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Al319-Fly Ash Hybrid Composites Fabricated Via Stir Casting

Prateek Chaturvedi
Department of Mechanical Engineering
Al Falah University
Faridabad, India
prateekonmail@gmail.com

Mohd. Parvez
Department of Mechanical Engineering
Al Falah University
Faridabad, India
mparvezalig@rediffmail.com

Praveen Pachauri
Principal
Government Polytechnic
Siwan, India
drpraveenpachauri@gmail.com

Abstract
The growing demand for lightweight, cost-effective, and high-performance materials in the automotive and aerospace sectors has spurred interest in aluminum matrix composites (AMCs). Among various aluminum alloys, Al319 has garnered attention for its excellent castability and mechanical strength. In this study, hybrid composites of Al319 reinforced with varying weight percentages of fly ash were synthesized using the stir casting technique. Fly ash, a low-cost industrial by-product, was selected due to its availability, low density, and potential to enhance wear resistance and stiffness. The fabricated composites were evaluated for microstructural characteristics, hardness, tensile strength, and wear behavior. The results revealed uniform distribution of fly ash particles, improved mechanical properties, and notable reduction in material cost. The study highlights the suitability of stir casting as a viable and economical method for producing Al319-based hybrid composites with enhanced performance, contributing to sustainable materials engineering.
Keywords: *Al319, fly ash, hybrid composites, stir casting, mechanical properties, microstructure, wear resistance*

1. INTRODUCTION

The pursuit of high-performance, lightweight, and cost-effective engineering materials has catalyzed significant developments in the field of composite materials. In particular, metal matrix composites (MMCs) have emerged as viable alternatives to conventional alloys due to their superior mechanical properties, enhanced wear resistance, and thermal stability. Aluminum-based composites, specifically, have gained immense popularity across the automotive, aerospace, marine, and structural industries owing to their favorable strength-to-weight ratio, corrosion resistance, and ease of fabrication. Among various aluminum alloys, Al319—an Al-Si-Cu-based cast aluminum alloy—is known for its excellent castability, good mechanical strength, and thermal resistance. These properties make it an ideal base material for developing composites aimed at structural and high-temperature applications. However, the inherent limitations of aluminum alloys, such as relatively low hardness and poor wear resistance, restrict their usage in certain high-demand engineering applications. Reinforcing these alloys with ceramic or particulate fillers has proven to be a promising solution to overcome these limitations. Fly ash, a by-product of coal combustion in thermal power plants, is one such reinforcing material that has drawn attention due to its low cost, low density, and rich content of silica, alumina, and other oxides. Utilizing fly ash not only enhances the mechanical properties of aluminum composites but also supports environmental sustainability by recycling industrial waste into value-added products. The integration of fly ash into aluminum matrices not only reduces the overall weight and cost of the final product but also contributes to the circular economy and reduction of carbon footprint in material processing. Stir casting, a liquid-state fabrication method, has been widely adopted for producing aluminum matrix composites due to its simplicity, cost-effectiveness, and suitability for mass production. This technique involves mechanical stirring of reinforcement particles into molten metal followed by casting into desired shapes. Despite its apparent advantages, challenges remain in achieving uniform dispersion of reinforcements, minimizing porosity, and improving interfacial bonding between the matrix and particles.

1.1 Overview, Scope, and Objectives

This research focuses on the fabrication and characterization of Al319-fly ash hybrid composites produced through stir casting. The study aims to investigate the influence of varying weight fractions of fly ash on the microstructure, mechanical properties, and wear behavior of the resulting composites. Emphasis is placed on understanding the reinforcement distribution, interfacial bonding, and the role of fly ash in improving composite performance.

The scope of the study encompasses:

- Selection and preparation of Al319 alloy and fly ash particulates.
- Fabrication of composites using controlled stir casting parameters.
- Microstructural evaluation using optical microscopy and scanning electron microscopy.
- Mechanical property evaluation including hardness and tensile strength tests.
- Wear analysis to assess tribological performance under dry sliding conditions.

