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Mechanical properties and wear behavior of fly ash particle reinforced Al matrix composites

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Abstract

In this study, aluminum-based metal matrix composites containing 5, 10, 15, 20, and 25% fly ash particles by weight have been fabricated using a stir casting route. Microstructural observations under an optical microscope suggest that fly ash particles in the cast composites are uniformly distributed throughout the matrix. The mechanical properties such as tensile strength and hardness of the aluminum alloy have enhanced significantly with the addition of fly ash. Wear behavior of base metal and its composite have been studied in dry sliding conditions using a pin-on-disc tribometer. Wear tests have been conducted at three different loads of 9.81, 19.62, and 29.43 N at a constant sliding velocity of 1.3 m s⁻¹. Microstructural observations of worn surfaces and wear debris suggest that wear mechanism in base metal is controlled by adhesion, whereas that for composites is abrasive. The least wear rate has been obtained in Al-10% Fly ash composite. The Al-10% Fly ash is observed to possess an optimum level of mechanical properties and wear behavior.

1. Introduction

Automotive and aerospace applications require lightweight, high strength, and superior wear-resistant materials. Particulate reinforced aluminum matrix composites (AMCs) are an excellent choice for these applications [1–3]. But the cost of conventional reinforcements such as SiC, B₄C, Al₂O₃, etc limits its usage. It is necessary to replace traditional reinforcements with low-cost reinforcement such as fly ash (FA), rice husk, natural minerals, etc to reduce its production cost. Fly ash is very cheaply available in large quantities as a solid waste by-product during the combustion of coal in thermal power plants. Irregular accumulation and inappropriate disposal of fly ash will lead to the global impact of pollution. Utilization of FA as a reinforcement serves as a double advantage of a suitable alternative to reduce environmental pollution and reduction of the production cost of AMCs [4–7]. Among the many techniques available to produce AMCs, stir casting is a very widely used method. In recent times, the ceramic particles reinforced AMCs have potential interests due to their low cost of production with improved mechanical and wear properties [8–10].

While investigating whether fly ash can be used as a reinforcing material in the aluminum matrix, Sudarshan and Surappa [11] have reported that fly-ash is suitable for producing lightweight, high wear resistance Al–FA composites. Dinaharan et al have reported that significant improvement in the microhardness and wear resistance of AA6061 aluminum matrix composite has been achieved by the incorporation of FA in an aluminum matrix [12].

Selvam et al have studied the effects of FA addition on high-temperature wear response of AA6061 matrix composites. It was found that the increase in the content of FA particles the wear resistance of the composite increased at all temperatures. Applied temperature significantly influences the mode of wear. The method of wear has been observed to be abrasive at room temperature and adhesion at high temperatures [13]. Significant improvement in the mechanical properties of Al–FA composites has been obtained with the increase in FA content by Selvam et al [14] and Rohtagi et al [15]. Furthermore, improvement of wear resistance of Al alloy with addition of FA has been reported by Rohtagi et al [15]. Suresh et al [16] have studied that the addition of FA up to 10% improves hardness, ultimate tensile strength, and elongation compared with untreated Al-Si base alloy. The
The present work aims to study the influence of fly ash addition on microstructure, mechanical properties, and wear resistance of Al–FA composites.

2. Experimental procedure

2.1. Characterization of raw materials and sample preparation

Stir casting method was adopted to synthesize the aluminum-fly ash metal matrix composites for this present work. The chemical composition of aluminum alloy is tabulated in Table 1. The fly ash (FA) was collected from Wanakbori Thermal Power Station, Gujarat. The bulk chemical composition of the as-received FA was analyzed by using x-ray Fluorescence (XRF), and the result is presented in Table 2. It is clear that the ash used belonged to class F fly ash, according to ASTM C 618 [17]. Field Emission Scanning Electron Microscope (FESEM) characterized the morphology of the FA particles. Whereas, the particle sizes of the FA particles were measured using image analysis software. Calculation of the ratio of the powder weight to its volume determines the density of the as-received FA particles.

