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# Evaluation of Microstructural and Mechanical Behavior of Al319-Fly Ash Hybrid Composites Processed by Stir Casting

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***Abstract***
*This study investigates the mechanical and microstructural characteristics of Al319 aluminum alloy reinforced with varying weight percentages (3.5–9.5 wt.%) of dry fly ash, fabricated using the stir casting technique. The influence of fly ash reinforcement on tensile strength, microstructural evolution, and fracture behavior was systematically analyzed. The tensile testing results revealed that Sample 2, containing 5.5 wt.% fly ash, exhibited the highest ultimate tensile strength (157.74 MPa), surpassing the base Al319 alloy (140 MPa). The enhancement in mechanical properties was attributed to grain refinement and uniform dispersion of reinforcing particles. However, excessive fly ash content (7.5–9.5 wt.%) led to a decline in tensile strength due to microstructural defects and increased porosity. The stress-strain behavior indicated that optimized reinforcement contributes to improved strength and ductility. Samples with increased fly ash content exhibited brittle fracture features based on scanning electron microscopy (SEM) analysis, whereas mixed-mode failure was noted in the optimally reinforced sample. Balancing strength with toughness, these are the applications and its implications of fly ash-reinforced Al319 composites in structural and automotive applications.*
***Keywords:*** *Al319 aluminum alloy, Hybrid metal matrix composite, Fly ash reinforcement, Stir casting, Tensile strength, Mechanical properties, Microstructural analysis*

## INTRODUCTION

Recently, Metal Matrix Composites (MMCs) have gained much interest due to their superior mechanical properties, including high strength-to-weight ratio, higher wear resistance, and higher thermal stability. They are used widely in aerospace, automotive, and structural applications where durability and performance are critical [1]. Among various matrices of metals, Al-based composites are especially preferred due to their low weight, corrosion resistance, and high machinability [2]. Aluminum alloy Al319 is one of the most common casting alloys and possesses advantages such as a good castability, corrosion resistance, and mechanical properties [3]. Aluminum alloys are commonly used for automotive applications, in particular, aluminum silicon (Al-Si) alloys are often used in automotive manufacturing for low density, high strength-to-weight ratio, and high castability [4]. Such alloys are especially fitted for elements like cylinder heads, pistons, and cylinder blocks, and so on. Al-Si alloys have a diverse microstructure, comprising principal and eutectic phases of various components including eutectic silicon and other intermetallic compounds [5]. Al-Si Alloys have different metalloid (such as zinc and copper) content, along with other elements such as Magnesium and Iron, based on the base material percentage. The mechanical properties of the alloy are strongly affected by the size, shape and distribution of the second Al-Si phase [6]. Yet, the mechanical strength and wear resistance of these alloys can be enhanced with the addition of appropriate reinforcement materials [7]. The use of hybrid metal matrix composites (HMMCs), in which two or more types of reinforcement materials are used, is a strategic concept that has emerged because of advantageous aspects of various reinforcement materials utilized [8]. An example of such reinforcing material is fly ash, an abundant, low-cost by-product of coal combustion, possessing ceramic properties, which makes it one of the appropriate reinforcing materials for low-weight composite materials [9]. Stir casting is the cheapest and simple method to produce Metal Matrix Composites because uniform dispersion is obtained in metal matrix [10].

The objective of this experimental study involves fabricating the hybrid matrix composites from the fly ash reinforcement by utilizing the stir casting technique. This study aims at characterizing the mechanical and micro-structural properties of the prepared composites and to investigate the effect of fly ash reinforcement on the performance of PMC. This study is aimed at exploring the feasibility of developing Al319-fly ash hybrid composites for advanced engineering applications by investigating the Crucial properties like tensile strength, hardness, wear resistance, and microstructural evolution. The results are expected to contribute to industrial applications in complex manufacturing processes and to the advancement of sustainable materials.