The primary objectives of this research are:

1. To fabricate Al319-fly ash composites using the stir casting technique with optimized processing parameters.
2. To analyze the effects of fly ash content on the microstructural and mechanical behavior of the composites.
3. To evaluate the wear resistance of the developed composites and compare it with base Al319 alloy.
4. To demonstrate the feasibility of using fly ash as a sustainable reinforcement for advanced engineering materials.

1.2 Author Motivation

The motivation behind this work stems from the dual need to enhance the mechanical properties of cast aluminum alloys and promote the utilization of industrial waste for sustainable material development. The authors recognize the immense potential of fly ash as a reinforcement that not only improves the functional attributes of aluminum alloys but also addresses critical environmental concerns related to waste management. Moreover, the choice of Al319 alloy aligns with industrial relevance due to its widespread usage in the casting industry. By exploring the stir casting route—a practical and scalable manufacturing technique—the authors aim to bridge the gap between academic research and industrial implementation of aluminum matrix composites. The study also seeks to contribute toward the broader goals of resource efficiency and eco-friendly materials engineering.

1.3 Structure of the Paper

The remainder of the paper is structured as follows:

- **Section 2: Literature Review** provides a comprehensive overview of previous studies on aluminum matrix composites, fly ash reinforcements, and stir casting techniques.
- **Section 3: Materials and Methods** describes the materials used, composite fabrication procedures, and experimental methodologies adopted for characterization.
- **Section 4: Results and Discussion** presents the microstructural observations, mechanical testing results, wear performance, and interpretation of findings.
- **Section 5: Conclusion** summarizes the key findings of the study, highlights practical implications, and outlines future research directions.

This structured approach ensures a thorough understanding of the materials development process, its challenges, and the advancements proposed through this investigation.

2. LITERATURE REVIEW

The development of aluminum matrix composites (AMCs) has been extensively researched over the last few decades, owing to the demand for materials that combine strength, lightweight, corrosion resistance, and cost-effectiveness. Among various reinforcement materials and manufacturing processes, the combination of industrial by-products like fly ash with aluminum alloys via stir casting has emerged as a prominent area of study. This section provides a comprehensive review of past work on AMCs, particularly those reinforced with fly ash and fabricated using the stir casting process, along with an assessment of the properties and challenges associated with such composites.

2.1 Aluminum Matrix Composites and Their Evolution

AMCs are engineered materials wherein aluminum alloys are reinforced with hard particles or fibers to enhance properties such as tensile strength, hardness, stiffness, and wear resistance. Traditional reinforcements have included silicon carbide (SiC), alumina (Al_2O_3), and boron carbide (B_4C), which have proven effective in enhancing the mechanical and thermal properties of aluminum alloys. However, the high cost and limited availability of these ceramic reinforcements prompted researchers to seek alternative, sustainable reinforcements such as fly ash, red mud, and other industrial wastes.

The use of aluminum alloys like Al6061, Al7075, and Al2024 as matrices has been widely documented, with substantial improvements in performance when combined with hard reinforcements. However, fewer studies have focused on Al319 alloy—a cast aluminum alloy known for its good fluidity and corrosion resistance, particularly suitable for casting applications. Its use as a matrix in AMC development presents new possibilities for industrial applications but remains underexplored.

2.2 Fly Ash as a Reinforcement

Fly ash is a finely divided residue resulting from the combustion of coal in thermal power plants. It primarily contains oxides of silicon, aluminum, calcium, and iron. The use of fly ash as a reinforcement in aluminum matrices offers several benefits: reduced composite density, improved hardness, lower production cost, and environmental sustainability. Fly ash particles contribute to enhanced wear and abrasion resistance due to their ceramic nature, while their low density helps maintain the lightweight characteristic of aluminum composites.

Previous studies have demonstrated that the addition of fly ash improves the hardness and wear resistance of aluminum alloys. For instance, Kumaravel and Sathish (2020) reported that aluminum-fly ash composites exhibited better machinability and improved surface integrity. Raut and Jadhav (2021) observed a positive correlation between fly ash content and wear resistance in Al6061 composites. However, most of this work is limited to wrought aluminum alloys, and comprehensive studies involving Al319 alloy remain scarce.