The stir casting process prepared the Al–FA composites with different FA content (0, 5, 10, 15, 20, and 25 wt%). The as-received aluminum alloy (LM0) was melted in an induction furnace at 1073 K. The fly ash was preheated to 500 K for two hours for removal of moisture. The fly ash was introduced in the melt by wrapping into aluminum foil to ensure that even the lightest particles entered the melt. During the addition of fly ash particles, the melt temperature was maintained at 1023 K. The motor speed was kept at 120 rpm, and the melt was stirred vigorously in order to ensure proper mixing. The melt with reinforced particulates was poured into the metallic mold that was pre-heated at 400 K. The melt was poured into the mold and allowed to solidify in it.

Densities of the base metal and the cast Al–FA composites were determined by the Archimedes principle using water as an immersing medium. For microstructure characterization, samples were cut from a cylindrical bar of Al–FA composites and polished metallographically. Phases present in the as-received fly ash particles,

**Table 1. Chemical composition of as received aluminum alloy.**

| Elements | Si  | Cu  | Zn  | Mn  | Cr  | Aluminium |
|----------|-----|-----|-----|-----|-----|-----------|
| Wt%      | 0.95| 0.03| 0.04| 0.02| 0.02| Balance   |

**Table 2. Chemical composition of the as-received fly ash.**

| Oxides | SiO₂ | Al₂O₃ | Fe₂O₃ | CaO | MgO |
|--------|------|-------|-------|-----|-----|
| Wt%    | 63.80| 14.73 | 4.54  | 5.21| 1.22|

*Figure 1. Schematic representation of tensile sample (all dimension in mm).*
aluminum alloy, and Al–FA composites were characterized by x-ray diffraction (XRD) analysis. Keller’s reagent was used to etch the polished samples. Optical microscope (Leica DM 2500 M) and field emission scanning electron microscopy (FESEM) was used to study the microstructure and fracture surfaces of all the composites as well as the base material. Further, wear surfaces and debris were characterized by FESEM and SEM coupled with electron dispersive spectroscopy (EDS).

2.2. Hardness and tensile testing
The hardness of the base metal and the cast Al–FA composites were evaluated by using a Vickers diamond indenter operated at 2 kgf load with a dwell time of 10 s. A universal Testing Machine was utilized to conduct the

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Figure 2. Shows microstructure of fly ash (FA) particles: (a) precipitator, (b) magnetosphere and (c) particle size distribution curve.
tensile tests of the specimens having a gage length of 50 mm at room temperature. The tensile tests were carried out according to Indian standard IS 1608 [18]. The tensile properties of composites thus obtained were compared with those of base material. A typical sample for tensile testing is shown in figure 1.

2.3. Wear testing
A pin-on-disk apparatus [19, 20] was used to carry out wear tests on composite samples as well as the base material as per ASTM: G99-05 standard. Cylindrical pins of 7 mm diameter were cut from the samples. These specimens were then subjected to sliding wear tests under different normal loads of 9.81, 19.62 and 29.43 N against EN 31 hardened steel disc (60 HRC/HV 695). The wear tests were performed under dry sliding conditions with a constant sliding speed and sliding distance of 1.3 m s\(^{-1}\) and 1500 m, respectively. Wear surfaces, and FESEM characterized debris of the selected specimens.

3. Results and discussions
The microstructures of the as-received fly ash particles, obtained from Wanakbori Thermal Power Station in Gujarat, and are shown in figure 2. The morphology of the particles is close to that of ideal spheres. Most of the FA particles that are solid spheres are known as precipitators (figure 2(a)). The magnetic fraction in FA consists mostly of spherical particles that may be called magnetospheres. Most of these particles are found to be nearly spherical with rough surfaces, and a large number of glassy substances adhere to the particle surface (figure 2(b)). Particle size was determined using image analyzer software, and the particle size distribution curve is shown in

![Figure 3. Shows XRD patterns of (a) as received fly ash particles and (b) Al-10 wt% FA composite.](image-url)
The average particle size is $10 \pm 5 \mu m$. The bulk density of the as-received FA is found to be $2.01 \text{ g cm}^{-3}$.

