



Research Paper

FABRICATION AND CHARACTERISATION OF ALUMINIUM-FLY ASH COMPOSITE USING STIR CASTING METHOD

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Metal matrix composites (MMCs) possess significantly improved properties including high specific strength; specific modulus, damping capacity and good wear resistance compared to unreinforced alloys. There has been an increasing interest in composites containing low density and low cost reinforcements. Among various discontinuous dispersoids used, fly ash is one of the most inexpensive and low density reinforcement available in large quantities as solid waste byproduct during combustion of coal in thermal power plants. Hence, composites with fly ash as reinforcement are likely to overcome the cost barrier for wide spread applications in automotive and small engine applications. It is therefore expected that the incorporation of fly ash particles in aluminium alloy will promote yet another use of this low-cost waste by-product and, at the same time, has the potential for conserving energy intensive aluminium and thereby, reducing the cost of aluminium products. Now a days the particulate reinforced aluminium matrix composite are gaining importance because of their low cost with advantages like isotropic properties and the possibility of secondary processing facilitating fabrication of secondary components. The present investigation has been focused on the utilization of abundantly available industrial waste fly-ash in useful manner by dispersing it into aluminium to produce composites by stir casting method.

Keywords: Particulate composites, Industrial waste, Applied load and sliding velocity

INTRODUCTION

Conventional monolithic materials have limitations in achieving good combination of strength, stiffness, toughness and density. To overcome these shortcomings and to meet the ever increasing demand of modern day

technology, composites are most promising materials of recent interest. Metal matrix composites (MMCs) possess significantly improved properties including high specific strength; specific modulus, damping capacity and good wear resistance compared to unreinforced alloys. There has been an

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Now a days the particulate reinforced aluminium matrix composite are gaining importance because of their low cost with advantages like isotropic properties and the possibility of secondary processing facilitating fabrication of secondary components. Cast aluminium matrix particle reinforced composites have higher specific strength, specific modulus and good wear resistance as compared to unreinforced alloys.

Composite material is a material composed of two or more distinct phases (matrix phase and reinforcing phase) and having bulk properties significantly different from those of any of the constituents. Many of common materials (metals, alloys, doped ceramics and polymers mixed with additives) also have a small amount of dispersed phases in their structures, however they are not considered as composite materials since their properties are similar to those of their base constituents (physical property of steel are similar to those of pure iron). Favorable

properties of composites materials are high stiffness and high strength, low density, high temperature stability, high electrical and thermal conductivity, adjustable coefficient of thermal expansion, corrosion resistance, improved wear resistance etc.

MATRIX PHASE

1. The primary phase, having a continuous character,
2. Usually more ductile and less hard phase,
3. Holds the reinforcing phase and shares a load with it.

REINFORCING PHASE

1. Second phase (or phases) is imbedded in the matrix in a discontinuous form,
2. Usually stronger than the matrix, therefore it is sometimes called reinforcing phase.

Composites as engineering materials normally refer to the material with the following characteristics:

1. These are artificially made (thus, excluding natural material such as wood).
2. These consist of at least two different species with a well-defined interface.
3. Their properties are influenced by the volume percentage of ingredients.
4. These have at least one property not possessed by the individual constituents.

CLASSIFICATION OF COMPOSITES

a) On the basis of Matrix

- **Metal Matrix Composites (MMC)**
Metal Matrix Composites are

composed of a metallic matrix (aluminium, magnesium, iron, cobalt, copper) and a dispersed ceramic (oxides, carbides) or metallic (lead, tungsten, molybdenum) phase.

- **Ceramic Matrix Composites (CMC)** Ceramic Matrix Composites are composed of a ceramic matrix and imbedded fibers of other ceramic material (dispersed phase).
- **Polymer Matrix Composites (PMC)** Polymer Matrix Composites are composed of a matrix from thermoset (Unsaturated polyester (UP), Epoxy) or thermoplastic (PVC, Nylon, Polysterene) and embedded glass, carbon, steel or Kevlar fibers (dispersed phase).

b) On the basis of Material Structure

- **Particulate Composites:** Particulate Composites consist of a matrix reinforced by a dispersed phase in form of particles.
- Composites with random orientation of particles.
- Composites with preferred orientation of particles.