## MATERIALS AND METHODS

In this study, Aluminum Alloy Al319 serves as the base matrix material, sourced from the Sahibabad Industrial Area, Ghaziabad, India. The chemical composition of Al319 was analyzed at AJEO Testing Lab and Consultancy LLP following the ASTM E 1251-2017 standard. The chemical testing results are presented in Table 1

Table 1: Chemical Composition of Al319 Alloy (Test Method ASTM E 1251-2017)

| Elements | Composition (%) |
|---|---|
| Aluminum | 85.460 |
| Silicon | 10.890 |
| Copper | 1.880 |
| Iron | 0.748 |
| Magnesium | 0.108 |
| Zinc | 0.490 |
| Manganese | 0.238 |
| Nickel | 0.033 |
| Lead | 0.054 |
| Tin | 0.008 |
| Titanium | 0.038 |

The dry fly ash used in this study was obtained from NTPC Dadri, G.B. Nagar, Uttar Pradesh. As an industrial by-product of coal combustion, dry fly ash was selected as a reinforcement material due to its low density, cost-effectiveness, and favorable ceramic properties. The chemical composition of Dadri Fly Ash is provided in Table 2.

Table 2: Chemical Composition of Dry Fly Ash

| Chemical Compound | Composition (%) |
|---|---|
| Silicon Dioxide ($SiO_2$) | 59.00 |
| Alumina ($Al_2O_3$) | 29.00 |
| Iron Oxide ($Fe_2O_3$) | 6.50 |
| Calcium Oxide (CaO) | 1.80 |
| Magnesium Oxide (MgO) | 1.44 |
| Sodium Oxide ($Na_2O$) | 0.80 |
| Sulphur Trioxide ($SO_3$) | 0.28 |
| Potassium Oxide ($K_2O$) | 0.10 |

Figure 1 presents the conceptual design for producing a hybrid composite material using Al319 and dry fly ash. The composite was fabricated through the stir casting method. Initially, Aluminum Alloy (Al319) was melted at 750°C in a muffle furnace, while ball-milled dry fly ash was preheated to 350°C. The preheated fly ash was then introduced into the molten Al319 alloy. A secondary stirrer was employed to ensure uniform dispersion of the reinforcing particles within the aluminum matrix. Four different composite compositions were developed using the stir casting technique, as outlined in Table 3.

Table 3: Composition of Al319-Dry Fly Ash based Hybrid Composites

| Sample No | Matrix Material | % Wt (Dry Fly ash) |
|---|---|---|
| Sample 1 | Al319 | 3.5 |
| Sample 2 | Al319 | 5.5 |
| Sample 3 | Al319 | 7.5 |
| Sample 4 | Al319 | 9.5 |

Throughout the process, argon gas was continuously supplied to the composite's surface to prevent oxidation. Figure 1 illustrates the evolution of hybrid composite technology.