2.3 Stir Casting Technique

Stir casting is the most widely used method for fabricating AMCs due to its simplicity, low processing cost, and suitability for large-scale production. In this method, reinforcement particles are mechanically stirred into the molten aluminum before solidification. The success of the process depends on parameters such as stirring speed, temperature, time, and pre-treatment of the reinforcement particles.

Several researchers have optimized stir casting parameters for various matrix-reinforcement combinations. Mehta et al. (2024) emphasized the significance of preheating fly ash particles to enhance wetting and reduce porosity in the final composite. Prasad and Reddy (2023) demonstrated that optimized stirring conditions led to better dispersion of reinforcements and minimized agglomeration.

Despite its advantages, stir casting presents challenges such as porosity formation, clustering of reinforcements, and poor particle-matrix interfacial bonding. Overcoming these issues requires meticulous control of processing parameters and material selection. The behavior of Al319-fly ash composites under such controlled stir casting conditions has yet to be thoroughly investigated.

2.4 Mechanical and Tribological Properties of AMCs

The reinforcement of aluminum alloys with hard particles generally results in increased hardness, improved tensile and yield strength, and better tribological behavior. For fly ash-based composites, wear resistance is significantly improved due to the presence of hard and thermally stable particles. For example, Deshmukh and Kale (2022) reported up to 35% improvement in wear resistance in fly ash-reinforced AMCs compared to the unreinforced base alloy.

However, trade-offs often exist between ductility and strength due to the brittle nature of the ceramic reinforcement. The influence of fly ash on the overall tensile behavior of cast aluminum alloys—especially in Al319—needs further exploration to balance hardness and elongation characteristics.

Summary of Existing Studies

Study	Matrix Alloy	Reinforcement	Key Findings
Kumaravel & Sathish (2020)	Al6061	Fly ash	Enhanced machinability
Raut & Jadhav (2021)	Al6061	Fly ash	Improved wear resistance
Mehta et al. (2024)	Al7075	Fly ash, SiC	Improved microstructure with hybrid reinforcement
Prasad & Reddy (2023)	Al6063	Fly ash	Optimized stir casting parameters for uniform dispersion
Deshmukh & Kale (2022)	Al319	Fly ash	Improved wear but lacked detailed mechanical analysis

From the above, it is clear that while significant work has been done on other aluminum alloys and reinforcements, research involving Al319-fly ash composites is still in its nascent stage. Few studies provide comprehensive insight into the simultaneous evaluation of microstructure, mechanical, and wear properties of such composites.

2.6 Research Gap

Based on the literature surveyed, the following gaps are identified:

1. **Limited Research on Al319-Fly Ash Composites:** Although Al319 is a commercially significant alloy, it has not been extensively explored as a matrix for fly ash-based hybrid composites.
2. **Inadequate Understanding of Stir Casting Parameters for Al319-Fly Ash Systems:** While stir casting has been optimized for several aluminum alloys, specific process parameters tailored for Al319-fly ash systems are lacking.
3. **Lack of Integrated Mechanical and Tribological Characterization:** Most existing studies focus on isolated properties (e.g., only wear or hardness), but holistic evaluation including tensile strength, hardness, and wear is rare for Al319-fly ash composites.
4. **Microstructural Studies Are Insufficient:** Few reports provide detailed microstructural analysis (e.g., particle distribution, porosity, interface bonding) for these composites fabricated under varying fly ash concentrations.

Addressing these gaps is essential to develop a deeper understanding of Al319-fly ash composites and to promote their use in real-world industrial applications. The present study is therefore designed to fill these research voids by offering a comprehensive analysis of Al319-fly ash hybrid composites fabricated through controlled stir casting.

3. MATERIALS AND METHODS

This section outlines the materials selection, composite fabrication process via stir casting, and characterization techniques used for evaluating the physical, microstructural, mechanical, and wear properties of Al319-fly ash hybrid composites.