Dispersed phase of these materials consists of two-dimensional flat platelets (flakes), laid parallel to each other.

Fibrous Composites

Short-fiber reinforced composites: Short-fiber reinforced composites consist of a matrix reinforced by a dispersed phase in form of discontinuous fibers (length $100 \times \text{diameter}$).

- Composites with random orientation of fibers.
- Composites with preferred orientation of fibers

Long-fiber reinforced composites: Long-fiber reinforced composites consist of a matrix reinforced by a dispersed phase in form of continuous fibers.

- Unidirectional orientation of fibers.
- Bidirectional orientation of fibers (woven).

Laminate Composites

When a fiber reinforced composite consists of several layers with different fiber orientations, it is called multilayer (angle-ply) composite.

RULE OF MIXTURES

Rule of Mixtures is a method of approach to approximate estimation of composite material properties, based on an assumption that a composite property is the volume weighed average of the phases (matrix and dispersed phase) properties.

According to Rule of Mixtures properties of composite materials are estimated as follows:

$$\text{Density } d_c = d_m \cdot V_m + d_f \cdot V_f$$

Where,

d_c, d_m, d_f - densities of the composite, matrix and dispersed phase respectively;

V_m, V_f - volume fraction of the matrix and dispersed phase respectively.

Coefficient of Thermal Expansion

- Coefficient of Thermal Expansion (CTE) in longitudinal direction (along the fibers)

$$\alpha_{cl} = (m \cdot E_m \cdot V_m + f \cdot E_f \cdot V_f) / (E_m \cdot V_m + E_f \cdot V_f)$$

Where,

α_{cl} , m , f - CTE of composite in longitudinal direction, matrix and dispersed phase (fiber) respectively;

E_m, E_f - modulus of elasticity of matrix and dispersed phase (fiber) respectively.

- Coefficient of Thermal Expansion (CTE) in transverse direction (perpendicular to the fibers)

$$\alpha_{ct} = (1 + P_m) m \cdot V_m + f \cdot V_f$$

P_m - Poisson ratio of matrix.

Poisson's ratio is the ratio of transverse contraction strain to longitudinal extension strain in the direction of applied force.

Modulus of Elasticity

- Modulus of Elasticity in longitudinal direction (**E_{cl}**)

$$E_{cl} = E_m \cdot V_m + E_f \cdot V_f$$

- Modulus of Elasticity in transverse direction (E_{ct})

$$1/E_{ct} = V_m/E_m + V_f/E_f$$

Tensile Strength

- Tensile strength of long-fiber reinforced composite in longitudinal direction

$$c = m \cdot V_m + f \cdot V_f$$

Where,

c, m, f - tensile strength of the composite, matrix and dispersed phase (fiber) respectively.

- Tensile strength of short-fiber composite in longitudinal direction (Fiber length is less than critical value L_c)

$$L_c = f \cdot d / c$$

Where,

d - Diameter of the fiber;

c -shear strength of the bond between the matrix and dispersed phase (fiber).

$$c = m \cdot V_m + f \cdot V_f \cdot (1 - L_c/2L)$$

Where,

L - Length of the fiber

- Tensile strength of short-fiber composite in longitudinal direction (fiber length is greater than critical value L_c)

$$c = m \cdot V_m + L \cdot c \cdot V_f / d$$

METAL MATRIX COMPOSITES (MMCs)

