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Development and characterization of fly ash-reinforced aluminium matrix composites using stir casting

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Abstract
Aluminium (Al) is well known for its advantageous combination of low density and a high strength-to-weight ratio. Nevertheless, ongoing research aims to further enhance its properties. This study investigates the potential of incorporating fly ash (FA)—a byproduct of coal combustion—into aluminium to develop a composite material. Due to its lightweight nature and fine particle size, FA presents a promising option for reducing the overall density of the composite while potentially maintaining or improving its mechanical strength. This research contributes to the development of lightweight and durable materials for various industrial applications. In this study, a stir-casting technique was employed to integrate varying weight percentages (5% to 20%) of FA particulates into a pure aluminium matrix. The resulting composite materials were evaluated using standard characterization techniques, including scanning electron microscopy (SEM), optical microscopy, hardness testing, tensile strength testing, and wear analysis. The findings revealed that increasing the FA content from 5% to 20% led to a progressive reduction in the overall density of the composite material. However, the influence of FA on mechanical properties such as hardness and tensile strength varied. These variations were attributed to factors such as particle size, distribution, and interfacial bonding of FA within the Al matrix. Notably, in certain cases, the incorporation of FA resulted in enhanced strength and hardness, indicating the feasibility of producing a more robust aluminium-based composite. Moreover, the study highlights that the addition of elements such as silicon (Si) and magnesium (Mg) to the Al-FA composite may further improve mechanical and wear properties. However, the extent of these enhancements depends on the specific composition, processing conditions, and the intended application of the composite material.

Keywords
Aluminium matrix composite, Fly ash reinforcement, Stir casting, Mechanical properties, Wear resistance, Density reduction.

1.Introduction
Composites have numerous engineering applications due to their enhanced properties. These characteristics are achieved by combining two or more distinct materials to form a new material with tailored functionality. The continuous phase of a composite is referred to as the *matrix*, while the discontinuous phase is known as the reinforcement [1]. The matrix is typically composed of metals, non-metals, polymers, or ceramics [2, 3].

The reinforcements may consist of materials such as silicon carbide (SiC), aluminium oxide (Al_2O_3), titanium carbide (TiC), graphite (Gr), boron carbide (B_4C), glass, and fly ash (FA), which may be introduced in the form of powders, whiskers, or fibers [4].

The field of metal matrix composites (MMCs) has been under active investigation for more than five decades, dating back to the 1960s. Metal-based composites are widely used in the aerospace, automotive, and other industrial sectors due to their superior strength, stiffness, damping capacity, thermal stability, wear resistance, and lightweight nature. However, these performance advantages often come with high manufacturing costs [5, 6].

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Compared to conventional reinforcements such as SiC, Al_2O_3, B_4C, and TiC, FA is considerably more cost-effective. FA is a major industrial byproduct from thermal power plants and is abundantly available in nature. Due to its low cost and low density, it has gained attention as a sustainable reinforcement material in composite fabrication [7–9].

Two primary forms of FA particles have been identified: cenospheres and precipitators. Cenospheres are hollow particles with a density less than 1 g/cm³, suitable for developing ultra-lightweight materials, while precipitator particles, with densities ranging from 2 to 2.5 g/cm³, are employed to enhance properties such as density and wear resistance [10, 11]. The incorporation of FA into aluminium (Al) has the potential to yield novel materials with enhanced performance characteristics, making them suitable for various applications, including aerospace, automotive, and construction sectors [12].

Recently, aluminium matrix composites (AMCs) have attracted considerable attention due to their improved mechanical and thermal properties. Reinforcements such as FA, SiC, and Al_2O_3 particles offer promising avenues for tailoring these properties. Previous studies have emphasized the need to examine the behaviour of AMCs with varying reinforcement percentages using the stir-casting method [13].

Despite extensive research on MMCs over the past five decades, achieving optimal performance while maintaining cost-effectiveness remains a hurdle. While traditional reinforcements like SiC, Alumina or Aluminium Oxide (Al_2O_3), B_4C, and TiC offer superior properties, they can be expensive. FA, a byproduct of thermal power plants, presents a more affordable alternative. However, understanding the impact of different FA particle types (cenosphere and precipitator) on composite properties (tensile strength, toughness, and hardness) and the influence of varying reinforcement percentages on MMC behavior requires further investigation and remains a challenge for future researchers [13–15]. In addition, an appropriate choice of the matrix composition that addresses the inherent contradiction between the wettability and reactivity of the reinforcement remains a major challenge in composites [5]. Moreover, the ability of load transfer from the matrix to the reinforcing material relies on strong interface bonding between them [6].

The motivation behind this research arises from the need to develop cost-effective and efficient MMC materials with enhanced mechanical properties. By investigating the influence of varying reinforcement percentages on the base aluminium alloy, this study aims to address existing research gaps and offer valuable insights for optimizing composite materials for diverse engineering applications. The primary objective of this research is to examine how variations in the percentage composition of FA, SiC particles, and Al_2O_3 affect the mechanical properties of MMCs. This includes a detailed evaluation of tensile strength, toughness, and hardness. The study utilizes the stir-casting technique to fabricate samples with different reinforcement compositions, with a particular focus on developing an affordable MMC using an aluminium-silicon-magnesium (Al-Si-Mg) alloy combined with FA. The overarching goal is to comprehensively assess the mechanical characteristics of the resulting composites to better understand their performance potential and suitability for real-world applications.

Based on the findings, aluminium–FA composites exhibit significant promise as lightweight and durable materials. The combination of aluminium's inherently low density and high strength-to-weight ratio, along with the lightweight nature of FA, results in a composite material that achieves a desirable balance between strength and weight. Mechanical testing has confirmed the composite's viability for various structural and functional applications, demonstrating tensile strength, hardness, and impact resistance that are comparable to or exceed those of conventional materials. The addition of silicon (Si) and magnesium (Mg) further enhances the composite's mechanical and wear properties, while also contributing to reduced environmental impact. Al–FA composites present a promising pathway for the development of advanced lightweight materials. Continued research is necessary to further optimize their composition and processing methods to tailor their properties for specific engineering and industrial applications.

This research contributes to the field of composite materials by:

- Investigating the impact of different reinforcement particle types and percentages on MMC properties.
- Developing an affordable and efficient MMC material using FA as reinforcement.
- Providing insights into the optimization of composite materials for various applications.

This research contributes significantly to the field of composite materials by investigating the effects of different reinforcement particle types and their varying percentages on the mechanical properties of MMCs. It focuses on the development of a cost-effective and efficient MMC material by utilizing FA as a sustainable reinforcement. Furthermore, the study provides valuable insights into the optimization of composite formulations, paving the way for their application in a wide range of engineering and industrial sectors.

This paper is organized as follows: Section 2 reviews relevant literature on MMCs, particularly FA-reinforced aluminium composites. Section 3 details the experimental methodology, while Section 4 presents the results of mechanical and microstructural analyses. Section 5 discusses the implications of the findings, and Section 6 concludes with key insights and future research directions.

2.Literature review

AMCs represent a promising class of materials with tailored properties suited for a wide range of applications. The incorporation of reinforcements such as FA, SiC, and Al_2O_3 into aluminium matrices has attracted considerable research interest due to their potential to enhance mechanical, thermal, and wear properties. This literature review examines recent advancements in understanding the behaviour of these MMCs, with a particular focus on the effects of varying reinforcement percentages of FA, SiC, and Al_2O_3.

Razzaq et al. [16] investigated the influence of FA and SiC particles on the mechanical and wear properties of AMCs. The research employed a stir casting technique to fabricate AMCs reinforced with varying weight percentages of FA and SiC particles. The study revealed that the addition of both FA and SiC particles to the aluminium matrix significantly enhanced the mechanical and wear properties of the AMCs. The tensile strength, compressive strength, and hardness of the composites increased with the addition of reinforcing particles. The optimal combination of FA and SiC content was found to be 10% FA and 10% SiC, which exhibited the highest mechanical properties. The use of FA as a reinforcement material in AMCs offers several advantages such as waste reduction, cost effectiveness and improved mechanical properties. However, the study also highlights some limitations of using FA in AMCs such as inconsistent composition, particle size distribution and potential for porosity.