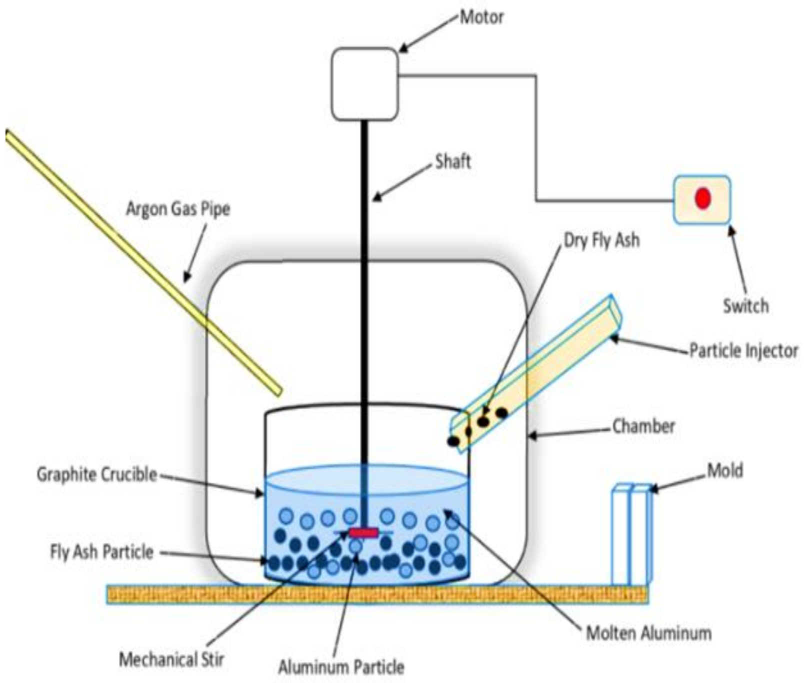


**Fig 1** Schematic setup of hybrid composite stir casting process used during the fabrication.

## RESULTS AND DISCUSSION

### Mechanical Properties

Figure 2(A) presents the engineering stress–strain curves for Samples 1 to 4, showing the mechanical behavior of Al319-based composites reinforced with varying fly ash contents. It is evident from the curves that Sample 2 demonstrates the highest engineering stress, followed by Sample 1, indicating improved strength at an optimal fly ash content. As the reinforcement content increases further (Samples 3 and 4), a noticeable reduction in both strength and ductility is observed. The initial linear region of each curve represents elastic deformation, followed by yielding and strain hardening. Sample 4, with the highest fly ash content, exhibits the lowest engineering stress and strain values, which may be attributed to increased porosity, poor particle dispersion, or reduced matrix ductility caused by excessive reinforcement. The comparative trend confirms that moderate reinforcement enhances the composite's strength, while excessive fly ash leads to early failure and reduced mechanical performance.Figure 2(B) shows the corresponding true stress–strain curves, which provide a more accurate representation of material behavior, particularly during plastic deformation [11]. Unlike engineering stress, true stress accounts for the actual cross-sectional area during deformation, thus presenting higher stress values beyond the yield point. In this figure, Sample 4 surprisingly shows the highest true stress value, indicating better strain hardening behavior despite lower engineering stress performance. This might be due to localized deformation and strain concentration around fly ash particles, leading to greater work hardening. However, the true strain values for Samples 3 and 4 remain relatively lower, suggesting a compromise in ductility with increased reinforcement. The overall trend from both plots highlights the critical role of reinforcement content in balancing strength and ductility, with Sample 2 showing optimal mechanical behavior among the tested composites.

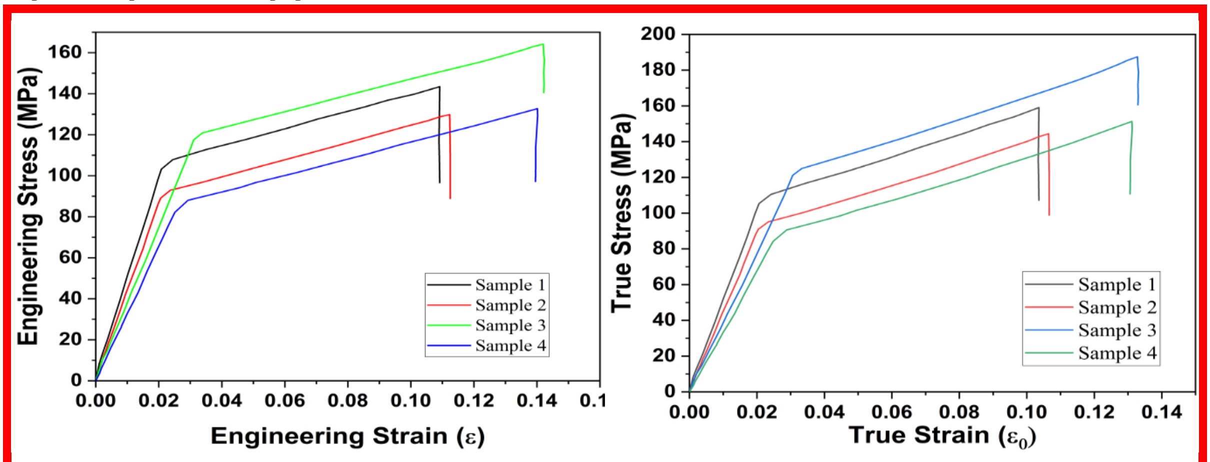


Figure 2: (a)Engineering Stress vs Strain diagram of Sample (1-4) (b) True Stress vs True Strain diagram of Sample (1-4)

Figure 3 illustrates the variation in ultimate tensile strength (UTS) across four samples of Al319-based composites reinforced with different weight percentages of fly ash. Sample 2 exhibits the highest UTS value of 157.474 MPa, indicating an optimal reinforcement-matrix interaction at that particular fly ash content. Conversely, the tensile strength values show a gradual decline from Sample 2 to Sample 4, with Sample 4 recording the lowest UTS of 130.176 MPa. This reduction in strength at higher fly ash contents may be attributed to increased porosity, particle agglomeration, or weak interfacial bonding, which can serve as stress concentrators and hinder effective load transfer between the matrix and reinforcement. Overall, the results suggest that while moderate fly ash addition enhances the mechanical strength of the Al319 matrix, excessive reinforcement content may adversely impact its tensile performance.