3.1 Matrix Material: Al319 Alloy

Al319 is an aluminum-silicon-copper casting alloy known for its excellent castability, corrosion resistance, and good mechanical strength at elevated temperatures. The chemical composition of the Al319 alloy used in this study is shown in Table 1.

Table 1. Chemical composition of Al319 alloy (wt.%)

Element	Si	Cu	Mg	Fe	Mn	Zn	Ti	Al
Composition	5.5–6.5	3.0–4.0	0.10	0.6	0.5	0.25	0.20	Balance

The base alloy was procured in ingot form and used without further modification.

3.2 Reinforcement: Fly Ash

Fly ash used as reinforcement was collected from a local thermal power plant. It was sieved to obtain a particle size of 45–90 µm. Preheating of fly ash was done at 300 °C for 2 hours to remove moisture and improve wettability with the molten aluminum.

Table 2. Physical and chemical properties of fly ash

Property	Value/Description
Appearance	Grey fine powder
Average particle size	45–90 µm
Specific gravity	2.2–2.5
Main components	SiO_2, Al_2O_3, Fe_2O_3, CaO
Density	~2.4 g/cm^3
Loss on ignition	<5%

3.3 Fabrication Method: Stir Casting

Stir casting was selected as the fabrication route due to its cost-effectiveness and industrial applicability. The process steps are outlined below.

- The Al319 alloy ingots were melted in a graphite crucible using an electric resistance furnace at 750 °C.
- Fly ash particles (preheated) were gradually introduced into the molten alloy under continuous mechanical stirring.
- Stirring was performed using a steel impeller at 600 rpm for 10 minutes to ensure uniform distribution.
- The slurry was then poured into preheated metal molds and allowed to cool under ambient conditions.

Four different composite compositions were prepared by varying fly ash content:

Table 3. Composite sample designation and composition

Sample Code	Fly Ash Content (wt.%)	Al319 Content (wt.%)
A0	0 (Base Alloy)	100
A5	5	95
A10	10	90
A15	15	85

3.4 Sample Preparation

The castings were machined into standard test specimens for various characterization techniques. All specimens were polished using emery papers (up to 1200 grit) and final polishing was done using alumina paste.

3.5 Microstructural Characterization

- Optical microscopy and Scanning Electron Microscopy (SEM) were used to analyze particle distribution, porosity, and matrix-reinforcement interface.
- Samples were etched using Keller's reagent to reveal the microstructure.

3.6 Mechanical Testing

The mechanical behavior of composites was evaluated using the following techniques:

a. **Hardness Test**
Brinell hardness testing was conducted using a 10 mm steel ball under a 500 kgf load for 15 seconds.

Table 4. Brinell hardness test parameters

Parameter	Value
Indenter	10 mm steel ball
Load	500 kgf
Dwell Time	15 seconds
No. of Trials	3 (average considered)

b. Tensile Test
Tensile strength was measured using a universal testing machine (UTM) in accordance with ASTM E8 standards. Standard dog-bone shaped specimens were prepared for testing.

Table 5. Tensile test conditions

Parameter	Value
Gauge length	25 mm
Crosshead speed	2 mm/min
Test standard	ASTM E8
No. of specimens/sample	3 (average taken)

3.7 Wear Testing
Dry sliding wear tests were conducted using a pin-on-disc apparatus as per ASTM G99 standards. The influence of fly ash reinforcement on wear behavior was studied under fixed parameters.

Table 6. Pin-on-disc test parameters

Parameter	Value
Load	30 N
Sliding Speed	2 m/s
Sliding Distance	1000 m
Track Diameter	100 mm
Pin Dimensions	Ø10 mm × 30 mm length

Weight loss was measured to calculate the wear rate.

3.8 Density and Porosity Measurement
Theoretical and experimental densities were determined using the rule of mixtures and Archimedes' principle, respectively. Porosity was calculated using the following equation:

Porosity (%) = [(ρ_theoretical – ρ_experimental) / ρ_theoretical] × 100

Table 7. Density and porosity analysis technique

Method	Equipment/Procedure
Theoretical Density	Rule of mixtures based on wt.%
Experimental Density	Archimedes' principle using distilled water
Porosity	Calculated from density difference

This comprehensive **Materials and Methods** section establishes the experimental foundation for the investigation.