Vinothkumar et al. [17] explores the impact of micro-sized SiC, Al_2O_3, and $ZrSiO_4$ particles on the mechanical properties of AA6063 MMCs, fabricated via stir casting. The study found that reinforcing AA6063 with ceramics significantly enhances tensile strength and hardness due to improved ceramic-matrix bonding. Optimal ceramic content was identified: 6–12% for AA6063-SiC and AA6063-$ZrSiO_4$, and 18% for AA6063-Al_2O_3 composites. Notably, $ZrSiO_4$ and Al_2O_3 proved most beneficial, boosting tensile strength by 53% and hardness by 127% respectively. Conversely, AA6063-$ZrSiO_4$ composites were softer than AA6063-Al_2O_3 and AA6063-SiC at similar reinforcing quantities.

Kumar et al. [18] focused on the fabrication and characterization of Al_2O_3-reinforced AMCs using the stir-casting method. Their study provided insights into the processing parameters and resulting microstructure-property relationships. The advantages of using the stir casting method for fabricating AMCs include its simplicity, low cost, and ability to produce large quantities of material. However, the method can result in a non-uniform distribution of reinforcement particles, which can affect the mechanical properties of the AMCs.

Ravindran et al. [19] conducted a comprehensive study on the mechanical behavior of aluminium MMCs containing varying percentages of FA, SiC particles, and Al_2O_3. The researchers used a stir casting process to fabricate the AMCs with different reinforcement ratios. The results showed that the addition of reinforcements significantly improved the mechanical properties of the AMCs compared to the unreinforced aluminium. The combination of FA and SiC particles provided the best mechanical properties, with a synergistic effect observed. The advantages of using FA as reinforcement in AMCs include its low cost, abundant availability, and potential for environmental benefits. The SiC and Al_2O_3 particles provided additional strength and hardness to the composites.

The limitations of the study include the relatively small sample size and the use of a single fabrication method. Further research is needed to explore the effects of different reinforcement ratios, fabrication methods, and processing parameters on the mechanical properties of AMCs.

Kök, and Özdin [20] investigated the abrasive wear resistance of 2024 aluminum alloy composites reinforced with 10, 20, and 30 wt.% Al_2O_3 particles, fabricated using a vortex method. Utilizing a pin-on-disc abrasion test, the research systematically examined the effects of sliding distance, Al_2O_3 particle content and size, SiC abrasive grit size, and wear load on wear properties. The findings indicate a significant improvement in the wear resistance of the composites compared to unreinforced aluminum alloy, increasing with higher Al_2O_3 particle content and size. Conversely, wear resistance decreased with increasing sliding distance, wear load, and abrasive grit size. Notably, the impact of Al_2O_3 particle size on wear resistance was more pronounced than that of particle content. Plastic deformation (micro-cutting and micro-ploughing) was identified as the primary wear mechanism.

Molina et al. [21] examined the thermal conductivity of aluminum matrix composites reinforced with mixtures of diamond and SiC particles of equal size. Produced through gas pressure-assisted liquid metal infiltration, the composites demonstrated a substantial increase in thermal conductivity, from 220 to 580 $Wm^{-1}K^{-1}$, as SiC was gradually replaced by diamond particles. Electrical conductivity measurements further indicated a decrease in silicon content within the matrix as diamond volume fraction increased. The findings were well‒predicted by a generalized differential effective medium scheme, which proved to be are liable tool for designing composites with specific thermal conductivity. The research highlights the potential for achieving a target thermal conductivity of 400 $Wm^{-1}K^{-1}$ with a cost-effective composition of 50-60% diamond and the remainder SiC.

Ji et al. [22] optimizes the Laser Powder Bed Fusion (LPBF) process for SiC-reinforced Aluminum Matrix Composites (AMCs), focusing on particle morphology and process parameters. Using a Box–Behnken Design, near-spherical β-SiC was selected, improving powder spreading. The research demonstrates enhanced tensile strength and plasticity in LPBF β-SiC/AlSi10Mg compared to α-SiC, attributed to better flowability and interface bonding. A chessboard scanning strategy significantly improved plasticity by forming a coarse remelted skeleton, providing a foundation for controllable SiC-reinforced AMC preparation.

Hu and Du. [23] explored the the fretting fatigue behavior of 2124 Al–Cu–Mg alloy reinforced with 17 vol% SiC particles and its monolithic counterpart. Finite element analysis (FEA) aligned with experimental observations of crack initiation and propagation. The composite exhibited superior fretting fatigue performance in the low-cycle regime due to higher wear resistance and delayed crack initiation, despite similar subsurface degradation. However, it showed inferior performance in the high-cycle regime due to weakened SiC-matrix adherence and shorter crack propagation life. These findings highlight the need to consider different material behaviors in varying cycle regimes for accurate damage modeling.

Karthikraja et al. [24] investigated the corrosion behavior of Al 7075 hybrid composites reinforced with SiC and Al_2O_3 particles (2.5-10 wt.% each), fabricated by squeeze casting. Tested in a 3.5% Sodium Chloride (NaCl) solution, the composites exhibited significantly improved corrosion resistance compared to pure Al 7075. The Al7075 + 10% SiC + 10% Al_2O_3 composite showed the lowest corrosion rate (0.9997 mmpy by weight loss, 0.630 mmpy by Tafel polarization), attributed to strong interfacial bonding.

Reddy et al. [25] conducted a parametric study to optimize the mechanical properties of AMCs using response surface methodology. Their research identified key factors influencing material performance and offered guidelines for designing and optimizing materials. The authors conducted uniaxial compaction tests to assess the compaction density and green strength of the composites. The results revealed that the addition of reinforcement improved the compaction density and green strength, with a maximum density achieved at 7.5 wt.% Al_2O_3 and 2.5 wt.% FA. The study highlights the advantages of using reinforcement in enhancing the compaction behavior of aluminium-based composites. However, a key limitation is the potential agglomeration of reinforcement particles, which may degrade the composite properties.

Mohanty et al. [26] examined the influence of FA and SiC particles on the mechanical and wear properties of AMCs. The authors fabricated composites with varying amounts of FA and SiC particles using a stir casting process. Mechanical properties, including tensile strength, hardness, and impact strength, were evaluated, while wear behavior was assessed under dry sliding conditions. The results showed that the addition of FA and SiC particles improved the mechanical properties of the composites compared to the base aluminium alloy. However, the wear resistance was found to depend on the particle composition and volume fraction. The study highlights the potential of FA-reinforced AMCs as a cost-effective and environmentally friendly alternative to conventional metal alloys. However, further research is needed to optimize the particle composition and processing parameters for improved wear resistance [26, 27].

Chak, et al. [28] provided a comprehensive overview of the available fabrication techniques, reinforcement materials, and the challenges associated with producing AMCs. It also emphasizes the importance of mechanical properties in assessing the performance of these composites. They reported that stir casting method is a simple and cost-effective technique for producing AMCs. However, it can lead to non-uniform distribution of reinforcement particles, which may affect the mechanical properties. Future research could focus on optimizing the stir casting process to achieve more homogeneous particle distribution and further improve the performance of AMCs.

Zoeram et al. [29] investigated the mechanical properties and microstructure of SiC particle reinforced AMCs. The composites were fabricated using a stir casting process. The effects of SiC particle content (0-20 wt.%) on the tensile strength, hardness, and microstructure were evaluated. Results showed that the addition of SiC particles significantly improved the tensile strength and hardness of the composites compared to the base aluminium alloy. The microstructure analysis revealed a uniform distribution of SiC particles in the aluminium matrix. However, the study also identified limitations, such as the potential for interfacial debonding and the increased cost associated with the addition of SiC particles. Overall, the study demonstrated the potential of SiC particle-reinforced AMCs as promising materials for applications requiring high strength and hardness.

Sahin [30] studied the wear behavior of aluminium alloy MMCs reinforced with FA and SiC particles. The authors utilized a pin-on-disc wear testing machine to evaluate the wear behavior of the composites under different loads and sliding speeds. The results indicated that the addition of FA and SiC particles significantly improved the wear resistance of the aluminium alloy. The composite with an optimal combination of FA and SiC particles exhibited the lowest wear rate. This enhanced wear resistance was attributed to the formation of a protective layer on the composite surface, which reduced the friction coefficient and prevented direct contact between the abrasive particles and the matrix material. While the study demonstrated the advantages of using FA and SiC as reinforcements in aluminium alloy composites, it also identified some limitations. The authors noted that the wear behavior of the composites could be influenced by factors such as the particle size distribution, interfacial bonding, and the manufacturing process. Further research is needed to fully understand the underlying mechanisms and optimize the properties of these composites for various applications.