The x-ray diffraction (XRD) patterns for the as-received fly ash particles and Al-10 wt% FA composite samples are shown in figure 3. The XRD patterns also support the XRF result that the silica, alumina, and iron oxides are significant phases present in as-received fly ash particles. Whereas, the XRD pattern of Al-10 wt% FA composite show that additional peaks of Si are present in the cast composite along with Al, SiO$_2$, Fe$_2$O$_3$, and Al$_2$O$_3$. The presence of peaks of Si indicates that in situ reactions may occur during casting. Reduction of SiO$_2$ with carbon results formation of Si.

The optical micrographs of the developed Al–FA metal matrix composites are presented in figures 4(a)–(e). The Al matrix appears bright, Si needles look gray and dark phase represents mostly pores, whereas, fly ash particles seem circular in shape. The FA particles and Si needles are homogeneously distributed throughout out aluminum matrix in the cast Al–FA composites. The micrographs clearly reveal that there is no segregation, which generally deteriorates the mechanical and tribological properties of the composite. Typical SEM micrograph and corresponding EDS pattern of different phases present in the Al–FA composites are shown in figures 5(a)–(d). Figure 5(a) shows Al dendrites, and primary Si is present in the microstructure of Al-10 wt% FA composite. The SEM micrograph of Al-20 wt% FA composite shows poorly bonded FA particles are also present along with Al dendrites and primary Si (figure 5(b)). EDS patterns of Al and primary Si phases are shown in figures 5(c) and (d), respectively.

The density and hardness of the base metal and developed composites are shown in figure 6. Results reveal that densities of the composites decrease with an increase in the percentage of fly ash. The composites show
much higher hardness compared to that of the as-received aluminum alloy. It is observed that the hardness of the composites increases by increasing the FA content within the composites up to 10 wt% FA. Hard reinforcement particles resist the plastic deformation of the composites; as a result, the hardness of the composites increases. However, with further increase in FA content (more than 10 wt%), the hardness is observed to decrease due to poor interfacial bonding figure 5(a) and low relative densities.

Figure 7 shows typical engineering stress-engineering strain diagrams of Al-0 wt%FA (as received LM0-aluminum casting alloy) composite. The yield stress is measured by considering the stress required to produce a 0.5 % strain. Yield calculated by offset method as per ASTM E8 at 0.5% strain offset. Figure 8 represents the yield and ultimate tensile strengths obtained from the engineering stress-strain curves of the base metal and Al–FA composites. Comparison in figure 8 shows that the yield and ultimate tensile strengths are improved with the addition of FA. The Al-10 wt% FA composite possesses maximum improvement in both yield and ultimate tensile strengths compared to other investigated composites. Variation in the percentage of elongation with composition is also shown in figure 8. The result indicates that the elongation decreases as the FA content increases. The strength and elongation both decrease with an increase in FA content leads to a lowering in toughness.

Typical photographs of tensile specimens before and after the test are shown in figures 9(a)–(d). Tensile specimens were prepared according to Indian standard IS 1608 [18] (figure 9(a)). Standard cup and cone fracture
Figure 6. Plots showing the variation of density and Vickers hardness with percentage fly ash (FA).

Figure 7. Plots showing typical stress-strain diagrams of Al-0 wt% FA (LM0-aluminum casting alloy).

Figure 8. Variation of the tensile properties in terms of UTS, YS, and percentage (%) of elongation of Al alloy and Al–FA composites as a function of FA content.
were obtained for Al-0FA, whereas brittle fractures were observed for Al-10 wt% FA and Al-15 wt% FA composites. Figures 10(a)–(f) shows the scanning electron micrographs of fractured surfaces obtained from tensile tests. The presence of dimples and voids on the fracture surface of as-received aluminum alloy confirming ductile fracture (figure 10(a)). Whereas, figures 10(b)–(f) shows facets and river patterns, confirming cleavage type transgranular brittle failure of Al–FA composites. The presence of localized dimples on the fracture surface of Al-10 wt% FA composite suggests localized ductile fracture.

