Enactment of aluminium-fly ash composites

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Abstract. Aluminium metal matrix composites (AMMCs) augmented with fly ash particulates have brought notable recognition due to their inherent extensive physical, mechanical, tribological, and chemical response towards a number of applications with low cost in current times. Besides that, due to low density (fly ash), it exposes high strength to weight ratio to the metal matrix composite. It is gathered in thermal power plants in huge volumes like solid left-over by-product. The utilization of fly ash as a reinforcement waives the necessity of its disposal and inhibits environmental pollution. The existing paper contributes a comprehensive research analysis on the different performance of the fly ash reinforced aluminium composites manufactured by multiple methods. The current discussion has classified into separate segments according to the needed performance of aluminium reinforced including fly ash particles.

Keywords: AMMC, Physical properties, Mechanical properties & Tribological properties, Fly ash

1. Introduction

Metal matrix composites (MMCs) are achieving applications in various fields due to their attractive features. Among them, aluminum metal matrix composite (AMMC) has a unique priority because of its high strength and strength to weight ratio. These properties execute it possible for its application in aircraft and automotive industries etc. [1-7]. However, these aluminum metal matrix composites are mainly reinforced with ceramic particles which are very expensive and sometimes outcome in a raise in weight density of composites [8-9]. So, there is a need for replacement of these reinforcements for economic and performance reasons and from literature, it is quite evident that fly ash can do this job in a very efficient manner along with the reduction of environmental pollution caused by it [10-12]. Fly ash is gathered due to burning of coal in electric power plant and consider as an industrial byproduct. A coal combustion residue (CCR) i.e. Fly ash is a non-homogeneous substance with the finest CCR (0.2µm -90µm). It is obtained because of the transformation of the mineral particles existing in coal particles throughout the combustion [13]. The fly ash can also be classified as precipitator fly ash and cenosphere fly ash. Precipitator fly ash is the solid spheres having the density ranging from 2.0g cm-3 to 2.5 g cm-3. Cenosphere fly ash is hollow spheres having the density very less than the precipitator fly ash. This is less than 1 gm cm-3 (approximately 0.306gm cm-3). Coal fly ash is used in many advanced industries like cement and concrete while nowadays creatively fly ash is being used for the fabrication of MMCs.

2. Physical Properties

2.1. Effect of fly ash weight percentage on Density
Figure 1. The density of various AMMCs with a varying amount of fly ash (wt.%)  

Figure 1 presents the density of various AMMCs with a varying amount of fly ash. Dwivedi et al. [19] reinforced various amounts of SiC and fly ash in to A356 aluminium alloy through modified electromagnetic stir casting route. It is revealed so as the experimental density is found to be less than theoretical density. It is because of the presence of adverse porosity and density that reduces with raising fly ash amount. Mahendra et al. [21] have exposed that the reinforcement addition decreases the density in the composite of Al-4.5% Cu alloy reinforced with silicon carbide with fly ash (added in equal proportion of 5, 10 and 15 wt.%). They have prepared MMC through conventional foundry techniques. Prakash [25] showed that adding fly ash with boron carbide (B, C) to the A356 matrix through stir casting decreases the density of the AMMC. The densities of fly ash (=2.09 g/cm³) and boron carbide (=2.52 g/cm³) are less than that of the aluminum alloys. The composite of Aluminum alloy (LM6) reinforced with different weight percentage of fly ash are prepared via compo casting method [26]. It is revealed that the addition of the fly ash reduces the density gradually. It is because of its low density of ash particles that reduce the combined density of the AMMCs. Prasat [27] found that density was found to decline with raising amount of fly ash in the composite of AlSi10Mg reinforced with fly ash along with 3% wt. of graphite prepared by liquid metallurgy route. Bharati [28] found that in the composite of LM25 reinforced by means particles of fly ash through stir-squeeze casting. It is experimented that the density reduces from 2.6515 gm/cm³ to 2.6190 gm/cm³ on addition of 5wt. % fly ash. Ramachandra [20] experimented on a new composite taking Al-Si alloy reinforced with fly ash through liquid metallurgy route. They proclaimed that the density reduces from 2.62 gm/cm³ to 1.613gm/cm³ on addition of 15wt. % fly ash. Bhaskar et al. [29] prepared an aluminum-based AA2024 alloy reinforced by SiC and fly ash primed with stir casting. They disclosed that the increase in porosity due to supplement of fly ash which is lower than the theoretical density of MMC. Reddy et al. [23] studied the effect of addition of fly ash in AA7075 alloy along with varying from 5 to 10 percent by weight using SiC processed through the stir casting technique. It is found that the fly ash and SiC particulate addition reduces the density of the resulting composites because of the low density of fly ash particles.
3. Mechanical Properties