Xiao et al. [31] analyzed the effect of processing parameters on the microstructure and mechanical properties of AMCs reinforced with Al_2O_3. The authors used a stir casting technique to fabricate composites with varying Al_2O_3 volume fractions and stirring speeds. Microstructural analysis revealed a uniform distribution of Al_2O_3 particles. Tensile strength and hardness increased with increasing Al_2O_3 content, while ductility decreased. Higher stirring speeds resulted in finer particle size and improved mechanical properties. The advantages of this study include the use of a simple and cost-effective fabrication method and the ability to tailor the properties of the composites by adjusting processing parameters. However, the study is limited to a specific range of Al_2O_3 content and stirring speeds, and the effects of other processing parameters were not investigated.

Prabu et al. [32] observed that FA is a potential reinforcing material to develop low-cost composite with improved properties. Using a stir-casting approach, Mondal et al. [33] developed cenosphere-filled aluminium syntactic foam to study its mechanical behaviour. The findings showed that the syntactic foam behaved like high-strength aluminium foam under compressive deformation. When the Cenosphere volume fraction rises, the SF plateau stress drops but the densification strain grows linearly [34]. Sharma et al. [35] reported that newly developed composites possess increasing wear resistance concerning an increase in FA contents. Furthermore, it has been found that composites with high FA composition reduced the wear by around 13.6% than those with low FA contents. Particles of FA have demonstrated very high potential as lightweight Al alloy reinforcements, resulting in improved mechanical characteristics. More precisely, when the FA content of these composites increases, the stiffness, tensile & compressive strength also increase. Conversely, as the amount of FA increases, density falls [36].

In recent years, research efforts have focused on enhancing the performance of aluminium MMCs by incorporating various types of reinforcements, such as FA, SiC particles, and Al_2O_3. FA, a byproduct of coal combustion is a lightweight and finely divided material that has shown promise as reinforcement in aluminium matrices due to its low cost and abundance. SiC particles and Al_2O_3, on the other hand, are renowned for their high strength, hardness, and thermal stability, making them ideal candidates for improving the mechanical properties of aluminium MMCs. Understanding the influence of varying percentages of these additives on the behaviour of aluminium MMCs is crucial for optimizing their performance in practical applications. Factors such as the distribution, size, and volume fraction of the reinforcements play a significant role in determining the overall properties of the composite material [37–39].

AMCs reinforced with various ceramic particles have been fabricated using a variety of traditional techniques that influenced their tribological and mechanical characteristics. The effective insertion of ceramic particles into the Al matrix and the establishment of strong bonds between them are necessary for improving the characteristics of AMCs [40, 41]. FA particles were mixed into the molten aluminium as depicted in *Figure 1*.

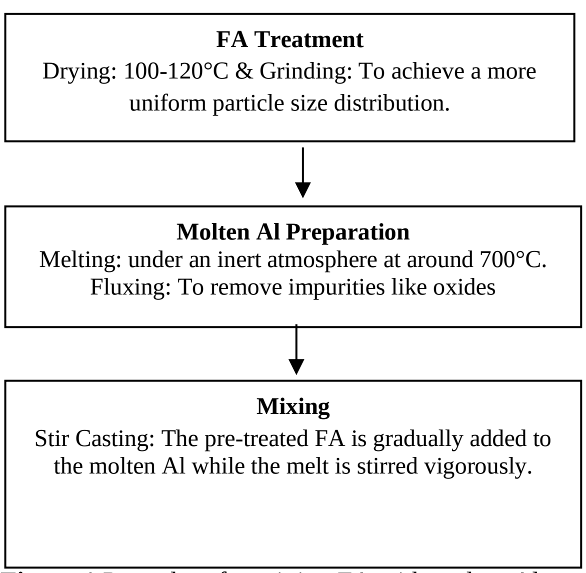

Figure 1 Procedure for mixing FA with molten Al

However, the high surface tension results in poor wettability among the constituents and the FA particles were shown to be floating on the molten aluminium surface. Since the gas layers at the particle surfaces may be the origin of the buoyant migration, mechanical stirring can be completed in a semi-solid state as opposed to a liquid state to break away the gas layers and lower surface tension. Raising the solids' surface energies, lowering the liquid matrix alloy's surface tension, & lowering the solid/liquid wettability can be improved by increasing interfacial energy at the reinforcement matrix interface. Therefore, the liquid processing stir casting technique is the preferred approach owing to its simplicity, adaptability, and suitability for large-scale manufacturing [42–44].

AMCs offer good mechanical and thermal properties and this makes them perfect for many different applications. Incorporating reinforcements such as FA, SiC particles, and Al_2O_3 into aluminium matrices offers an avenue for tailoring the performance characteristics of these composites [45]. Previous studies have underscored the importance of investigating the mechanical properties of AMCs reinforced with different proportions of FA, SiC particles, and Al_2O_3, fabricated through the stir casting technique. Key challenges include understanding how these additions affect the tensile strength, toughness, and hardness of the composites. However, understanding the impact of different percentages of these additives on the behaviour of the resulting MMCs presents a complex challenge [13–15].

The challenge is to examine the behaviour of the aluminium alloy (MMC) with different % additions of FA, SiC particles, and Al_2O_3 using the stir casting method. The tensile strength, toughness, and qualities related to hardness will also be taken into account. The experiment's goal is to investigate how changes in percentage composition affect the ability to forecast the mechanical characteristics of MMC. In recent years, research efforts have concentrated on enhancing the performance of aluminium Alloy MMCs by incorporating various types of reinforcements, such as FA, SiC particles, and Al_2O_3. FA, a byproduct of coal combustion, presents itself as a promising reinforcement due to its low cost and abundance, offering potential benefits in terms of lightweight and improved mechanical properties. SiC particles and Al_2O_3, renowned for their high strength, hardness, and thermal stability, also contribute significantly to enhancing the mechanical properties of aluminium MMCs. Understanding the influence of varying percentages of these additives on the behaviour of aluminium MMCs is crucial for optimizing their performance in practical applications [46]. Factors such as the distribution, size, and volume fraction of the reinforcements play a significant role in determining the overall properties of the composite material. Traditional fabrication techniques, such as stir casting, have been employed to effectively integrate ceramic particles into the aluminium matrix, ensuring strong interfacial bonds and improved mechanical characteristics [46]. Despite challenges such as poor wettability and uneven distribution of FA particles in the molten aluminium matrix, the stir casting method stands out as a preferred approach due to its simplicity, adaptability, and suitability for large-scale manufacturing. Further research focusing on optimizing processing parameters and understanding reinforcement-matrix interactions will undoubtedly contribute to the continued advancement and application of aluminium MMCs in various engineering fields [46].

3.Materials and methods

3.1Materials

Commercially pure Al was the matrix material employed in the experiment inquiry. Because pure aluminium has a higher thermal stability than aluminium alloys, it is chosen over other alloy matrices. Lower stability of the alloy matrix and grain coarsening are the reasons for lower working temperatures in the case of alloy matrices. Furthermore, because of the clean contact, load transmission is more efficient in the case of a pure aluminium matrix [47].

Commercially pure aluminium refers to aluminium alloys that primarily consist of the element aluminium without significant alloying elements. These alloys are known for their high corrosion resistance, excellent thermal conductivity, and relatively low strength compared to other aluminium alloys. Commercially pure aluminium is typically designated by the American Society for Testing and Materials (ASTM) system, with common grades including ASTM B209 Grade 1100, ASTM B209 Grade 1145, and ASTM B209 Grade 1200. Commercially pure aluminium alloys have high levels of purity, typically ranging from 99.0% to 99.9%. Grade 1100, for example, has a minimum aluminium content of 99.00%. However, pure Al exhibits excellent corrosion resistance, making them suitable for applications in marine environments and chemical processing industries. They also possess good thermal and electrical conductivity, making them ideal for heat exchangers, electrical conductors, and cooking utensils. However, their relatively low strength limits their use in high-stress applications.

FA is a fine powder consisting of spherical glassy particles that are produced as a byproduct during the combustion of pulverized coal in thermal power plants. It is commonly used as a supplementary cementitious material in concrete production due to its pozzolanic properties, which contribute to the strength and durability of concrete. FA can vary in composition and properties depending on factors such as coal source, combustion conditions, and particle size distribution. Common classifications include Class F (low-calcium FA) and Class C (high-calcium FA), based on their calcium oxide (CaO) content. FA typically contains varying levels of silica Oxide (SiO_2), alumina (Al_2O_3), iron oxide (Fe_2O_3), and CaO, among other constituents. Class F FA usually has a higher silica content and lower CaO content compared to Class C FA. Although, FA possesses pozzolanic properties, meaning it reacts with calcium hydroxide ($Ca(OH)_2$) in the presence of water to form compounds with cementitious properties. This reaction contributes to the strength, durability, and workability of concrete. Additionally, FA particles are spherical, which improves the flowability of concrete mixtures. FA can also improve the long-term performance of concrete by reducing permeability and mitigating alkali-silica reaction (ASR) and sulfate attack [48].