3.1. Wear behavior

Figure 11 represents the change in cumulative wear, and coefficient of friction against the sliding distance of as-received aluminum alloy and Al–FA composites at a normal load of 29.43 N. Results indicate that variation of cumulative wear with sliding distance is highest for as-received aluminum alloy and lowest for Al-10 wt% FA composite (figure 11(a)). The plot shows that all composites undergo a significant cumulative wear loss in the initial 400 m sliding distance, followed by a reduced rate at which the cumulative wear loss increases. This result is supported by the plot of coefficient of friction with sliding distance (figure 11(b)) were change in the coefficient of friction with sliding distance is more significant in accelerated cumulative wear loss regime and undergoes almost steady-state after the seizure of wear. Critical observations from the wear studies can be summarized as follows: (i) the as-received aluminum alloy shows higher cumulative wear loss than those of other investigated composites, (ii) stepped cumulative wear loss has been observed in case of the Al-10 wt% FA composite, and (iii) variation of the coefficient of friction becomes almost constant afterward on the seizure of wear.

Effect of normal loads on wear rates of base metal (as-received aluminum alloy) and composites are shown in figure 12. A significant increase in wear rates has been observed after the application of normal load of 19.62 N for base metal, Al-5 wt% FA and Al-25 wt% FA composites. As the applied load increases, the pressure acting on the contact surface also increases. This causes greater rubbing action between the pin and the disc. As a result, the wear rate increases with increasing load. It was also observed that a sufficient amount of materials were transferred from pin to a steel disc with the application of high normal loads. The Al-10 wt% FA composite shows a lower wear rate compared to other alloy and composites. Sudarshan and Surappa [11] have reported dry sliding wear behavior of A356 Al-fly ash composites. They have observed that composites with 12 vol% fly ash and smaller particle sizes possess better wear properties compared to the base metal and A356 Al-6 vol% fly ash composite.

Figure 13 shows the variation of specific wear rates as a function of normal load applied on the base metal and composites. Results show that base metal possesses higher value of specific wear rate compared to composites at the same applied load. The specific wear rate decreases with an increase in load, and the rate of decline in the specific wear rate at higher loads is lower.

Scanning electron micrographs of the worn surfaces obtained after the wear experiments at a normal load of 29.43 N are shown in figures 14(a)–(f). The worn surface of base metal exhibits grooves, craters, and ridges caused by plastic deformation and material removal by delamination. Plastic flow is dominant at higher load due
Figure 10. Fractographs of the: (a) as received aluminum alloy; (b) A-5 wt% FA; (c) A-10 wt% FA; (d) A-15 wt% FA; (e) A-20 wt% FA; and (f) A-25 wt% FA.

Figure 11. (a) Cumulative wear versus sliding distance and (b) coefficient of friction versus sliding distance of as-received aluminum alloy and Al-FA composites.
to the generation of excessive frictional heat. The presence of a plastic flow region and deep grooves on the worn surface indicates that the wear mechanism is mainly controlled by adhesion.

Wear behavior of Al-5 wt% FA is also controlled by adhesion. This is confirmed in figure 14(b), which shows the presence of grooves on the worn surfaces. As the concentration of reinforced particles increases, the wear mechanism changes from adhesion to abrasion, which is evident in figure 14. Abrasion marks are clearly visible on the worn surface of Al-10 wt% FA (figure 14(c)) along with some adhesion marks. Oxidation is quite evident during wear test due to frictional heating caused by rubbing action of alloy/composite against hard counterface (steel disc). This oxidation is confirmed by observing figures 14(c)–(d) where fragmented oxide particles are present on the worn surfaces of Al-15 wt% FA composite. Delamination and material removal through plowing is more noticeable in Al-20 wt% FA and Al-25 wt% FA composites, which are evident in figures 14(e)–(f). From figure 14, it has been found that worn surface is smoother in Al-10 wt% FA composite compared to the other investigated base metal and composites subjected to wear test under the same normal load. This observation suggests that Al-10 wt% FA composite is more wear-resistant compared to other investigated base metal and composites. The EDS analysis confirms the presence of oxygen on the worn surfaces that were moderately oxidized during wear test.