3.1. Effect of fly ash percentage on Ultimate Tensile Strength (UTS)

Figure 2. Ultimate Tensile Strength of Various Aluminium Matrix with respect to Fly ash (%)

Figure 2 presents the Ultimate Tensile Strength of Various Aluminum Matrix Composite including weight percentage of fly ash. Selvam [14] prepared different AMMC taking weight percentages of fly ash particles with AA6061 aluminum alloy through compocasting method. They reported there is a strain field created in between AA6061 particles and fly ash particles during solidification due to difference in coefficient of thermal expansion. The strain fields so generated that opposes the movement of dislocations which provides resistance to the crack propagation. Therefore, the fly ash particles refine the grains providing more grain boundary area for resisting the tensile strength. The clean interface and proper bonding between fly ash particles and AA6061 particles do not allow the detachment of particles. The Orowan strengthening occurs because of homogeneous distribution of fly ash particles and thus improving the UTS. It is experimented that AA6061 with 12wt % fly ash (AMMC) showed 56.95% higher value of UTS than that of base alloy. Kulkarni et al. [15] found that inclusion of alumina (Al2O3) with fly ash setup hybrid reinforcement with A356 that enhances the tensile strength, manufactured by ameliorated stir casting technique. They proclaimed that tensile load increases in their new composite because the particles of fly ash oppose the dislocations during tensile loading. Patel et al. [16] exposed their research work taking AL6061 aluminum alloy with E-Glass fiber and fly ash. They found that tensile strength of AMMC increases with increasing in fly ash amount made by through stir casting method. Gikunoo et al. [17] in their work exhibited the addition of fly ash with A535 alloy that multiplies porosity due to non-uniform distribution as well as segregation of aluminum dendrite along the boundaries causing particle clusters at the boundaries. This in turn influences both tensile as well as compressive properties of AMMC. The mechanical properties like tensile strength was investigated by Narasaraju et al. [18] implemented bio-composite such as rice husk ash (RHA) along with fly ash in AlSi10Mg alloy using stir casting method. Ten percentages (10%) of rice husk with ten percentages (10%) fly ash in AlSi10Mg alloy have presented the optimum tensile strength than any other samples because of its poor wettability problem with rise in RHA. Mechanical behavior such as tensile strength of the sample specimens have examined by Dwivedi et al. [19]. They have manufactured the composite matrix implementing A356 aluminum alloy that reinforced with various percentage of SiC and fly ash through modified electromagnetic stir
casting route. They have revealed that the composite made of A356 alloy containing 15% SiC and 5% fly ash showed best result (highest UTS) amongst all other samples for as-cast along with heat-treated composite. Ramachandra [20] have shown that UTS increases from 255.6 MPa to 305.8 MPa by 19.64% on addition of 15% fly ash to Al-Si alloy produce through liquid metallurgy process. Mahendra et al. [21] found that the reinforcement addition increases the tensile strength in the composite of Al-4.5% Cu alloy reinforced with fly ash and silicon carbide (added in equal proportion of 5, 10 and 15 wt.%) prepared through conventional foundry techniques. Fly ash addition raised the ultimate tensile strength (UTS) in the composite of Al-3Mg (wt. %) through liquid metallurgy route as reported by Sarkar et al. [22]. It is presented that Al-11.52 wt.% with fly-ash have raised UTS by 57.44%. The consequence of fly ash inclusion on tensile strength has investigated by Reddy et al. [23]. AA7075 alloy that manufactured with 5wt.% and 10 wt.% of fly ash along with SiC through stir casting technique reported to be improving the tensile strength.