Silicon dioxide is one of the major components of FA, contributing to its structural integrity and thermal stability. Al_2O_3 provides strength and hardness to FA particles, enhancing their effectiveness as reinforcements in composite materials. Fe_2O_3 imparts colour to FA and can influence its mechanical properties. CaO and Magnesium oxide (MgO) act as fluxing agents and influence the reactivity and phase composition of FA. FA particles typically range in size from a few micrometers to submicron scales, with a distribution influenced by the combustion process and subsequent collection methods. FA particles may contain internal pores or voids, affecting their packing density and interfacial bonding with the matrix material. The surface of FA particles can vary in roughness and irregularity, influencing their adhesion to the matrix and interlocking within the composite structure. FA may exhibit pozzolanic reactivity, wherein its constituents react with calcium hydroxide in the presence of water to form cementitious compounds, enhancing the mechanical properties of composites over time [48]. FA is often considered a manufacturing waste product. Utilizing it in the composite material with aluminium may result in a cost-effective solution, especially if the FA is obtained as a byproduct from nearby industries [46]. FA recycling in Aluminium-Fly Ash (Al-FA) composites offers several environmental advantages. By incorporating FA into aluminium-based matrices, the demand for primary aluminium can be reduced, leading to energy savings and decreased greenhouse gas emissions associated with primary aluminium production [44]. Moreover, the incorporation of FA into composites can enhance their mechanical properties, extending their service life and reducing the need for replacement or maintenance, thereby lowering overall material consumption and waste generation. Additionally, Al-FA composites have the potential for end-of-life recycling. At the end of their service life, these composites can be recycled through processes such as melting and remanufacturing into new products or components, thus closing the materials loop and reducing the environmental burden associated with disposal. However, challenges related to the separation and purification of FA from other waste streams may affect the feasibility and efficiency of recycling processes. Addressing these challenges requires innovative separation technologies and effective waste management strategies to maximize the recycling potential of FA in Al-FA composites. This can contribute to the sustainability of the material. The fracture mode in particle-reinforced composites is dependent on several factors, including the degree of coherency between the second phase and the matrix, the nature of the interface, the volume fraction of reinforcement, the fabrication route taken, the amount of hot work done, and the presence of any intermetallic precipitates. FA was gathered from Guru Gobind Singh Super Thermal Power Plant Ghanauli, Ropar, Punjab. *Table 1* enumerates the main ingredients of FA that were obtained from the source and utilised as reinforcement. FA is mostly composed of SiO_2 and Al_2O_3. *Figure 2* displays the structural properties of FA particles scanned through SEM.

Table 1 Chemical composition of FA

Compounds	Weight %
SiO_2	57.2
Fe_2O_3	0.6
CaO	0.66
Al_2O_3	39.6
MgO	2.1

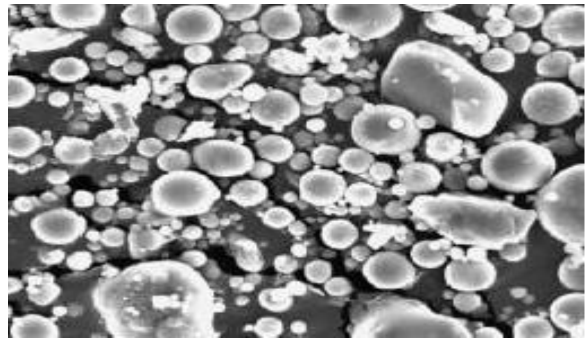

Figure 2 SEM image of FA particles

The Malvern particle size analyzer was utilized to measure the particle size of the ground powder (*Figure 3).* First, the sample holder held the liquid dispersant, which contained 500 millilitres of distilled water. After that, the device was operated with the pump speed set to 1800 rpm and the ultrasonic displacement set to 10.00 microns.

Figure 3 Malvern particle size analyzer

FA particles that were gathered from the Guru Gobind Singh Super Thermal Power Plant Ghanauli, Ropar, Punjab, FA sample exhibit a broad range of particle sizes (ranging from 0.1 to 100 µm). The manufactured composite can be classified as partially reinforced or dispersion strengthened based on the size range of the FA particles. The particle size distribution shows that both extremely small and coarse particles are present. Thus, both dispersion strengthening and particle reinforcement may contribute to the strengthening of the composite. Particle strengthening involves load sharing in the mechanism, whereas dispersion strengthening is caused by the addition of extremely small particles that aid in limiting the movement of dislocation.

3.2Fabrication of composite

AMCs can be produced using a variety of fabrication techniques, each with its own advantages and limitations. Some methods are significantly more expensive than others, and in most cases, manufacturers prefer cost-effective approaches. As a result, a substantial portion of MMCs in commercial applications are produced using the stir-casting method. In this study, stir casting was employed to fabricate MMCs from aluminium and FA, following the parameters recommended by Sahu and Sahu [49]. Initially, commercially pure aluminium and the required amount of FA particles were weighed using a high-precision electronic balance. To remove any residual moisture, the FA particles were preheated to 300°C for three hours. A resistive furnace was used to melt commercially pure aluminium. The hexachloroethane tablets were purged and the melt temperature was increased to 7200C. Next, a mild steel turbine stirrer was used to assist with the melt stir. At 200 rpm for five to seven minutes, the impeller speed was kept churning. 7000C was the melt temperature that was maintained when FA particles were added in three stages during 12 minutes of fabrication time. The vortex approach was used to disperse the FA particles. The permanent metallic mould was warmed before the melt containing reinforced particles was put into it. At 6800C, the pouring temperature was kept constant. The moulds were thereafter allowed to harden in the melt. The FA content of the composites was varied, ranging from 5, 10, 15, and 20 weight per cent. To improve the wettability of the FA particles, Si and Mg were added. *Table 2* depicts the number of composites fabricated in this study along with ingredient compositions.

By carefully controlling the mixing parameters and employing suitable stirring techniques the stir casting process facilitates the uniform dispersion of FA particles within the molten aluminium matrix.

Table 2 Ingredients and composition of composites

Composite No.	**Ingredients and their percentage**			
	Al (gm.)	**Mg %**	**Si %**	**FA%**
1	100	0	0	0
2	100	0	0	5
3	100	0	0	10
4	100	0	0	15
5	100	0	0	20
6	100	2	0	10
7	100	0	2	10

3.3Testing of composites

After the fabrication process, the material was carefully selected from defect-free areas of the casting to ensure sample integrity and reliability of test results. These sections were thoroughly cleaned to remove any contaminants that might interfere with subsequent analyses. The cleaned material was then precisely machined to create standardized samples suitable for a series of mechanical and micro-structural evaluations and the details are given as under:

3.3.1Scanning electron microscopy (SEM)

On unreinforced samples, microstructural characterization investigations were carried out. The SEM was conducted according to ASTM E766 with specimens having dimensions of 20 mm ×10 mm × 5 mm size. Before being examined, the composite samples were first polished using metallographic alloy. Etched conditions are used for characterization. Keller's reagent was employed to achieve etching. The SEM was used to obtain the SEM micrographs of the wear debris and composite.

3.3.2Optical microscopy

The case structure was ascertained by examining the casting process under an optical microscope (OM). The Optical Microscopy was conducted according to ASTM E883 with dimensions of 20 mm × 10 mm × 5 mm size. A portion of the casting was removed. It is belt-ground first, then polished with emery paper of several grades. Following a thorough cleaning and dressing, they were once again cleaned, dried, and etched using Keller's solution before being seen under an OM.

3.3.3Hardness test

The standard Brinnel hardness test was employed to assess the bulk hardness of the base metal and composite samples. Measurements of Brinell hardness were performed to look into how the particle weight fraction affected the matrix hardness. Hardness testing was performed according to the ASTM E18 standard for the Brinell hardness testing method. Typically, a hardness test is conducted on a cylindrical specimen which is cleaned and polished before testing. The hardness tests were conducted at room temperature in a controlled laboratory environment. Specimens may be prepared and tested under dry conditions.

3.3.4Tensile test

Tensile testing was performed using the universal testing machine. Tensile testing can be performed according to ASTM E8 or ISO 6892 standards for determining the tensile properties of metallic materials.

