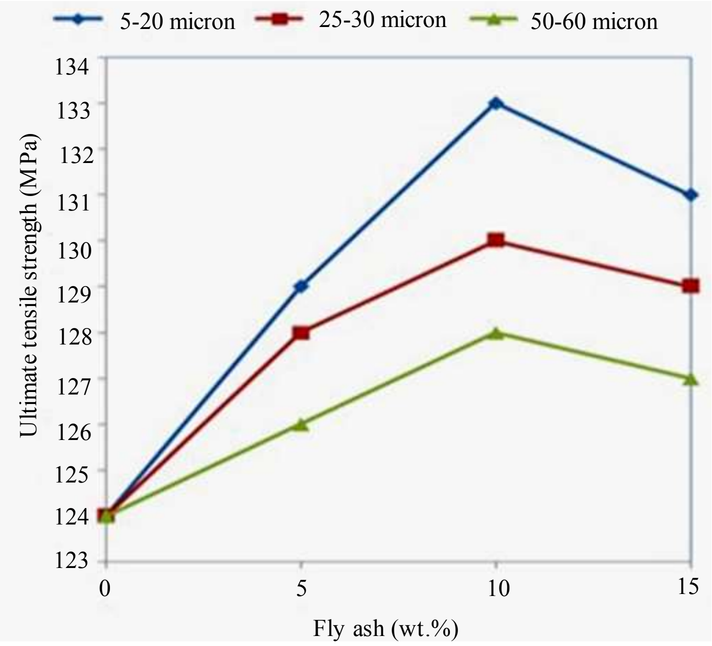

Figure 4. Ultimate tensile strength with the weight % of fly ash.

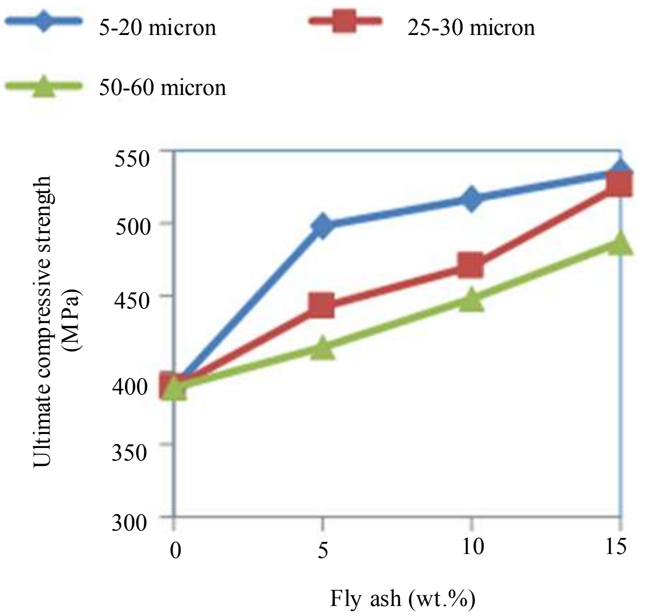

Figure 5. Ultimate compressive strength with the weight % of fly ash.

Furthermore, when the reinforcement's particle size increased, the percentage gain in compressive strength decreased. This suggests that smaller fly ash particles bond more effectively with the matrix, leading to better mechanical performance.

Hardness

The results of the Brinell hardness test, conducted as per ASTM E10, for all the MMCs under investigation are presented in Figure 6.

The percentage improvements with different weight fractions of reinforcements are also provided. The influence of the weight percentage of reinforcement on the hardness of the Al6061 alloy is clearly evident. As shown in Figure 8, the hardness of the composite increased with the higher weight fraction of fly ash particles. Furthermore, an increase in the percentage improvement in hardness was observed as the particle size of the reinforcement decreased. This behavior suggests that the harder fly ash particles contribute to enhancing the hardness of the aluminum alloy (Al6061) matrix by providing greater resistance to indentation.

