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Enhancing Mechanical Properties: A Comprehensive Literature Review on the Impact of Fly Ash Reinforcement in Powder Metallurgy-based Metal Matrix Composites

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ABSTRACT

The incorporation of fly ash into composites provides a cost-efficient option for applications that involve ductile metallic matrices. Fly ash is a residue from coal combustion in thermoelectric plants and can offer an eco-friendly solution. Its properties resemble those of a ceramic material. However, there is a lack of understanding about the mechanical and metallurgical behavior resulting from the interaction between the matrix and the fly ash-based reinforcement. This review of existing literature investigates the significant impacts of fly ash as a strengthening agent in metal matrix composites (MMCs) produced through the powder metallurgy process. The investigation focuses on the enhancement of mechanical, Tribological and morphological properties. By synthesizing existing research findings, this review aims to provide a comprehensive understanding of the synergistic interactions between fly ash particles and metal matrices. Various processing parameters, such as sintering temperature, time, and particle size distribution, are examined to unravel their influence on the final composite's performance. Moreover, attention is given to the microstructural changes induced by the incorporation of fly ash, shedding light on the mechanisms behind the observed improvements in mechanical behavior. The knowledge synthesized in this review contributes to advancing the understanding of fly ash-reinforced MMCs, offering valuable insights for researchers involved in the development and optimization of advanced materials for diverse engineering applications.

Keywords: **Powder metallurgy Fly ash Mechanical properties Mechanical behavior Metallic composites**

INTRODUCTION

There is an increasing interest in using waste materials in powder metallurgy to improve economic and environmental efficiency in manufacturing processes. Coal-fly ash is widely used in the production of various engineering materials such as bricks, cement, and metal-matrix composites (MMCs) [1]–[3]. In particular, low weight MMCs are successfully being made by effectively reinforcing inexpensive coal-fly ash to improve their mechanical and tribological properties[4]. This literature review embarks on an in-depth exploration of the synergistic effects of fly ash reinforcement within the realm of powder metallurgy-based MMCs, aiming to provide a holistic understanding of the transformative impact on mechanical properties.

The composition of coal-fly ash primarily comprises spherical particles of SiO2, Al2O3, Fe2O3, and TiO2, with particle sizes ranging from 1 µm to 100 µm. The ash consists of both dense particles termed precipitator and hollow particles termed cenosphere [5]–[7]. The SiO2-rich nature of Indian coal-fly ash, falling into the F-category per ASTM C618, makes it particularly suitable for strengthening MMCs, contributing to more than 50% of SiO2 particles [8]–[10].

The properties of resulting MMCs are heavily influenced by the type, amount, and distribution of the reinforcement within the matrix. However, challenges arise due to poor wettability and low density of ceramic reinforcements compared to matrices, resulting in non-uniform distribution in liquid state fabrication methods.

To address these issues, powder metallurgy (PM) techniques are widely employed as a solid-state method to produce denser, precise, and high-strength MMCs. The PM technique allows for a uniform dispersion and a higher percentage of reinforcements, with upper limits of 50% and 30% for PM and stir casting processes, respectively [11]–[14]. This highlights the broader scope of tailoring MMC properties through PM.

Recent studies, such as Sahoo et al [15], have explored the synthesis of MMCs through PM techniques, evaluating the effects of reinforcement on stainless steel (AISI 304) matrix.

The studies consider the volume percentage of reinforcement and sintering parameters, demonstrating significant enhancements in hardness, elastic modulus, and strength. Other works, like Abdollahi et al [16], Zhang et al [17], Sharma et al [18], Gupta et al [19], and Sahoo et al [20], have investigated the sintering behavior, mechanical properties, and wear resistance of MMCs fabricated through PM routes using different reinforcements and matrices.

Guo and Rohatgi [21] specifically characterized the powder compacting process of aluminum-coal-fly ash, studying parameters such as green strength, green hardness, green density, spring back, and densification. Rajan et al [22] conducted a comprehensive study on copper-coal-fly ash composites, exploring microstructural, electrical, thermal, and tribological aspects.