Tensile specimens are typically prepared as per ASTM E8 standard, with specific dimensions for gauge length, width, and thickness. Tensile tests were conducted at room temperature under ambient atmospheric conditions. Cross-head speed was 5.0 mm/ min, and the sample rate was 9.103 points per second. Evaluation of the ultimate tensile strength was conducted using standard specimens with a gauge length of 30 mm. The characteristics of the composite material and commercially pure Al were compared.

3.3.5Sliding wear behaviour

Wear is the result of material displacement brought on by hard characteristics, wherein the hard particles are pushed up against and along a solid surface. A composite specimen that had been constructed was used for wear testing. Wear testing was performed according to ASTM G99 standard for wear testing of metallic materials. Cylindrical wear test specimens (diameter 10 mm and length 30 mm were used to evaluate their wear behaviour. Specimens are typically prepared with standardized dimensions and surface finish. Wear tests are conducted under controlled environmental conditions, including temperature, humidity, and lubrication. Testing parameters such as sliding speed, load, and sliding distance are selected based on the intended application and wear mechanism of interest. For these tests, computerized pin-on-disc wear test equipment manufactured by Ducom, Bangalore was used.

4.Results

4.1Optical micrograph study

The optical micrograph (OM) of Al-FA composites is depicted in *Figure 4 (a-f)*. This suggests a material composed of aluminium with 5% FA. However, a fine powder known as FA is formed as a by-product of burning pulverized coal in power plants. It consists mainly of the mineral components present in coal, such as quartz, clay, and minerals containing iron, aluminium, and calcium.

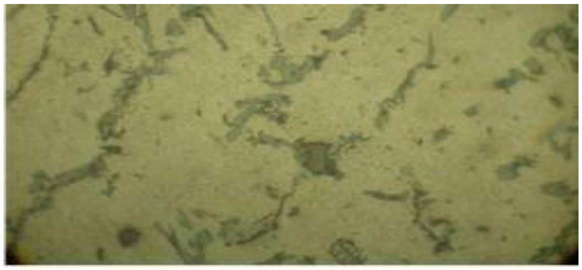

Figure 4 (a) Optical micrograph of the Al–5% FA composite

Particle distribution examines how evenly the FA particles are dispersed within the Al matrix. The microstructure: Look for the microstructure of both Al and FA, observing features like grain boundaries and phase boundaries. The Interactions assess if there are any interactions or bonds between the Al and FA, which could influence the composite's properties. This examination can provide insights into the structural and compositional aspects of the Al-5% FA composite, which is valuable for understanding its properties and potential applications.

The particle distribution analysis evaluates how uniformly the FA particles are dispersed within the Al matrix. A well-distributed reinforcement phase is essential for achieving consistent mechanical properties throughout the composite. The microstructural examination focuses on identifying features such as grain boundaries in the aluminium matrix and phase boundaries between Al and FA particles. Additionally, the nature of the interfacial interactions or bonding between the aluminium and FA is assessed, as these interactions significantly influence the composite’s mechanical behaviour and overall performance. This comprehensive microstructural evaluation provides critical insights into the structural integrity and compositional uniformity of the Al–5% FA composite, aiding in the assessment of its suitability for various engineering applications.

Figure 4 (b) Optical micrograph of Al–10% FA composite

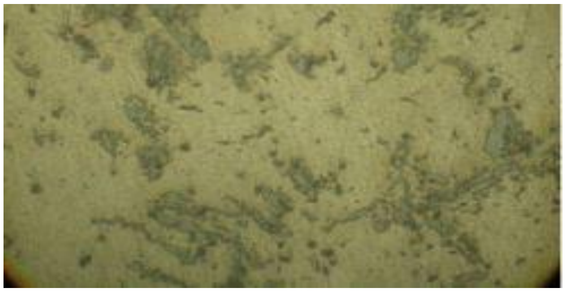

Figure 4 (c) Optical image of Al–15% FA composite

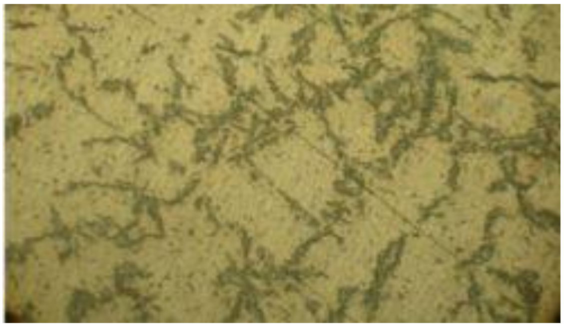

Figure 4 (d) Optical micrograph of Al–20% FA composite

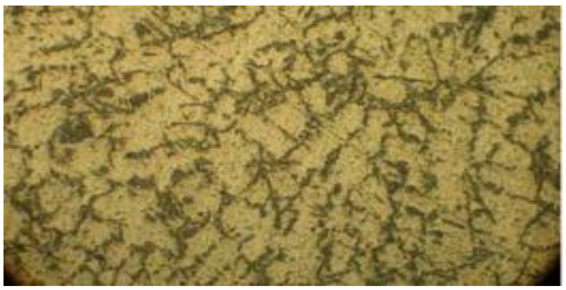

Figure 4 (e) Optical micrograph of the Al–2% Si–10% FA composite

Figure 4 (f) Optical micrograph of the Al–2% Mg–10% FA composite

The optical micrographs of Al–FA composites were employed to examine the morphology and composition of FA particles within the aluminium matrix. These images enable the analysis of the spatial distribution of aluminium and FA particles, their respective sizes, and their interactions within the composite structure. Such analysis provides valuable insights into the material's microstructure and enhances understanding of how compositional variations influence its overall properties. The observed microstructure suggests that the composite consists of approximately 85% aluminium and 15% FA by volume or weight ratio. The mechanical strength, thermal conductivity, and other performance characteristics of the composite can vary significantly depending on the proportion of FA used. The addition of Mg was found to influence the microstructure by promoting grain refinement. Finer grains typically lead to improved mechanical properties, including enhanced strength and better overall performance. While the results section presents a qualitative overview of the optical micrographs, a more detailed quantitative analysis offers critical insights into the microstructural features of the material. Using advanced image analysis software, precise measurements were performed to quantify particle distribution, phase composition, and grain size. This analysis revealed the spatial arrangement and dimensions of inclusions or precipitates, highlighting their impact on material behavior. The integration of this quantitative data with qualitative observations facilitates a more comprehensive understanding of the composite's microstructural evolution and its correlation with mechanical performance.

4.2SEM analysis

A SEM is a great tool employed to examine the surface structure of materials at a very high magnification. In an SEM image, electrons are used instead of light, providing detailed information regarding the surface morphology & composition of the sample. When Al and FA are combined and examined under a scanning electron microscope (SEM), the surface morphology of the composite can be observed at high resolution, revealing details such as particle dispersion, interfacial bonding, and surface texture. The SEM image reveals critical details such as the size and distribution of FA particles, the overall microstructural features of the composite, and the nature of interactions or interfacial bonding between the aluminium matrix and FA particles. *Figure 5 (a-f)* illustrates the SEM images of Al-FA composites.