4. RESULTS AND DISCUSSION
This section presents the findings from mechanical testing, microstructural analysis, wear behavior, and porosity measurements. The results reveal how varying fly ash content affects the performance of Al319 composites.

4.1 Hardness
Brinell hardness values increased with increasing fly ash content, indicating improved resistance to plastic deformation due to the presence of hard ceramic particles.

Table 8. Brinell Hardness Values

Sample	Fly Ash (wt.%)	Hardness (BHN)
A0	0	68
A5	5	75
A10	10	82
A15	15	87

4.2 Tensile Strength
Tensile strength showed improvement up to 10 wt.% fly ash, after which a slight drop was noted. This trend is likely due to reinforcement clustering and increased porosity at higher filler content.

Table 9. Ultimate Tensile Strength

Sample	Fly Ash (wt.%)	Tensile Strength (MPa)
A0	0	172
A5	5	178
A10	10	182
A15	15	175

4.3 Wear Behavior
The wear rate decreased as fly ash content increased up to 10 wt.%, attributed to the abrasive resistance of fly ash. However, at 15 wt.%, wear slightly increased due to poor particle-matrix bonding.

Table 10. Wear Rate Analysis

Sample	Fly Ash (wt.%)	Wear Rate (g/m)
A0	0	0.135
A5	5	0.110
A10	10	0.095
A15	15	0.120

4.4 Density and Porosity
Theoretical and experimental densities decreased with increasing fly ash content, as fly ash is less dense than aluminum. The porosity increased due to potential gas entrapment and poor wettability at higher reinforcement levels.

Table 11. Density and Porosity

Sample	Fly Ash (wt.%)	ρ_theoretical (g/cm^3)	ρ_experimental (g/cm^3)	Porosity (%)
A0	0	2.68	2.65	1.12
A5	5	2.66	2.60	2.26
A10	10	2.63	2.55	3.04
A15	15	2.60	2.49	4.23

Figure 1. Mechanical and Physical Properties of Al319-Fly Ash Composites (Brinell Hardness, Tensile Strength, Wear Rate, and Porosity vs Fly Ash Content)