These studies collectively contribute to the understanding of utilizing coal-fly ash as a reinforcement in MMCs, offering insights into enhancing properties while considering factors such as composition, fabrication techniques, and distribution within the matrix.

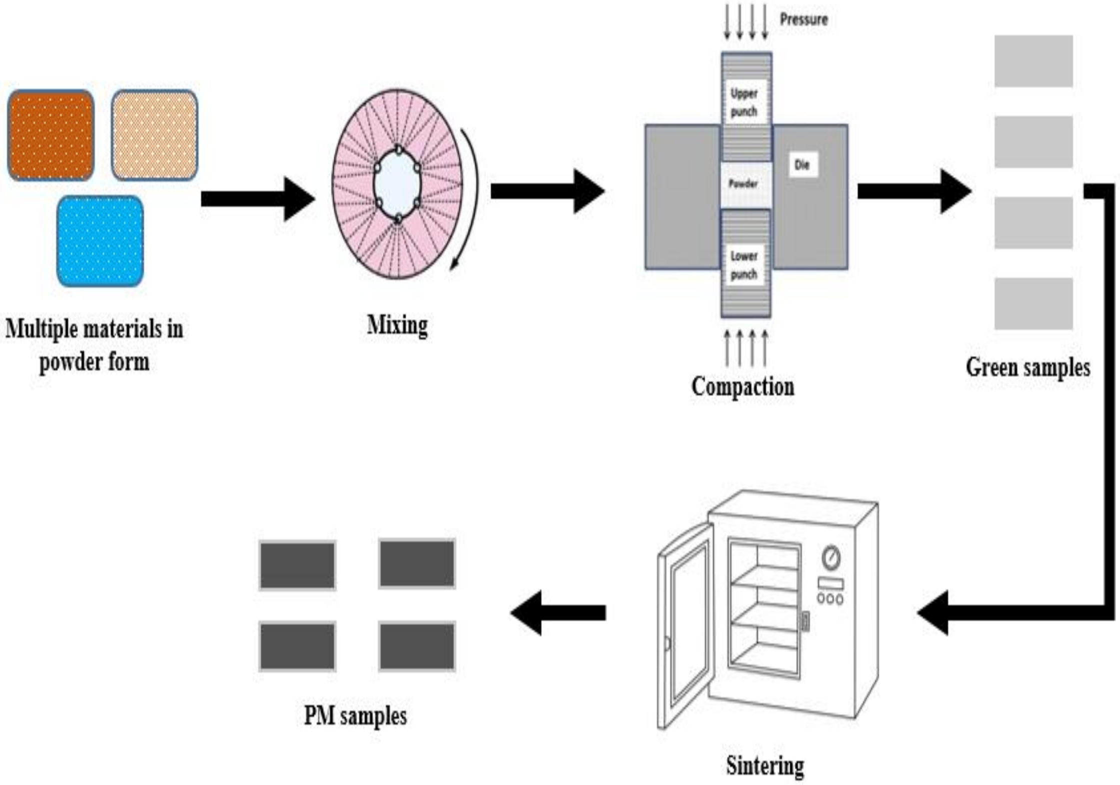
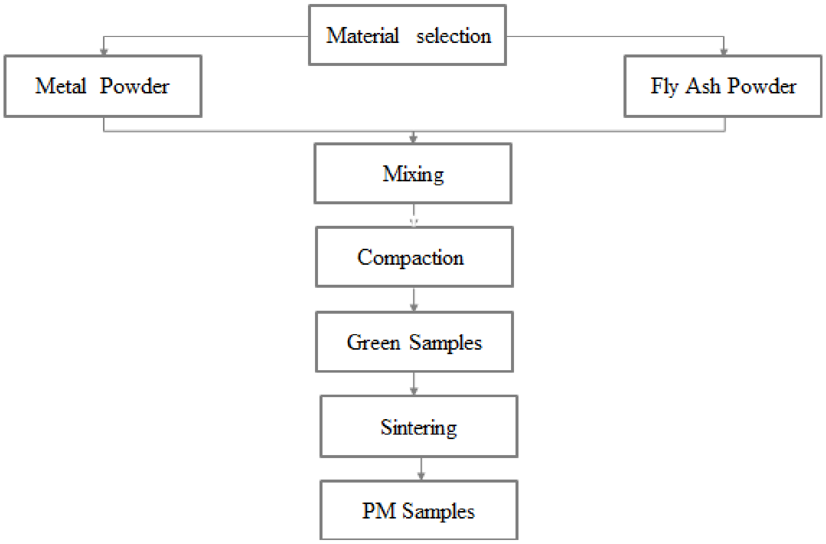