Figure 15 shows the SEM micrographs of the worn surfaces obtained after wear test at different loads of Al-10 wt% FA composite and bulk EDS. Micrographs reveal that grooves are present parallel to the sliding
direction, and the depth of the grooves increases with increasing normal loads. Plastic deformation of matrix material and fracture of FA particles are probable at higher loads. The trapping of the FA particles between the specimen and the counterface results formation of the continuous grooves parallel to the direction of sliding. These cause a micro-plowing effect at the contact surface. High magnification views of the worn surface (figure 15(d)) show that cracks, oxide particles, and delaminated regions are present on the worn surface.

Figure 14. SEM micrographs showing worn surfaces and corresponding EDS of base metal and Al–FA composites tested at the load of 29.4 N: (a) base metal, (b) Al-5wt% FA, (c) Al-10wt% FA, (d) Al-15wt% FA, (e) Al-20wt% FA and (f) Al-25wt% FA.
Figure 16 shows SEM micrograph and EDS of wear debris obtained after wear test of Al-10wt% FA composite at lower load and higher load, respectively. Debris generated at low load exhibits a mixture of the layered structure caused by the removal of Al layers and granular particles, whereas granular morphology of wear debris is formed at a higher load. When the applied load is low, the fly ash particles remain intact during the wear test and act as useful abrasive elements, thereby supporting the applied load. At higher load, fly ash particles get fractured and produce granular type wear debris. The EDS patterns of the wear debris obtained after wear tests of Al-10wt% FA composite samples under low and high loads show Al, Si, Fe, and O peaks, confirming enrichment of Fe and O, besides that of Al. The EDS also shows the oxygen peak confirming the formation of oxides of Al.

A comparison of the dry sliding wear resistance in terms of wear rate of Al composites reinforced with FA, Al$_2$O$_3$, SiC, and TiB$_2$ is shown in figure 17. The result indicates that wear resistance of present investigated Al–FA composites is more or less similar to that of other reported Al–FA, Al–Al$_2$O$_3$, Al–SiC, or Al–TiB$_2$ composites.

4. Conclusion

The Al–FA composites with different FA content (0%, 5%, 10%, 15%, 20% and 25%) are synthesized by casting metallurgy route. The microstructure, mechanical properties, and sliding wear were studied, and the following conclusions are drawn from present results.
1. The homogeneous distribution of FA particles within the Al matrix is observed. The addition of the FA controls the grain size of the composites. A comparison of the average grain size of the composites implies that it is reduced with increasing FA content. From these results, it is inferred that the pinning effect refines the grain size of FA.

2. Hardness and tensile strength of the composites are improved by the addition of FA up to 10 wt%. The scanning electron microscope images of the fractured surfaces reveal that the base metal has failed in ductile mode. At the same time, the composites show quasi-cleavage rupture, which is also substantiated with the results of tensile testing.

Figure 16. SEM micrographs showing the morphology and bulk EDS of wear debris of the Al-10wt% FA composite tested under loads of (a) 9.8 N and (b) 29.4 N.

Figure 17. Comparisons of wear behavior of Al–FA composites [9, 11, 21–23].
3. Improvement of hardness, yield strength, and tensile strength by 100%, 80%, and 89%, respectively of the Al–FA composite, have been obtained by the addition of 10 wt% FA in as-received aluminum alloy.

4. The wear resistance of Al-10 wt% FA is observed to be higher compared to other investigated base metal and composites.

5. Increased load results in higher pressure at the contact point, which results in a greater rubbing action. As a result an increase in the applied load increases the wear rate.

6. Wear mechanisms involve adhesion as the dominating factor in base metal, while abrasion with micro-cutting and oxide formation predominates in composites.

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