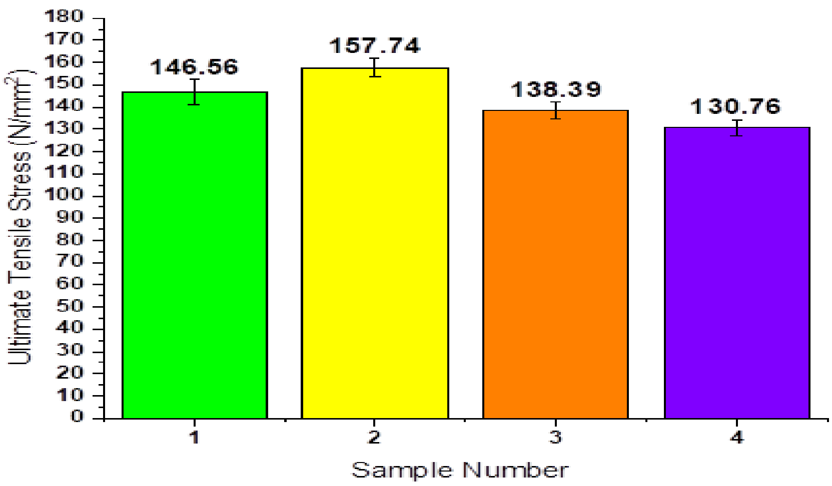


**Figure 3:** Ultimate tensile stress of Sample (1-4)

### 3.2 Scanning Electron Microscopy

The scanning electron microscopy (SEM) images presented in Figure 4 (a–d) depict the microstructural characteristics of the Al319-fly ash hybrid metal matrix composites at a 10,000× magnification. These images reveal differences in particle distribution, morphology, and bonding properties, all of which affect the composite's mechanical performance. Figures 4 (a) and 4 (c) display a well-distributed arrangement of fly ash particles within the Al319 matrix, suggesting effective wettability and interfacial bonding. However, the presence of micro-cracks and voids in Figure 4 (c) indicates possible processing defects or suboptimal interfacial adhesion, which could serve as stress concentration points and diminish mechanical strength [15]. In contrast, Figure 4 (b) shows a relatively uniform microstructure exhibiting minimal agglomeration, which is essential for achieving homogeneous mechanical performance. Additionally, the smooth surface morphology suggests effective integration of reinforcement particles, thereby improving load transfer efficiency and resistance to deformation [14,16]. Conversely, Figure 4 (d) features a striated surface with directional texture, likely resulting from plastic deformation or external forces during fabrication. This pattern is often linked to shear band formation due to non-uniform stress distribution, potentially affecting wear resistance and fracture behavior, as noted in comparable hybrid aluminum composites [17]. The microstructural analysis indicates that the addition of fly ash as reinforcement leads to grain refinement, improved dispersion, and better interfacial adhesion. These factors are crucial for enhancing the mechanical performance of Al319-fly ash composites. Nonetheless, the presence of micro-voids and agglomeration in certain areas may necessitate the optimization of processing parameters, including stirring speed and reinforcement pre-treatment, to improve composite integrity and overall durability.