Fig. 1: Steps involved in powder processing

Methodology to Fabrication Fly ash/MMC composites using powder metallurgy

The methodology for developing a metal matrix composite (MMC) reinforced with varied percentages, compaction loads, and sintering temperatures involves several sequential steps. Firstly, appropriate materials are selected based on desired properties and applications, followed by the preparation of composite powders through milling and blending.

Compaction experiments are then conducted using varying loads to assess their impact on density and microstructure. Subsequently, sintering is performed at different temperatures to optimize densification and bonding between matrix and reinforcement [23]–[25].



Characterization techniques such as SEM and XRD are employed to analyze the microstructure, while mechanical and thermal properties are measured through standard testing methods. The experimental data are then analyzed to identify the optimal combination of parameters, considering factors like cost-effectiveness and scalability. Validation of the optimized composite formulation is conducted through rigorous testing, and findings are documented in a comprehensive report for dissemination and potential further research.

REVIEWS

Fly Ash

Coal fly ash is a byproduct produced during the burning of coal in power plants. It usually appears as round particles, either hollow or solid. The principal chemical components of fly ash are oxides, primarily SiO_2, followed by Al_2O_3, Fe_2O_3, and other oxides. These oxides are utilised to improve metal matrix composites (MMCs). The chemical composition of fly ash varies based on the kind of coal and the combustion circumstances. Table 1 shows the chemical composition of coal fly ash from various countries and divides it into two categories based on ASTM C 618: Class F and Class C. Class F fly ash, which is generated by burning bituminous coal, is preferable for the production of aluminium MMCs because it contains less calcium oxide (CaO) than Class C, which is formed from sub-bituminous coal and lignite. The usual oxide compositions of bituminous coal fly ash vary from 20-60% SiO_2, 5-35% Al_2O_3, 10-40% Fe_2O_3, and 1-12% CaO, with a loss on ignition (LOI) of 0-15%. Fly ash from subbituminous coal is composed of 40-60% SiO_2, 20-30% Al_2O_3, 4-10% Fe_2O_3, and 5-30% CaO, with a LOI of 0-30%. Lignite fly ash typically contains 15-45% SiO_2, 20-25% Al_2O_3, 4-15% Fe_2O_3, and 15-40% CaO, with a LOI of 0–5%. Fly ash has a low density, with a bulk density of 540 to 800 kg/m^3 and a packed density of 1120 to 1500 kg/m^3, making it lighter than other ceramic reinforcements in Table 2. Its cheap cost makes it an attractive option for reinforcing aluminium, lowering both the density and cost of the composite material.