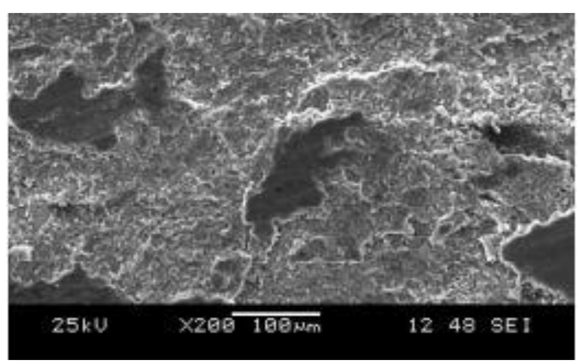

Figure 5 (a) SEM image of Al–5% FA composite

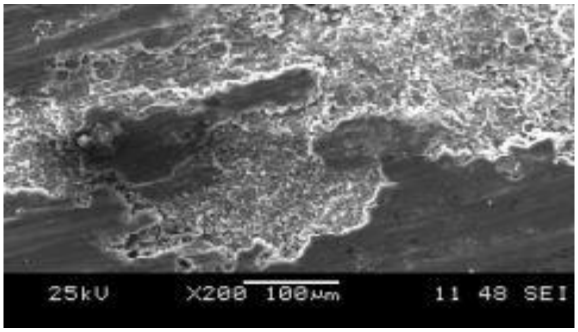

Figure 5 (b) SEM image of Al–10% FA composite

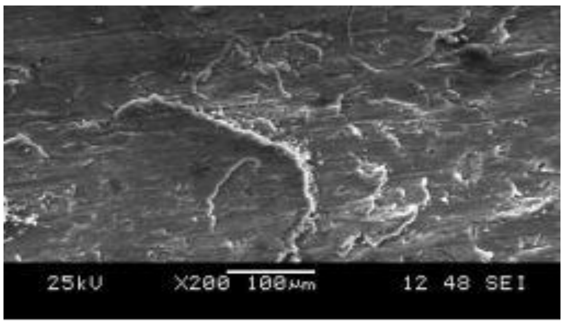

Figure 5 (c) SEM image of Al–15% FA composite

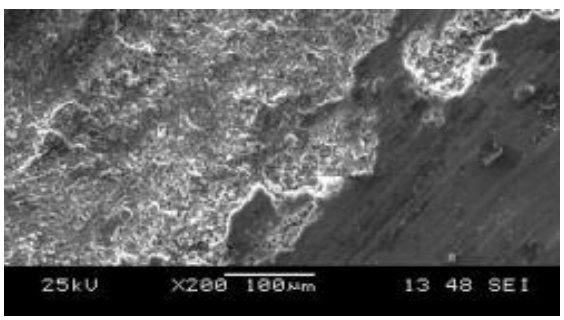

Figure 5(d) SEM image of Al–20% FA composite

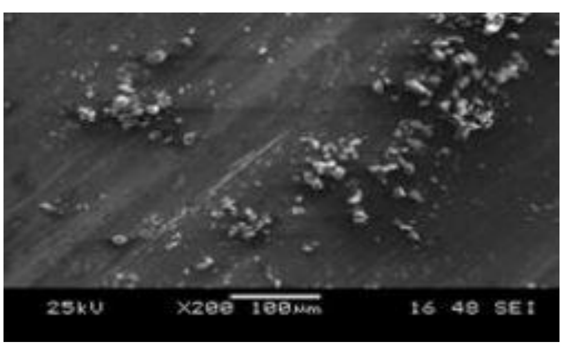

Figure 5 (e) SEM image of Al–2% Si–10% FA composite

The characteristics and functionality of the Al-FA composites can be significantly impacted by the addition of Si in several ways.

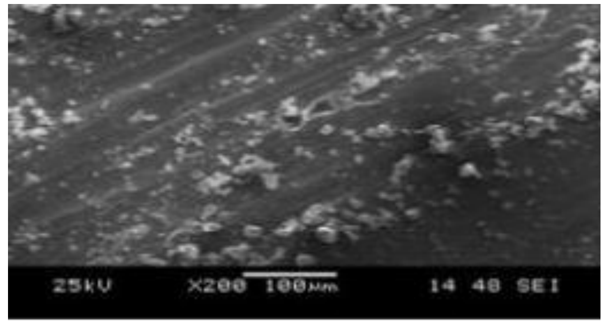

Figure 5 (f) SEM image of Al–2% Mg–10% FA composite

Magnesium can potentially interact with FA particles, influencing the distribution and spreading of FA within the composite. This interaction can significantly influence the overall performance of the composite material. It is important to note that the specific effects depend on factors such as the material composition, processing methods, and the intended application of the composite. Experimental testing and analysis are essential to accurately determine the impact of magnesium addition on a specific Al–FA composite.

The aluminium might appear as distinct particles or a continuous phase, depending on how it is combined with the FA. However, the FA particles, being fine and often irregular in shape, would also be visible. The SEM image can provide insights into the microstructure and composition of the composite material, which is valuable for understanding its properties and potential applications.

To fully interpret the SEM image, additional analysis, such as energy-dispersive spectroscopy (EDS), can be performed to identify the elemental composition of specific regions in the image. This would help in confirming the presence of Al and FA, and understanding their spatial distribution in the composite material.

While the SEM micrographs offer a visual depiction of the material's microstructure, a deeper quantitative analysis unveils crucial insights into its composition and characteristics. Through advanced image analysis techniques, the distribution of particles within the microstructure can be precisely quantified, shedding light on the material's homogeneity and potential areas of interest. Furthermore, phase quantification provides valuable information about the relative proportions of different phases present, elucidating the material's overall composition and its impact on mechanical properties. Detailed grain size measurements offer key data regarding the material's crystalline structure, influencing its strength, ductility, and other mechanical behaviours. By quantitatively assessing these parameters, a more comprehensive understanding of the material's microstructural features emerges, facilitating informed decisions regarding its suitability for specific applications and highlighting areas for further optimization or refinement. This quantitative approach enhances the depth and accuracy of the analysis, enabling more robust conclusions and insights into the material's properties and performance characteristics.

4.3Analysis of wear behavior

The wear behaviour of various composites was examined under different parameters, including applied load and sliding velocity. The following subsections present the results and corresponding discussion.

Effect of sliding behaviour

Under a constant load of 10 N, the composite was tested for a duration of 30 minutes at a sliding velocity of 1 m/s. The corresponding results are illustrated in *Figures 6 to 10.*

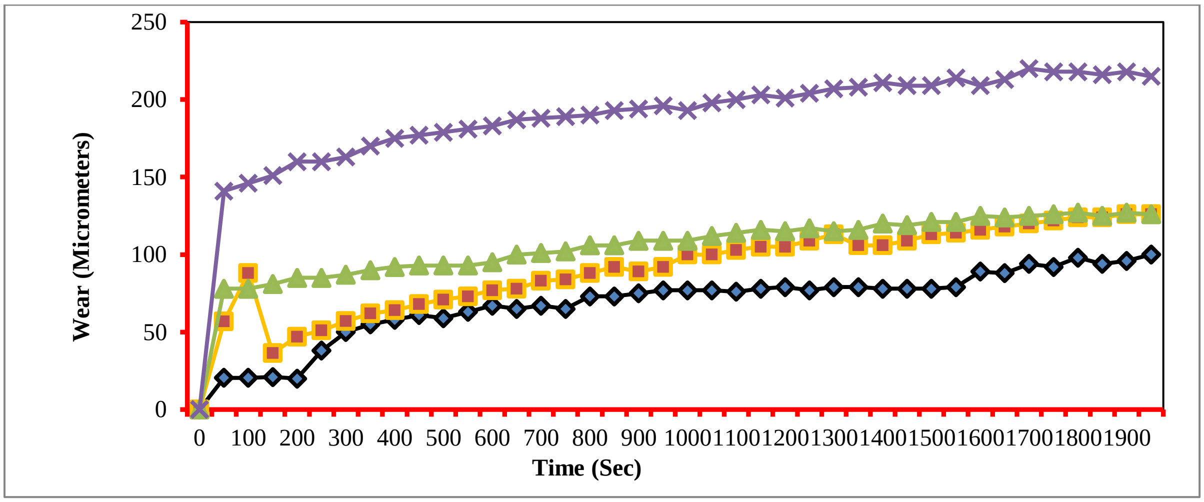

Figure 6 Wear curves of MMC specimens for different compositions: Pure Aluminium, Al + 10% FA, Al + 2% Si + 10% FA, and Al + 2% Mg + 10% FA

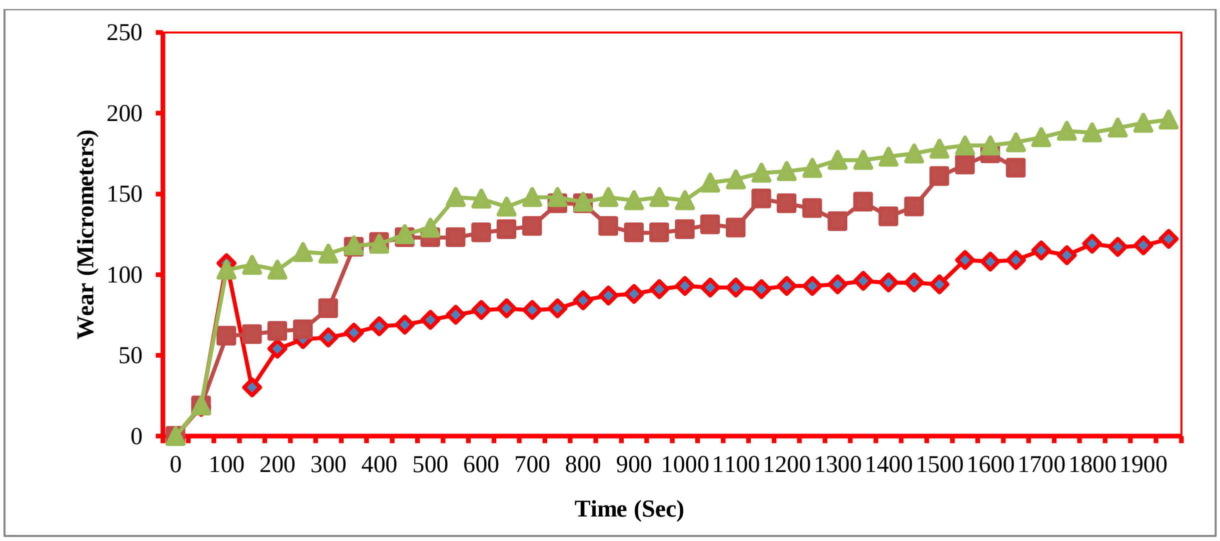

Figure 7 Wear curves of MMC specimens with varying compositions: Al + 10% FA, Al + 2% Mg + 10% FA, and Al + 2% Si + 10% FA