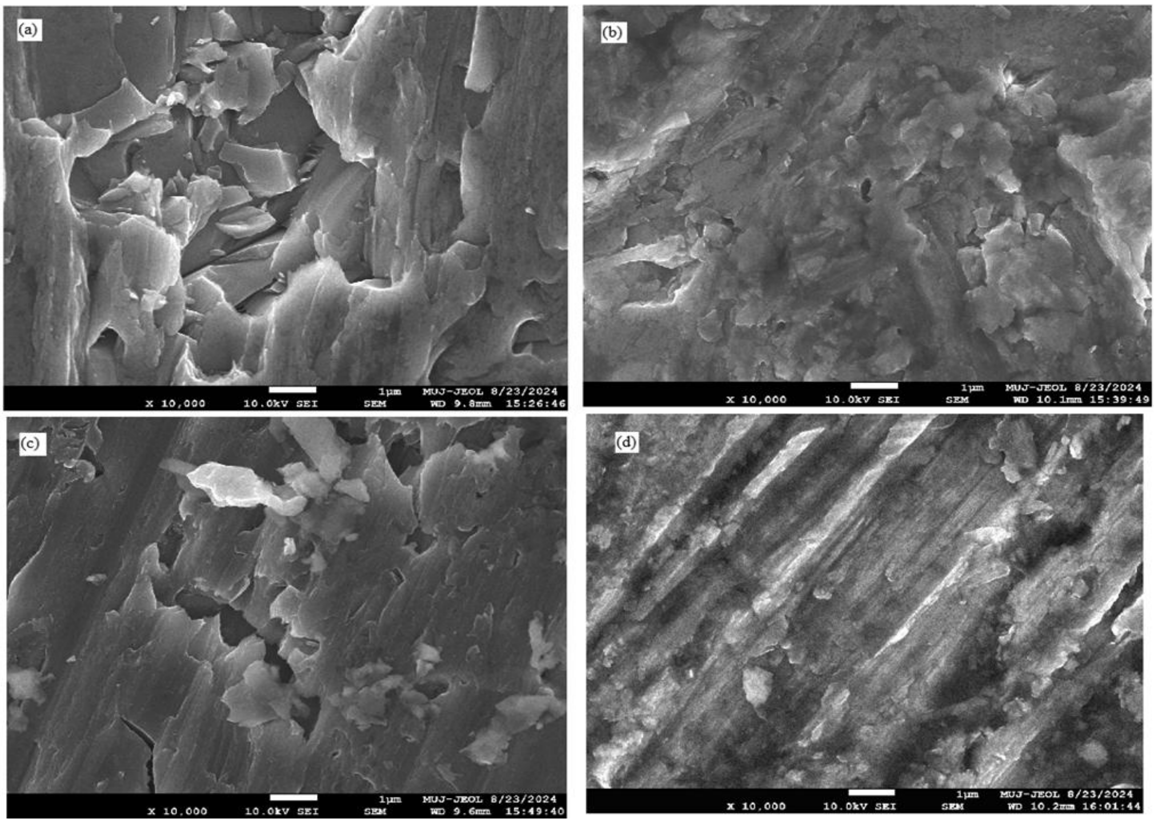

**Fig 4 (a-d)** The scanning electron microscopy (SEM) images of the Sample 1-4

### 3.3 XRD Analysis and Residual Stress Evaluation

X-ray diffraction (XRD) analysis was carried out to investigate the phase composition and crystallographic features of the Al319 matrix composites reinforced with fly ash particles. Figure 5 shows the XRD patterns of Sample 3 (Al319 + 7.5 wt% fly ash) and Sample 4 (Al319 + 9.5 wt% fly ash), both fabricated via the stir casting process. The major diffraction peaks observed in both samples correspond to the face-centered cubic (FCC) structure of aluminum. No significant shifts in the peak positions were detected, indicating that the incorporation of fly ash does not alter the primary crystal structure of the Al matrix. However, minor peaks related to possible secondary phases such as $SiO_2$, mullite ($3Al_2O_3 \cdot 2SiO_2$), or $Al_2O_3$ common constituents of fly ash may also be present.