3.2. Effect of fly ash percentage on percentage elongation of AMMCs

![Figure 3. Effect of Percentage Elongation Metal Matrix Composite with respect to Fly ash (%)](image)

Figure 3 presents the Percentage elongation of Various AMMC with varying fly ash weight percentage. Selvam [14] who reinforced various weight percentages of fly ash particles into AA6061 aluminium alloy through compocasting method reported that the addition of fly ash particles reduces the ductile matrix amount as well as refines the grains leading to reduce the ductility and % elongation of the AMMCs. Gikunoo et al. [17] in their work revealed that inclusion of fly ash content decreases % elongation in both casting and heat treated condition in A535 that reinforced with fly ash. This reduction in % elongation value of the aluminum composites is due to particle clustering and porosity, which rise with raising the fly ash amount. Bhandarkar et al. [24] reveal that fly ash addition decreases the % elongation in the composite of AA2024-fly ash-silicon carbide prepared by stir casting through liquid metallurgy followed by hot extrusion process. Percentage elongation decreases from 10.1%(AA2024 matrix) to 1.1% (AA2024 + 5% fly ash) and then increased to 2.09% (AA2024 + 10% fly ash) as shown in figure 3. Ramachandra [20] found that %elongation decreases from 6.8% to 2.1% in the composite of Al-Si alloy reinforced with fly ash particles on addition of 15wt% fly ash in the composite of Al (12 wt. % Si) reinforced with fly ash and prepared by vortex method. Patel et al. [16] found that percentage elongation increases with addition of fly ash except at 6% fly ash sample in the AA6061 alloy reinforced with E-Glass fiber and fly ash made through stir casting method.
3.3. Rockwell Hardness Vs fly ash amount

Figure 4 represents the Sintered hardness for different AMMCs with varying fly ash content. Jailani et al. [32] prepared their composite of aluminium silicon alloy reinforced with fly ash (5-15%) by powder metallurgy. The hardness of the composites increased with increase in fly ash content (up to 12 wt.-%). It also increased with increase in sintering temperature from 575 to 600°C. However, the hardness decreased above 12 wt.-% of fly ash irrespective of sintering temperature. The reason for the decrease in the hardness of the composites containing more than 12 wt.-% of fly ash is due to clustering of fly ash particles leading to degradation in the quality of sintering. The degradation is attributed to higher melting point (1300°C) of the fly ash, which is not properly sintered due to the clustering nature of fly ash above 12 wt.-% in the composites. It is also observed that the maximum hardness of the composites occurs at 12 wt.-% of fly ash content.

Guo et al. [33] prepared Al-fly ash composites with different weight fractions of fly ash by powder metallurgy. Hardness increased a little up to 10 wt.-% and then decreased for sintering temperature of 645°C but increasing weight per cent of fly ash for sintering temperature of 625°C results in a decrease in hardness of aluminium fly ash compacts. The results revealed that for improved properties of aluminium-fly ash composite, longer sintering times and higher sintering temperatures are favorable.
3.4. UTS Vs fly ash particle size

![Graph showing the effect of fly ash particle size on ultimate tensile strength of AMMC. The graph depicts the relationship between UTS (MPa) and Fly Ash (wt%).](image)

Figure 5. Effect of fly ash particle size on ultimate tensile strength of AMMC

Figure 5 represents the effect of fly ash particle size on ultimate tensile strength of AMMC. Anilkumar et al. [34] reported the effect of size of fly ash in fly ash and silicon carbide reinforced aluminium alloy Al6061 prepared by stir casting route. The results revealed that fly ash addition enhances the tensile strength up to 15wt% of fly ash and after it decreases because of adverse porosity effect and poor wettability. The increase is due to the fact that the hard fly ash particles act as barrier to dislocation motion as well as they bear the load transferred by the matrix leading to strengthening. Higher particle size of fly ash reduces the tensile strength as smaller size particles make good bonding with the matrix.