Figure 8 displays the wear curves of MMC specimens with 10% FA, 10% FA with 2% Si, and 10% FA with 2% Mg content. *Figures 6* and *7* depict the same specimens under typical loads of 10N, 15N, and 20N. A relatively limited initial nonlinear wear regime was observed in all MMCs. A steady state wear regime is indicated when the wear increases linearly with time after a certain sliding distance. Within a few minutes (2–3 minutes) after the test started, the first wear regime gave way to the steady-state regime. The graph makes it clear that composite material has far higher wear resistance than commercially available pure aluminium. Bulk wear is reduced when Mg is added. Wear is greatly decreased when the FA component is included. The amount of wear seen in commercially pure aluminium and composites with a 2% magnesium + 10% FA mix provides proof for this. This improvement is attributed to the presence of hard FA particles, which contribute to an increase in the overall bulk hardness of the composite.

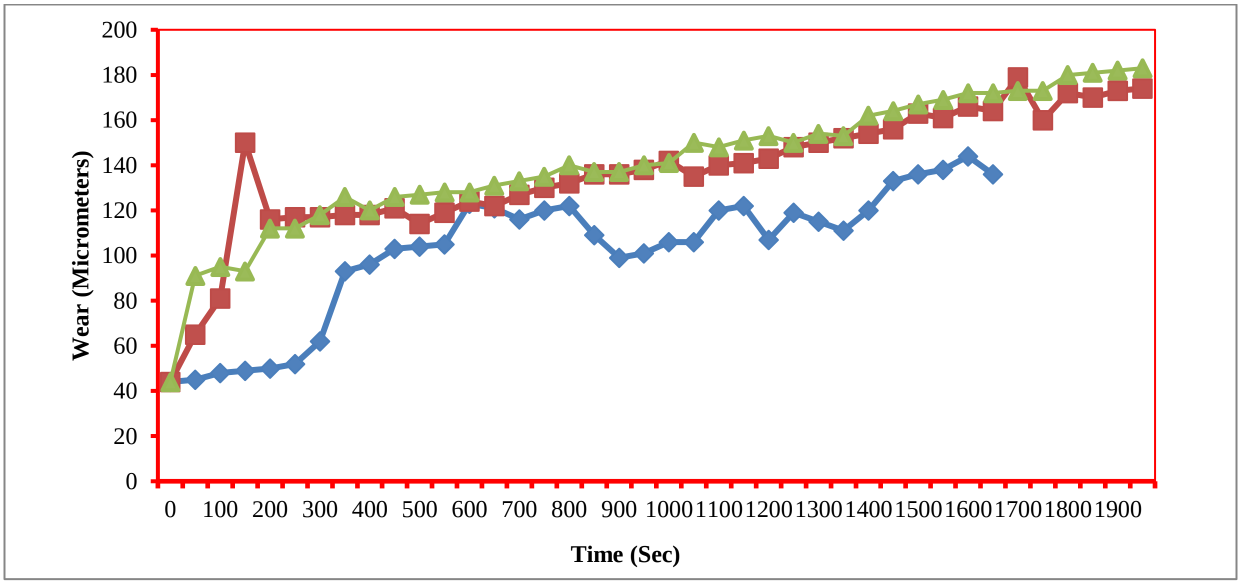

Figure 8 Wear behaviour with variation in normal load 10N, 15N, 20N

The reinforcing particles serve as load-bearing components, adhesion-inhibiting agents against plastic deformation, and load-bearing elements during the first wear regime. The worn particles get displaced from their locations in the matrix and combine with the wear in the later phases of the wear regime. The relationship between the MMCs' (Al+2% Mg+10% FA) wear and applied load at a certain velocity of 1 m/sec. An increase in the typical load has increased wear. *Figure 9* clearly demonstrates that the addition of FA significantly improves the wear resistance of the composite. The incorporation of FA enhances the hardness of the material by hindering dislocation movement within the aluminium matrix. As a result, the composite exhibits a markedly higher resistance to abrasive wear. This improvement is primarily attributed to the presence of hard aluminosilicate components in the FA particles, which act as effective barriers against wear-induced deformation. The typical coefficient of friction for cast aluminium and the Al–10% FA composite is illustrated in *Figure 10*. Compared to pure cast aluminium, the Al–10% FA composite exhibits a noticeably lower friction coefficient. This significant reduction is primarily due to the incorporation of FA particles into the aluminium matrix. From a materials science perspective, several factors influence the CoF, including the composition and strength of the matrix–reinforcement interface, the mechanical properties of the matrix, and the hardness and chemical stability of the reinforcement particles. The presence of hard, stable FA particles contributes to improved tribological performance by reducing direct metal-to-metal contact and minimizing surface deformation during sliding.

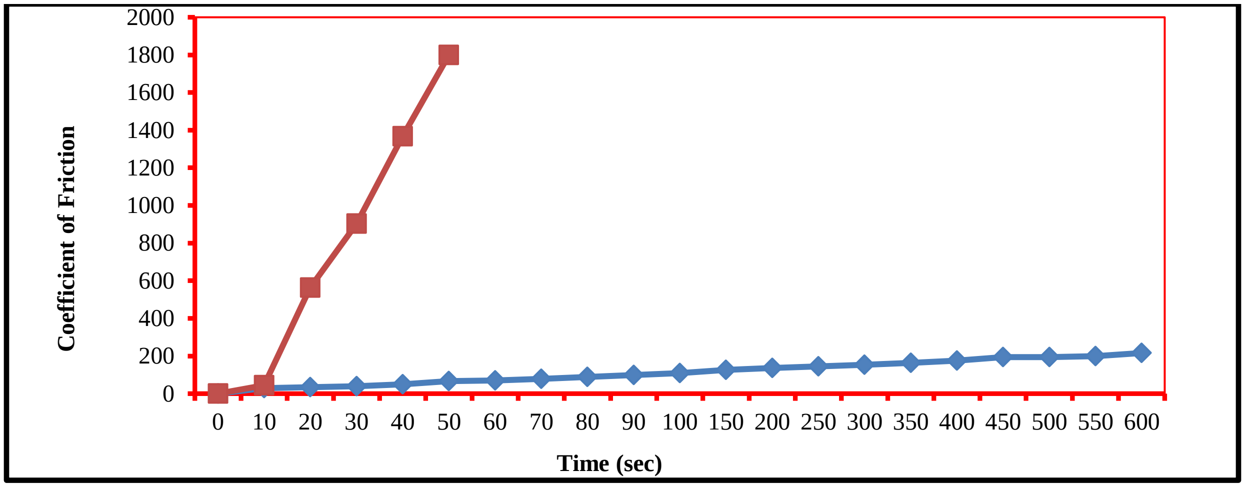

Figure 9 Wear vs. Time graph comparing pure Aluminium (red curve) and Al–10% FA composite (blue curve)