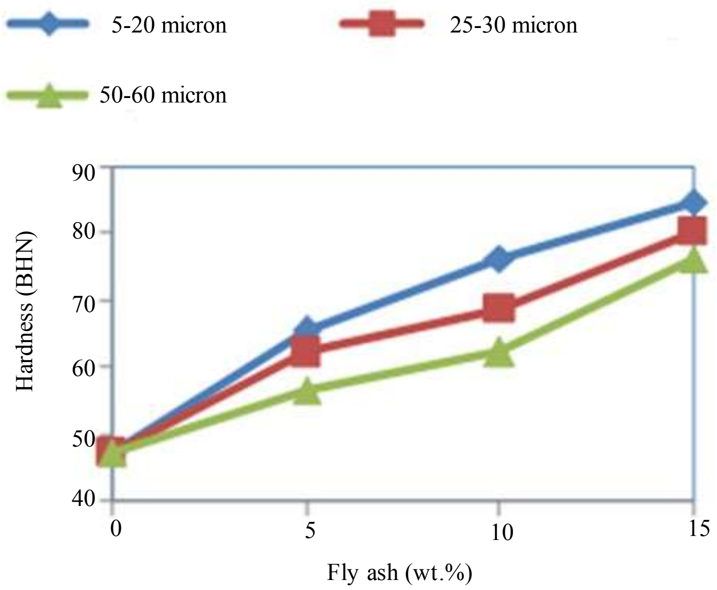

Figure 6. Hardness with the weight % of fly ash.

Ductility

The Figure 7 displays the findings of the ductility test that was performed on each MMC that was selected for further examination.

Additionally included are the percentage gains for various reinforcement weight fractions. As the weight proportion of fly ash increased, the composite's ductility dropped, as seen in the figure 9. The hardness of the fly ash particles or particle clumping might be the cause of this. Even in composites without defects, the percentage of elongation is influenced by a number of parameters, such as particle size, weight, and the percentage of reinforcement [20].

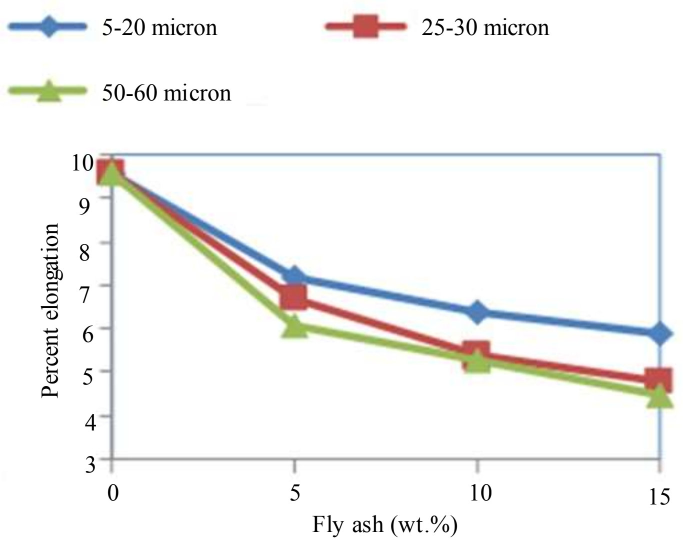

Figure 7. Ductility in relation to fly ash weight percentage.

RESULT ANALYSIS

The Table 3 shows that adding fly ash to the MMCs increases tensile strength, compressive strength, and hardness, but reduces elongation. Finer fly ash particles (FA-1) give the best improvement in these properties compared to the other sizes. In contrast, larger particles (FA-3) provide smaller increases, showing that particle size plays an important role in the overall mechanical performance.

Table3. Results of tests carried on various MMCs.

Reinforcement	Weight % of fly ash	Ultimate tensile strength (UTS) in Mpa	Ultimate compressive strength (UCS) in Mpa	Brinell hardness (BHN)	% Elongation
Fly ash with particle size 5- 20µm (FA-1)	0	124	388.8	47.5	9.6
	5	129	498.8	65.5	7.2
	10	133	517.4	76.3	6.4
	15	131	535.8	84.9	5.9
Fly ash with particle size 25-30µm (FA-2)	0	124	388.8	47.5	9.6
	5	128	444.3	62.4	6.7
	10	130	472.1	68.8	5.4
	15	129	527.6	80.4	4.8
Fly ash with particle size 50-60µm (FA-3)	0	124	388.8	47.5	9.6
	5	126	416.6	56.8	6.1
	10	128	449.8	62.4	5.3
	15	127	488.8	76.3	4.5

Table 4. ANOVA table for mechanical properties.