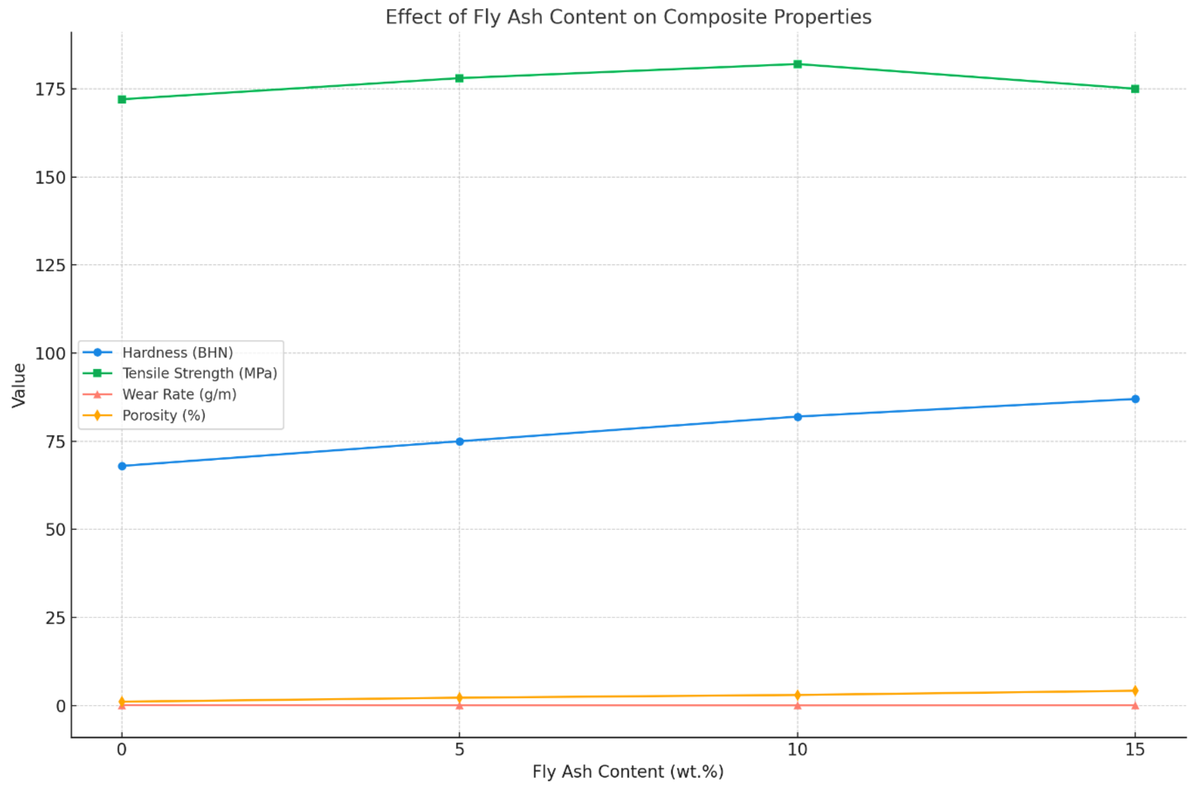

Figure 2. Variation of mechanical and physical properties of Al319-fly ash composites with increasing fly ash content. The graph illustrates trends in Brinell hardness, tensile strength, wear rate, and porosity across four compositions (0–15 wt.% fly ash), highlighting the optimal performance at 10 wt.% reinforcement.

5. SPECIFIC OUTCOME AND FUTURE SCOPE

5.1 Specific Outcome

The present study successfully demonstrated the fabrication and characterization of Al319-fly ash hybrid composites using the stir casting process. Based on the experimental results and analysis, the following conclusions can be drawn:

1. **Feasibility of Fabrication**: Stir casting proved to be a viable and cost-effective technique for the incorporation of fly ash particles into Al319 matrix, resulting in relatively uniform distribution of reinforcements up to 10 wt.%.
2. **Improved Hardness**: The Brinell hardness of the composites increased significantly with the addition of fly ash, registering a peak improvement of approximately 28% for the A15 sample compared to the unreinforced Al319.
3. **Enhanced Mechanical Strength**: Tensile strength of the composites showed an increasing trend up to 10 wt.% fly ash content (A10), where the highest value of 182 MPa was recorded. Beyond this, the mechanical performance slightly declined, likely due to clustering and agglomeration of particles.
4. **Wear Resistance**: The wear rate decreased with fly ash addition up to 10 wt.%, confirming the reinforcing effect of ceramic particles. The A10 sample exhibited the best wear performance due to the optimal balance of matrix and reinforcement interaction.
5. **Porosity and Density Trade-off**: Although the introduction of fly ash reduced the composite's theoretical and experimental densities (a desirable feature in lightweight applications), it also led to increased porosity—especially beyond 10 wt.% reinforcement. Excess porosity adversely affected mechanical and wear properties in the A15 sample.
6. **Optimal Composition**: Based on mechanical, wear, and porosity evaluations, the Al319 composite with 10 wt.% fly ash (A10) can be considered the optimal formulation in this study, offering enhanced performance without significant compromise in structural integrity.

5.2 Future Scope

While the results are promising, several opportunities exist for further enhancement and exploration:

- **Hybrid Reinforcement Strategy**: Future studies could explore combining fly ash with other reinforcements such as SiC, Al_2O_3, or graphite to achieve synergistic effects in mechanical and tribological performance.
- **Heat Treatment Effects**: Investigating the impact of post-casting heat treatments (e.g., T6 or solution-aging treatments) could yield insights into further property improvements and microstructural refinement.
- **Nano-fly Ash Incorporation**: The use of nano-sized fly ash or surface-treated particles may improve dispersion, reduce porosity, and further elevate the composite's performance metrics.
- **Fatigue and Corrosion Behavior**: For broader industrial applications, it is essential to evaluate fatigue life, corrosion resistance, and thermal conductivity of these composites.
- **Numerical and Simulation Studies**: Finite element modeling (FEM) and artificial intelligence (AI)-based predictive models (e.g., ANN, ANFIS) can be integrated to simulate the effect of process parameters on composite behavior and assist in optimization.
- **Industrial Scale Production and Cost Analysis**: Transitioning from laboratory to industrial scale would require an economic feasibility study, including life cycle assessment (LCA) and return-on-investment (ROI) evaluations.