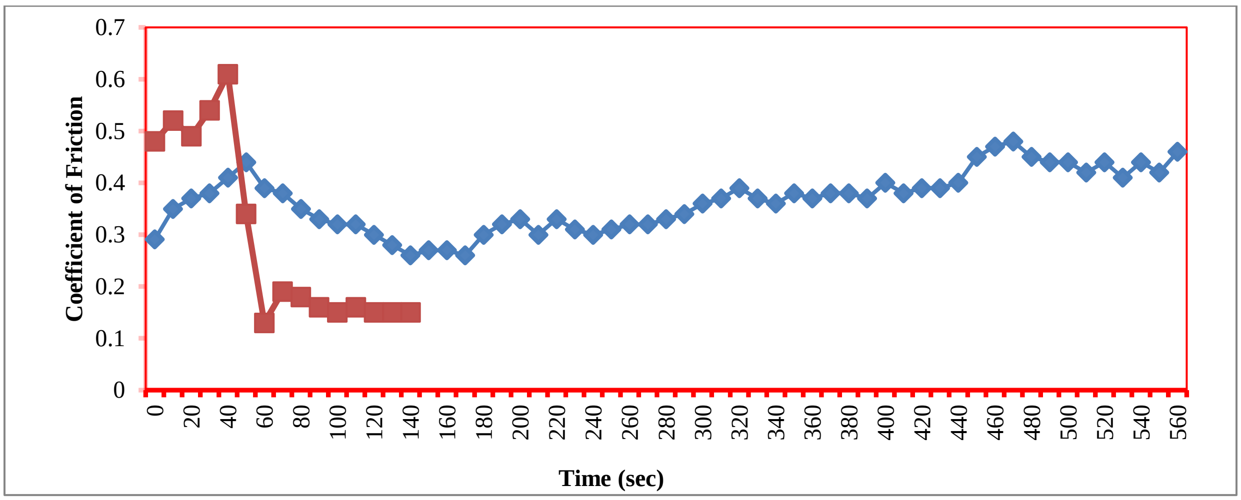

Figure 10 Coefficient of friction vs. time graph comparing pure Aluminium (red curve) and Al–10% FA composite (blue curve)

4.4Mechanical behaviour

The addition of silicon and magnesium to Al–FA composites can significantly enhance wear resistance through various mechanisms, including increased hardness, the formation of hard intermetallic phases, grain refinement, solid solution strengthening, and improved ductility, as presented in *Table 3*. The specific extent of these improvements depends on factors such as the composite's chemical composition, processing parameters, and the requirements of its intended application. BHN stands for Brinell Hardness Number.

Table 3 Properties of composites

Sample No.	Ingredients and their percentage				Density (g/cm^3)	Tensile strength (N/mm^2)	Hardness BHN
	Al (gm.)	Mg %	Si %	FA %			
1	100	0	0	0	2.6900	90	48.30
2	100	0	0	5	2.6000	134	55.04
3	100	0	0	10	2.4660	129	67.05
4	100	0	0	15	2.3125	165	86.30
5	100	0	0	20	2.4400	145	90.63
6	100	0	2	10	2.2700	145	70.09
7	100	2	0	10	2.2000	159	85.95

5.Discussion

FA is a lightweight material that, when incorporated into Al, significantly reduces the composite's density—a key advantage for weight-sensitive applications in the automotive and aerospace industries. The performance of particulate-reinforced composites depends heavily on the size, distribution, and type of reinforcement particles. Factors such as solidification rate, melt fluidity, reinforcement type, and wettability influence dispersion during fabrication. Preheating FA particles enhances their wettability and interfacial bonding, improving hardness due to better integration within the Al matrix [49].

The addition of FA not only reduces costs and weight but also improves mechanical properties through both dispersion strengthening and particle reinforcement mechanisms. Particle analysis reveals a wide size range (1–100 µm), where finer particles help restrict dislocation motion and coarse particles aid in load-bearing capacity. The composite thus benefits from improved tensile strength, stiffness, and wear resistance [49–51].

The incorporation of Mg into Al–FA composites further enhances mechanical performance. Mg forms intermetallic phases such as Al_3Mg_2, contributing to precipitation strengthening and grain refinement. This results in higher tensile strength, improved hardness, and better wear resistance. Moreover, Mg's low density helps reduce the overall weight of the composite, which is advantageous in aerospace applications [49]. Similarly, Si enhances strength and wear resistance by forming hard intermetallic compounds and refining the microstructure through heterogeneous nucleation, leading to finer grains and increased durability [49].

Experimental investigations confirm that the addition of Si and Mg improves the composite's mechanical behaviour, as evidenced in *Table 3*. While Si increases strength and hardness, Mg enhances ductility and corrosion resistance. These enhancements are influenced by the specific composition, processing parameters, and intended application [49–51]. However, limitations such as particle agglomeration, inconsistent FA composition, and thermal mismatch must be addressed through optimized processing and careful material selection [52–56]. Surface treatments such as anodizing, shot peening, and plasma coating can further enhance performance and functional longevity.

Comparative analysis with earlier studies shows alignment in reduced density and intermetallic formation at the matrix-reinforcement interface. While some studies [57–59] report decreased mechanical performance with higher FA content, the present work indicates that, under controlled processing, FA can improve both strength and hardness. These discrepancies highlight the role of particle size distribution, alloying elements, and fabrication methods in determining final properties.

This study highlights the potential of Al–FA composites reinforced with Si and Mg as lightweight, high-performance materials for industrial applications. Further research should focus on optimizing reinforcement content, improving particle dispersion, and evaluating fatigue and corrosion resistance to expand their applicability across diverse engineering domains [49–53].

Limitations

The current study acknowledges certain limitations, particularly the need for additional testing—such as wear behaviour, fatigue resistance, and long-term durability—to provide a more comprehensive understanding of the composite's performance. Moreover, further investigation is required to optimize processing parameters and post-processing techniques in order to achieve the desired balance of mechanical and functional properties.

A complete list of abbreviations is listed in *Appendix I*.

6.Conclusion and future work

This study investigated the development of AMCs reinforced with FA using the stir casting technique. The results demonstrated that incorporating FA into pure aluminium produces a lightweight and mechanically robust composite. The material showed notable improvements in tensile strength, hardness, and impact resistance. Further enhancement in mechanical and wear properties was observed with the addition of silicon and magnesium, attributed to mechanisms such as grain refinement and intermetallic phase formation. These findings support the potential of Al–FA composites as cost-effective, sustainable alternatives for applications in weight-sensitive and high-performance sectors such as automotive and aerospace. However, comprehensive evaluation of long-term performance, corrosion resistance, and environmental impact is essential before large-scale adoption.

To build upon the findings of this study, future research may focus on the following areas:

- Optimizing the FA content in the aluminium matrix to achieve the best balance between mechanical performance and density reduction.
- Exploring alternative processing techniques, such as powder metallurgy or ultrasonic-assisted casting, to improve FA particle dispersion and composite uniformity.
- Employing advanced characterization methods, such as transmission electron microscopy (TEM) and X-ray diffraction (XRD), to investigate microstructural features and interfacial bonding mechanisms.
- Evaluating the corrosion resistance of Al–FA composites under various environmental conditions to determine their suitability for marine, automotive, or structural applications.
- Comparing the performance of FA-reinforced aluminium with other commonly used reinforcements, such as SiC and Al_2O_3, to identify the most effective material systems.

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Conflicts of interest

The authors have no conflicts of interest to declare.

Data availability

The SEM images used in this study were obtained from IIT Ropar, Punjab, while the wear tests were conducted using a Pin-on-Disc apparatus available at NIT Jalandhar, Punjab. The data is not publicly available but may be provided by the authors upon reasonable request.

Author's contribution statement

Sahil Duggal: Writing – review & editing, writing – original draft, Visualization, Validation, methodology, investigation, formal analysis, Data curation, conceptualization. **Jatinder Kumar**: Writing – review & editing, supervision. **Santosh Kumar**: Supervision, editing, and conceptualization.

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Appendix I

S. No.	Abbreviations	Description
1	Al	Aluminium
2	Al_2O_3	Alumina or Aluminium Oxide
3	Al-FA	Aluminium-Fly Ash
4	Al-Si-Mg	Aluminium-Silicon-Magnesium
5	AMCs	Aluminium Matrix Composites
6	ASR	Alkali-Silica Reaction
7	ASTM	American Society for Testing and Materials
8	B_4C	Boron Carbide
9	CaO	Calcium Oxide
10	EDS	Energy-Dispersive Spectroscopy
11	FA	Fly Ash
12	Fe_2O_3	Iron Oxide
13	Gr	Graphite
14	MgO	Magnesium Oxide
15	MMCs	Metal Matrix Composites
16	NaCl	Sodium Chloride
17	OM	Optical Microscope
18	SEM	Scanning Electron Microscope
19	SiC	Silicon Carbide
20	SiO_2	Silicon Oxide
21	TEM	Transmission Electron Microscopy
22	TiC	Titanium Carbide
23	XRD	X-Ray Diffraction