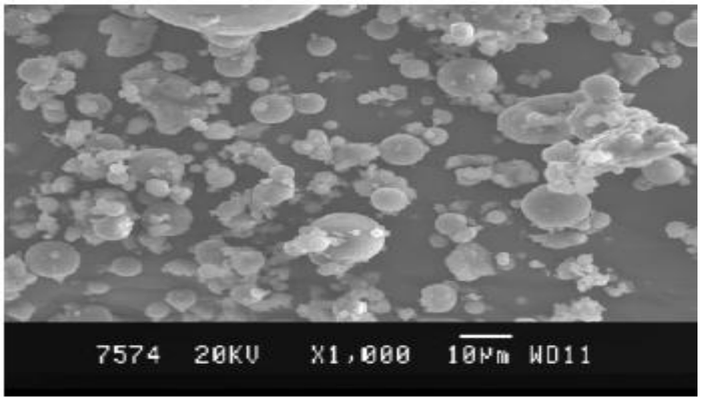


Image (SEM) of fly ash powder [13]

Table 1.Classification of coal fly ash by ASTM C 618 [28].

Class: ASTM C618	SiO2 + Al2O3 + Fe2O3 (%)	Moisture (%)	SO3 (%)	LOI (%)
C	>50	<3	<5	<6
F	>70	-	-	<12

Flow ability and compressibility evaluation of the starting powders

The ability of a powder to flow at a particular pressure and temperature is crucial for compacting a powder with the least amount of porosity in powder metallurgical procedures. The powders' flow ability is influenced by their bulk and tap densities, which are primarily determined by the size and form of the particles. The flow ability and compressibility of materials that resemble powder are frequently demonstrated using the Hausner ratio and Carr's index [62].

The tap density to bulk density ratio, or Hausner ratio, is always C 1. Its rating of C 1.25 indicates that the powder has poor flow ability. Compressibility index, or Carr's index, is expressed as shown in Table 8. Powders with a Carr's index of C 25 are thought to have poor flow ability, whereas those with a value of B 15 are thought to have acceptable flow ability.

In order to demonstratethe iron powder and coal-fly ash's appropriateness for powder metallurgy, their Hausner ratio and Carr's index were calculated. As shown in table 8 [63], these beginning materials showed good flow ability and compressibility, with numerical values of the Hausner ratio and Carr's index being within acceptable ranges.

Table 8. Hausner ratio and Carr's index of the starting materials [63]

Material	**Bulk density(P_B)**	**Tap density(P_T)**	**Hausner ratio=(P_T/P_B)**	**Carr's index=100(1-P_B/P_T)**
Iron Powder	3.351g/cm^3	3.810 g/cm^3	1.130	12.1
Coal-Fly Ash	0.710 g/cm^3	0.770 g/cm^3	1.110	10.02

Impact of Fly Ash Content as Reinforcement on the Density of composite

Fly ash composites were found to have a lower density than those reinforced with Al2O3. The density of fly ash-based composites reduces as the fly ash component increases. In contrast, the density of Al2O3-reinforced composites increases with increasing Al2O3 content.

Boopathi et al. used Archimedes' principle to investigate the densities of Al2024 composites reinforced with SiC and fly ash particles, and they discovered that the density of Al-SiC, Al-fly ash, and Al-SiC-fly ash composites decreased linearly as the concentrations of fly ash and SiC increased. This is owing to the lower density of fly ash and SiC particles than the aluminium matrix.

Several studies show that fly ash composites have consistently lower densities than those reinforced with Al2O3. Density of fly ash-based materials declines with increasing fly ash content, but density increases in Al2O3-reinforced composites as the Al2O3 concentration increases. Similarly, the density of Al2024 composites enhanced with SiC and fly ash particles was investigated using Archimedes' principle. The density of Al-SiC, Al-fly ash, and Al-SiC-fly ash composites decreased linearly with increasing fly ash and SiC concentration. This can be attributable to the fact that fly ash and SiC have lower densities than the aluminium matrix.

Table 6 shows the observed and predicted densities and porosities of as-cast and extruded A356 alloys, as well as A356-based composites such as C6S, C12S, and C12AR. The densities of these composites were measured experimentally using Archimedes' technique.

Table 6: Densities and porosities of A356 alloy and A356 based C6S, C12S, and C12ARcomposites [53].