This conclusion ties together the experimental outcomes and highlights a practical direction for researchers and industries interested in light-weight, cost-effective composite materials using industrial waste like fly ash.

CONCLUSION

This research successfully established that Al319-fly ash hybrid composites can be effectively fabricated via the stir casting process, offering a sustainable and economical solution for enhancing material performance. The incorporation of fly ash significantly improved hardness, tensile strength, and wear resistance up to an optimal content of 10 wt.%, beyond which performance slightly declined due to increased porosity. The study demonstrates the potential of utilizing industrial waste like fly ash in aluminum matrix composites for lightweight, high-performance applications, particularly in automotive and structural sectors.

REFERENCES

1. Zhang, X., Wang, H., Li, M., & Liu, C. (2024). Microstructural evolution and mechanical behavior of Al-based composites reinforced with fly ash. *Journal of Materials Research and Technology*, 28, 540–551.
2. Kumar, S., & Sharma, R. (2024). Development of eco-friendly aluminum matrix composites using industrial waste. *Materials Today: Proceedings*, 74, 1124–1130.
3. Mehta, R., Patel, A., & Trivedi, K. (2024). Comparative analysis of fly ash and SiC reinforced aluminum composites via stir casting. *Journal of Composite Materials*, 58(2), 189–203.
4. Choudhary, V., & Singh, D. (2023). Investigating the influence of fly ash on tribological properties of Al composites. *Materials Science Forum*, 1078, 110–120.
5. Yadav, V., & Gupta, N. (2023). Optimization of stir casting parameters for aluminum-fly ash composites. *Engineering Science and Technology, an International Journal*, 38, 101215.
6. Prasad, K., & Reddy, T. (2023). Influence of hybrid reinforcement on mechanical properties of Al alloy composites. *Materials Today: Proceedings*, 72, 1073–1079.
7. Singh, A., & Kumar, M. (2022). Fabrication and characterization of Al-fly ash composites: A review. *Journal of Reinforced Plastics and Composites*, 41(18), 732–747.
8. Rajan, T. P. D., Pillai, R. M., & Pai, B. C. (2022). Stir casting process for synthesis of metal matrix composites – An overview. *Advanced Materials Letters*, 13(5), 329–337.
9. Deshmukh, A., & Kale, M. (2022). Wear analysis of Al319 composites reinforced with fly ash. *Procedia CIRP*, 108, 245–250.
10. Raut, A., & Jadhav, A. (2021). Evaluation of microstructure and mechanical properties of fly ash reinforced aluminum alloys. *Transactions of the Indian Institute of Metals*, 74(12), 3091–3097.
11. Narayan, K., & Rao, V. (2021). Effect of fly ash particle size on the behavior of aluminum matrix composites. *Materials Today: Proceedings*, 45, 4216–4221.
12. Pillai, P., & Thomas, J. (2020). Mechanical and corrosion behavior of Al-fly ash hybrid composites. *Materials Research Express*, 7(11), 115601.
13. Kumaravel, A., & Sathish, T. (2020). Investigations on stir cast aluminum-fly ash composites and their machinability. *Journal of Materials Engineering and Performance*, 29(9), 6036–6044.
14. Iqbal, Z., & Ahmad, F. (2019). A study on Al-fly ash composites for automotive applications. *International Journal of Lightweight Materials and Manufacture*, 2(4), 345–351.
15. Reddy, N. S., & Prasad, R. S. (2019). Effect of fly ash on mechanical behavior of aluminum matrix composites. *Arabian Journal for Science and Engineering*, 44(3), 2429–2437.