Property	Sum of squares	Mean square	F-value	p-value	R^2 Value
Tensile Strength	18.75	18.75	25.00	0.0041	0.9593
Compressive Strength	30359.46	10119.82	25.51	0.0002	0.9054
Hardness	1829.46	609.82	67.61	< 0.0001	0.9621
Ductility	3.97	3.97	34.83	0.0020	0.9853
Optimum values for performances					
FA%	FA	TS	CS	HV	D
15.000	FA1	131.750	547.050	84.555	6.065

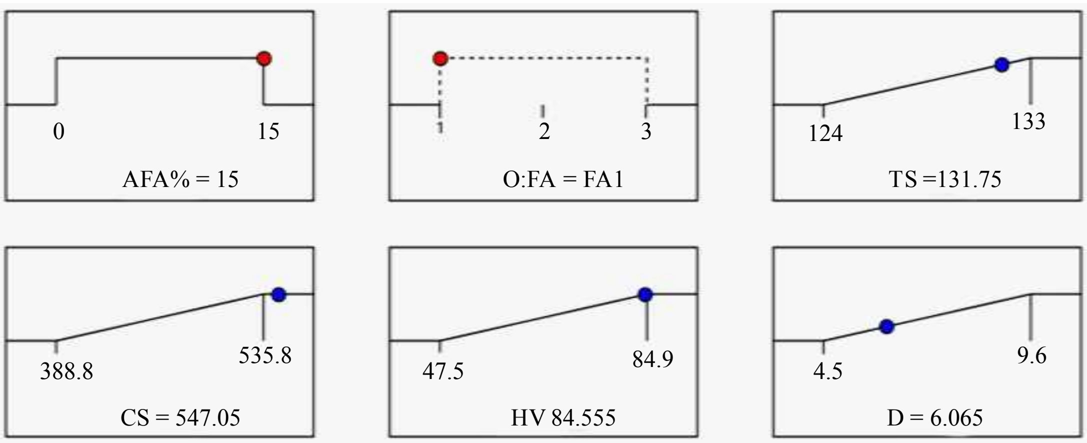

Figure 8. Ramped plot for optimized result.

A mathematical analysis using Central Composite Design (CCD) was conducted to model, validate, and optimize the particle size and weight percentage of fly ash for maximizing properties of the AL6061/fly ash metal matrix composite. The Analysis of Variance (ANOVA) in Table 4 shows P-values below 0.05 for all four properties, indicating a significant model for reliable prediction of values not yet tested experimentally. High R^2 values, close to unity, suggest minimal noise in the model [17] Optimization results in Table 4 show that optimal property enhancement occurs at a fly ash particle size of 5-20µm and 15% reinforcement. Figure 8 presents the ramped plot for the optimized result. A test experiment is pending to validate these optimized conditions.

CONCLUSION

Based on a variety of mechanical and microstructural investigations, the following findings were reached.

- *Production and testing of MMCs:* MMCs with fly ash as reinforcement were successfully produced and tested for various mechanical and tribological properties. It was found that the fly ash content can be increased up to 15% by weight.
- *Mechanical properties:* An increase in the weight % of fly ash was shown to improve the MMCs' mechanical qualities.
- *Ultimate tensile strength*: The weight % of fly ash resulted in an increase in the ultimate tensile strength. However, for composites containing 15% fly ash, a reduction in tensile strength was observed. By adding 10% fly ash, the tensile strength increased by 3.9% and 6.4% for particle sizes ranging from 5 to 20 µm. However, strength was shown to diminish at 15% fly ash.
- *Ultimate compression strength and hardness:* Both the ultimate compression strength and hardness were found to increase with the rise in fly ash content. However, a noticeable decrease in these values occurred with larger fly ash particle sizes.
- *Ductility:* As the weight percentage of fly ash in the composite increased, its ductility dropped.

In conclusion, the study demonstrates that the addition of fly ash as a reinforcement in AL6061 aluminum matrix composites improves mechanical strength properties, especially with smaller particle sizes and optimal weight percentages. Mathematical modeling using Central Composite Design (CCD) effectively predicted optimal parameters, with the best performance observed at a fly ash particle size of 5-20µm and 15% reinforcement. The ANOVA results confirm a strong predictive model, with high R^2 values and statistically significant P-values (<0.05), indicating reliability in untested predictions. These findings highlight the potential of optimized fly ash reinforcement for enhanced mechanical properties, though experimental validation of the predicted optimal combination is still required.

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