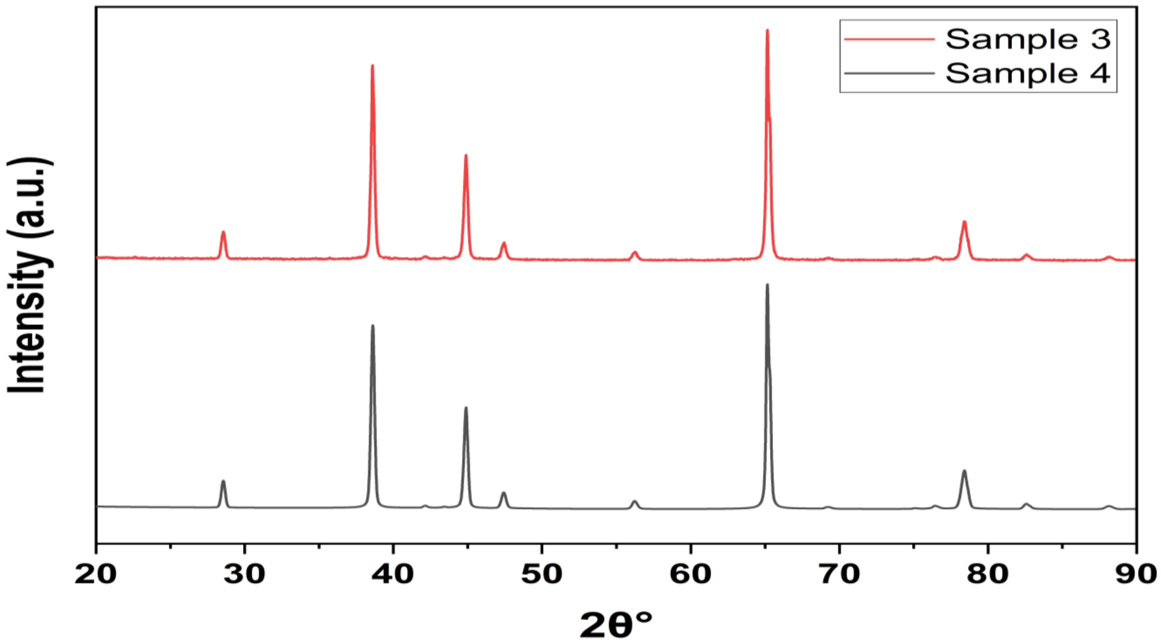


Figure 5: XRD patterns of Sample 3 (Al319 + 7.5 wt% fly ash) and Sample 4 (Al319 + 9.5 wt% fly ash)

A notable difference between the two samples is observed in the intensity and broadness of the peaks. Sample 3 exhibits sharper and more intense peaks compared to Sample 4, suggesting a relatively higher degree of crystallinity and lower lattice imperfections. In contrast, the peaks of Sample 4 are broader and less intense, which can be attributed to increased lattice strain and microstructural refinement. This broadening effect is often associated with microstrain, reduced crystallite size, and higher dislocation density, all of which are typical consequences of reinforcement addition and thermal mismatch effects during solidification.

To quantify the residual stress in the samples, the Full Width at Half Maximum (FWHM) of the diffraction peaks was analyzed [12,13]. An increase in FWHM is generally indicative of higher internal stresses and smaller crystallite sizes. The residual stresses develop due to the difference in thermal expansion coefficients between the aluminum matrix and the fly ash particles, leading to localized strain fields during the cooling phase of the stir casting process. In Sample 4, the higher fly ash content (9.5 wt%) contributes to an increased number of matrix–particle interfaces, thereby enhancing the likelihood of strain accumulation and dislocation generation.

Furthermore, the micro strain induced by these residual stresses can be estimated using the Williamson-Hall method, where a plot of $\beta cos\theta$ versus $4sin\ \theta$ allows for the separation of crystallite size and strain effects. From the slope of this plot, microstrain can be calculated and subsequently used to estimate the residual stress using the relationship1:

$$\sigma = \frac{E\varepsilon}{1+\nu} \quad (1)$$

where E is the Young's modulus of aluminum and ν is the Poisson's ratio. Although a complete quantitative evaluation requires precise numerical FWHM values, the qualitative analysis based on peak broadening clearly indicates that Sample 4 experiences greater residual stress compared to Sample 3 due to its higher fly ash content [18]. The XRD results demonstrate that the addition of fly ash to the Al319 matrix significantly influences the internal structure of the composite. Increased reinforcement content leads to higher residual stress and microstrain, which are manifested in the broadening of XRD peaks. These effects can have critical implications for the mechanical performance and thermal stability of the fabricated composites [19].

## CONCLUSION

1. The addition of dry fly ash as a reinforcement in Al319 alloy significantly impacts its mechanical properties. Sample 2, containing 5.5 wt.% fly ash, displays the highest ultimate tensile strength at 157.74 MPa, exceeding that of the base Al319 alloy, which is 140 MPa.
2. The stress-strain behavior indicates that optimal reinforcement content enhances both strength and ductility, whereas excessive fly ash content leads to premature failure due to microstructural defects and clustering of Si-rich phases.
3. Fractographic analysis using SEM confirms that Sample 2 demonstrates a mixed-mode fracture, indicating improved strain accommodation, while Samples 3 and 4 exhibit brittle fracture due to excessive reinforcement, resulting in stress concentration sites.
4. The presence of fine Si particles dispersed within the Al matrix contributes to strengthening effects, but beyond a critical concentration, embrittlement and porosity reduce mechanical performance.
5. The stir casting technique successfully dispersed the fly ash particles, but further process optimization is required to minimize defects such as porosity and segregation, ensuring uniform reinforcement distribution.
6. The findings demonstrate the potential of Al319-fly ash hybrid composites for lightweight structural applications, particularly in the automotive and aerospace sectors, where an optimal balance between strength and weight is essential.

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**Data Availability** All data sets utilized in this study, whether collected or analyzed, are available from the corresponding author upon reasonable request.

**Declarations**

The author's declare that there are no potential conflicts of interest related to this work.

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