Metal Matrix Composites are composed of a metallic matrix (Al, Mg, Fe, Cu etc) and a dispersed ceramic (oxide, carbides) or metallic phase (Pb, Mo, W etc). Ceramic reinforcement may be silicon carbide, boron, alumina, silicon nitride, boron carbide, boron nitride etc. whereas Metallic Reinforcement may be tungsten, beryllium etc. MMCs are used for Space Shuttle, commercial airliners, electronic substrates, bicycles, automobiles, golf clubs and a variety of other applications. From a material point of view, when compared to polymer matrix composites, the advantages of MMCs lie in their retention of strength and stiffness at elevated temperature, good abrasion and creep resistance properties. Most MMCs are still in the development stage or the early stages of production and are not so widely established as polymer matrix composites. The biggest disadvantages of MMCs are their high costs of fabrication, which has placed limitations on their actual applications. There are also advantages in some of the physical attributes of MMCs such as no significant moisture absorption properties, non-inflammability, low electrical and thermal conductivities and resistance to most radiations. MMCs have existed for the past 30 years and a wide range of MMCs have been studied.

Compared to monolithic metals, MMCs have

- Higher strength-to-density ratios
- Higher stiffness-to-density ratios
- Better fatigue resistance
- Better elevated temperature properties

- Higher strength
- Lower creep rate
- Lower coefficients of thermal expansion
- Better wear resistance

The advantages of MMCs over polymer matrix composites are:

- Higher temperature capability
- Fire resistance
- Higher transverse stiffness and strength
- No moisture absorption
- Higher electrical and thermal conductivities
- Better radiation resistance
- No out gassing
- Fabric ability of whisker and particulate reinforced

MMCs with conventional metalworking equipment.

Some of the disadvantages of MMCs compared to monolithic metals and polymer matrix composites are:

- Higher cost of some material systems
- Relatively immature technology
- Complex fabrication methods for fiber-reinforced systems (except for casting)
- Limited service experience

MATERIALS AND METHODS

Stir Casting Method Of Fabrication Of Mmcs

Liquid state fabrication of Metal Matrix Composites involves incorporation of dispersed phase into a molten matrix metal, followed by its Solidification. In order to provide high level of mechanical properties of the composite, good interfacial bonding (wetting) between the dispersed phase and the liquid matrix should be obtained.

Wetting improvement may be achieved by coating the dispersed phase particles (fibers). Proper coating not only reduces interfacial energy, but also prevents chemical interaction between the dispersed phase and the matrix.

The simplest and the most cost effective method of liquid state fabrication is Stir Casting.

Stir Casting

Stir Casting is a liquid state method of composite materials fabrication, in which a dispersed phase (ceramic particles, short fibers) is mixed with a molten matrix metal by means of mechanical stirring. The liquid composite material is then cast by conventional casting methods and may also be processed by conventional Metal forming technologies.

Figure 1: Stir Casting Setup



Stir Casting is characterized by the following features

- Content of dispersed phase is limited (usually not more than 30 vol. %).
- Distribution of dispersed phase throughout the matrix is not perfectly homogeneous:
- There are local clouds (clusters) of the dispersed particles (fibers);
- There may be gravity segregation of the dispersed phase due to a difference in the densities of the dispersed and matrix phase.

- The technology is relatively simple and low cost.

Strengthening Mechanism Of Composites

The strengthening mechanisms of the composites are different with different kind of reinforcing agent morphology such as fibers, particulate or dispersed type of reinforcing elements.

Dispersion Strengthening Mechanism of Strengthened Composite

In the dispersion strengthened composite the second phase reinforcing agents are finely dispersed in the soft ductile matrix. The strong particles restrict the motion of dislocations and strengthen the matrix. Here the main reinforcing philosophy is by the strengthening of the matrix by the dislocation loop formation around the dispersed particles. Thus the further movement of dislocations around the particles is difficult. Degree of strengthening depends upon the several factors like volume % of dispersed phase, degree of dispersion, size and shape of the dispersed phase, inter particle spacing etc. In this kind of composite the load is mainly carried out by the matrix materials.