Materials	Theoretical densities(g/cc)	Measured density		Porosity (vol. %)	
		As-cast	Extruded	As-cast	Extruded
A356 AI	2.681	2.666	2.677	0.561	0.148
C6(S)	2.646	2.617	2.641	1.097	0.188
CI2(S)	2.610	2.443	2.590	6.402	0.691
CI2(AR)	2.610	2.459	2.603	5.861	0.346

The microstructure of composites made of fly ash and Al-Si alloy is displayed. Fly ash particles second phase are found in the grain boundary following sintering, as can be shown in Figure 9. The amount of grain growth will be regulated by the pinning effect (zener pinning) created by these particles.

Impact of Fly Ash content as a reinforcement on the tensile properties of composite

Increasing ash content in Al7075 alloy improves tensile strength to a certain threshold, beyond which it declines (31). Similarly, it has been discovered that in LM25 metal matrix composites (MMCs) reinforced with fly ash and alumina, the tensile strength rises as the fly ash concentration increases (32).

When higher particle sizes are employed, the amount of fly ash has no effect on the ultimate tensile strength (UTS), according to research. However, for smaller fly ash particles, UTS diminishes at greater concentrations due to particle agglomeration (33).

Table 1: Chemical composition of Al-Si alloy powder [47]

Compound	AI	Si	Fe	Mg	Cu	Zn
Weight (%)	86.41	12.13	0.55	0.43	0.18	0.064

Impact of Fly Ash content as reinforcement on the Compressive properties of composite

The compressive strength of all fly ash reinforced composites increases as the fly ash content increases. However, composites reinforced with Al2O3 have a higher compressive strength than those reinforced with fly ash. Furthermore, composites reinforced with E-glass fibre and fly ash have a higher density, which improves their compressive strength [29]. In the context of Al6061, reinforcing using fly ash particles has been shown to boost the composite's compressive strength. It has also been noted that when the fly ash particle size increases, the compressive strength of the composite decreases. Concrete composites enhanced with fly ash and nano-SiO2 have a better compressive strength than concrete composites without steel fibre reinforcement [35].

Impact of Fly Ash content as reinforcement on the Wear behavior of composite

As the concentration of fly ash rises in Al6061 composites, they change from ductile to brittle (36). This leads in an increase in the hardness of these composites (31, 33). Adding fly ash to polymers increases their resistance to plastic deformation, resulting in greater hardness ratings. Polymer matrix composites containing 300-nm fly ash particles have higher toughness compared to other particle sizes (37). This enhancement has been ascribed to enhanced interaction between the filler and the matrix (38). The use of silicon carbide (SiC) particles as reinforcement enhances the hardness of these composites.

The studies were carried out across a sliding distance of 2000 meters, with weights of 10, 20, and 30 N with sliding speeds of 0.5 and 1 m/s. The flatness of the pin and disc was maintained by aligning the pin perpendicular to the disc surface. The pin's original weight was determined using a digital balance with a precision of 0.1 mg. After moving the requisite distance, the pin was cleaned with acetone, dried, and weighed again to calculate the mass loss. A scanning electron microscope was then utilised to examine the wear grooves on the pin.

Sharma et al. discovered that the wear resistance of Al metal matrix composites (MMCs) reinforced with fly ash increased as the fly ash concentration rose. Composites with a high concentration of fly ash showed approximately 13.6% reduced wear compared to those with lower fly ash content (39). Medium fly ash content (~4%) had the lowest average coefficient of friction (~0.12), whereas greater fly ash content (~6%) produced a higher coefficient of friction (~0.161). Based on these findings, it was determined that the fly ash content in the Al matrix should not exceed 4% to prevent a high coefficient of friction. Sudarshan, Surappa, and Rohatgi et al. (34), investigated the dry sliding wear behaviour of A356 Al composites supplemented with fly ash particles. Adding 6% fly ash to A356 Al alloy decreased dry sliding wear rates at mild loads (10-20 N). Composites treated with ~12 vol.% fly ash showed reduced wear rates than non-reinforced alloys at 20-80 N. The wear rate in composites containing 12 vol.% fly ash reduced with decreasing particle size. However, the coefficient of friction rose from ~0.49 to ~0.58 when the fly ash concentration climbed from 6 to 12 percent (27, 34). Non-reinforced metals predominantly underwent adhesive wear, whereas composites displayed abrasive wear (34-40). Moreover, subsurface delamination was found as the primary wear process in both alloys and composites at higher stresses (34).