3.5. Hardness (BHN) vs fly ash particle size

Figure 6 represents the effect of fly ash particle size on Brinell hardness of AMMC. Anilkumar et al. [34] reported the effect of size of fly ash in fly ash and silicon carbide reinforced aluminium alloy Al6061 prepared by stir casting route. The results revealed that fly ash addition enhances the hardness due to the inclusion of the hard fly ash particles. Higher particle size of fly ash reduces the hardness.
4. Wear Properties

4.1. Effect of fly ash percentage on wear rate

Figure 7 outlines the change of wear rate with fly ash at varying temperatures for several AMMCs. Kumar et al. [30] continued their research work by adding fly ash with AA6061 to form a new composite through the powder metallurgy approach. They discussed that the inclusion of the fly ash limits the rate of wear. It is because of the fine size of Fly ash that doesn't support any fracture as well as creates sound bonding which supports the matrix not to deform. Therefore, the removals of material from the sliding surface have checked. Consequently, it proved a higher wear resistance in the temperature range as studied. They also represented an interesting phenomenon that the unreinforced alloy exposed three state of wear. Mild to severe wear limits between 2000°C to 3000°C. It is happening due to severe plastic deformation of the base matrix. In the case of composites, there is subsurface hardening by the presence of fly ash particles which helps the composite not to expose any such transition state up to 300°C. This “particulate hardening” of the sub-surface at higher temperatures is the reason for the lower wear rate of AMMC (AA6061+fly ash) than that of the base alloy AA6061 at the severe wear regions. It is normally found that by raising the contact surface’s hardness here transition shifts to higher loads and higher temperatures.
Investigation for Wear analysis of AMMC (AA6061-fly ash) has been carried out by Selvam et al [31] employing “pin-on-disc apparatus”. They conducted experiments with varying fly ash amounts accompanying with different values of temperatures and at a fixed load of 24.5N, through a fixed sliding distance of 2km. Simultaneously they fixed sliding speed of 1.57m/s. They followed the compo-casting method in stir casting furnace. They found that Wear rate decreases with a raise in fly ash components. It because of the harder fly ash components opposes dislocation motion. Therefore, both hardness as well as the wear increases. For a constant amount of fly ash, rate of increasing Wear is a function of temperature. As the sliding progresses for a longer duration of time, the pingets softened due to a rise in temperature. As a result of this softening of the aluminum alloy AA6061, the interfacial stress exceeds the bonding strength among the matrix and reinforced fly ash particles leading to pulling out of fly ash particulates. These bug-off particles of fly ash are trapped around the pin surface that the harder counter face and then crushed into fine particles. The softer base alloy and finer fly ash particles generate a protective layer owing to the higher temperature leading to decreased wear rate. Composite prepared by powder metallurgy route had shown better wear resistance than that made by the compo-casting technique.

5. Conclusion
From the above literature review, the following conclusions can be drawn.
1. Mechanical properties such as tensile strength, hardness of AMMC increases with increasing fly-ash content.
2. The wear rate of composite decreases in comparison to that of base metal. As the fly ash percentage in the MMC increases the wear resistance gets improved.
3. The effective use of the fly-ash in the production of the composites and this industrial waste can be recycled into an industrial asset for which storing and dumping of fly ash problem can be minimized.

4. Industrial waste can be utilized to solve the problem of fly ash disposal.

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