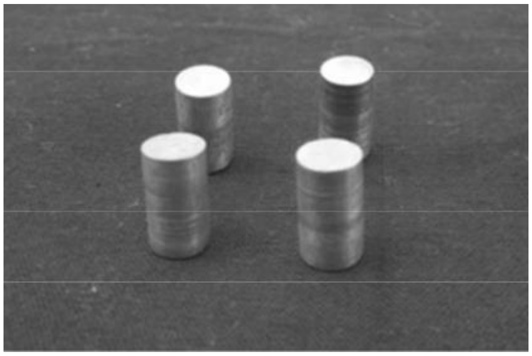


Figure 4: Specimens for wear test [48].

Desai et al. found that high load causes high pressure at the area of contact, resulting in a strong rubbing action. As a result, increasing the applied load causes an increase in the wear rate. It is worth noting that wear processes requiring adhesion are prevalent in base metals, whereas abrasion with micro-cutting and oxide production dominate in Al-based fly ash composites [41].

CONCLUSION

Finally, this study article provides a full overview of the utilisation of coal fly ash as a reinforcement in metal-matrix composites (MMCs), with a focus on powder metallurgical techniques. The important findings and conclusions taken from the supplied data are as follows:

Fly Ash Composition: Coal fly ash, an industrial byproduct of coal combustion, is mostly made up of SiO_2, Al_2O_3, Fe_2O_3, and other oxides. The chemical composition changes according on the type of coal burnt and the combustion circumstances. ASTM C 618 Classification: According to ASTM C 618, fly ash is classed as Class C or Class F, with Class F being preferred for aluminium MMCs because to reduced CaO concentration. Table 1 details the composition of fly ash derived from various coal types. Fly ash has a low density, making it a useful and cost-effective reinforcing material for aluminium composites. As fly ash content increases, the total composite density drops, resulting in lighter materials.

Mechanical Properties: Adding fly ash to aluminium alloys like Al7075 boosts their tensile strength up to a degree. Similarly, the tensile strength of alumina-reinforced LM25 MMCs improves as the fly ash content increases. The size of the fly ash particles determines ultimate tensile strength (UTS), with higher concentrations resulting in agglomeration and lower UTS. Compressive Properties: Fly ash-reinforced composites have a higher compressive strength as the fly ash content increases, whereas composites reinforced with Al_2O_3 have even higher compressive strength. The inclusion of E-glass fibre and fly ash increases compressive strength.

Hardness: As the fly ash component in Al6061 composites increases, the material changes from ductile to brittle, resulting in increased hardness. Fly ash and SiC particles improve toughness in polymers by increasing phase contact.

Wear Resistance: The wear resistance of aluminium MMCs improves with greater fly ash concentration. However, the coefficient of friction fluctuates with fly ash concentration, emphasising the importance of properly controlling fly ash levels in the matrix. The use of fly ash minimises dry sliding wear rates, which include adhesion and abrasion.

Cost and Density Reduction: Because fly ash is inexpensive, it is an economical alternative for reinforcing aluminium, resulting in lower density and more cost-efficiency in the composites produced.

In conclusion, the study demonstrates the great potential of coal fly ash as a reinforcing material for powder metallurgy-based MMC construction. The findings emphasise the need of carefully regulating fly ash concentration and particle size to optimise mechanical and tribological characteristics, making these composites ideal for numerous industrial applications.

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