Strengthening Mechanism of Particulate Composite

In the particulate reinforced composite the size of the particulate is more than 1 μm , so it strengthens the composite in two ways. First one is the particulate carry the load along with the matrix materials and another way is by formation of incoherent interface between the particles and the matrix. So a larger number of dislocations are generated at the interface, thus material gets strengthened. The degree of strengthening depends on the amount of particulate (volume fraction),

distribution, size and shape of the particulate etc.

Fly Ash

Fly ash is one of the residues generated in the combustion of coal. It is an industrial by product recovered from the flue gas of coal burning electric power plants. Depending upon the source and makeup of the coal being burned, the components of the fly ash produced vary considerably, but all fly ash includes substantial amounts of silica (silicon dioxide, SiO_2) (both amorphous and crystalline) and lime (calcium oxide, CaO). In general, fly ash consists of SiO_2 ,

Al_2O_3 , Fe_2O_3 as major constituents and oxides of Mg, Ca, Na, K etc. as minor constituent. Fly ash particles are mostly spherical in shape and range from less than 1 μm to 100 μm with a specific surface area, typically between 250 and 600 m^2/kg . The specific gravity of fly ash vary in the range of 0.6-2.8 gm/cc . Coal fly ash has many uses including as a cement additive, in masonry blocks, as a concrete admixture, as a material in lightweight alloys, as a concrete aggregate, in flowable fill materials, in roadway/runway construction, in structural fill materials, as roofing granules, and in grouting. The largest application of fly ash is in the cement and concrete industry, though, creative new uses for fly ash are being actively sought like use of fly ash for the fabrication of MMCs.

Classification of Fly Ash on the Basis of Chemical Composition

i. Class F fly ash

The burning of harder, older anthracite and bituminous coal typically produces Class F fly ash. This fly ash is pozzolanic in nature, and contains less than 10% lime (CaO). Possessing pozzolanic properties, the glassy silica and alumina of Class F fly ash requires

a cementing agent, such as Portland cement, quicklime, or hydrated lime, with the presence of water in order to react and produce cementitious compounds. Alternatively, the addition of a chemical activator such as sodium silicate (water glass) to a Class F ash can lead to the formation of a geopolymer.

ii. Class C fly ash

Fly ash produced from the burning of younger lignite or sub bituminous coal, in addition to having pozzolanic properties, also has some self-cementing properties. In the presence of water, Class C fly ash will harden and gain strength over time. Class C fly ash generally contains more than 20% lime (CaO). Unlike Class F, self-cementing Class C fly ash does not require an activator. Alkali and sulfate (SO₄) contents are generally higher in Class C fly ashes.

On the basis of size, shape and structure

i. Precipitator fly ash

It is spherical in nature, the spheres are solid and the density is in the range of 2.0-2.5 g/cm³.

ii. Cenosphere fly ash

It is also spherical in shape but these spheres are hollow, so the density of this kind of fly ash is very less as compared to the precipitator fly ash. Here density is less than 1 gm/cm³ (0.3-0.6 gm/cm³)

WHY FLY ASH

1. The preference to use fly ash as a filler or reinforcement in metal and polymer matrices is that fly ash is a byproduct of coal combustion, available in very large quantities (80 million tons per year) at very low costs since much of this is currently land filled. Currently, the use of manufactured glass microspheres has limited applications due mainly to their

high cost of production. Therefore, the material costs of composites can be reduced significantly by incorporating fly ash into the matrices of polymers and metallic alloys. However, very little information is available on to aid in the design of composite materials, even though attempts have been made to incorporate fly ash in both polymer and metal matrices. Cenosphere fly ash has a lower density than talc and calcium carbonate, but slightly higher than hollow glass. The cost of cenosphere is likely to be much lower than hollow glass. Cenosphere may turn out to be one of the lowest cost fillers in terms of the cost per volume.

2. The high electrical resistivity, low thermal conductivity and low density of fly-ash may be helpful for making a light weight insulating composites.
3. Fly ash as a filler in Al casting reduces cost, decreases density and increase hardness, stiffness, wear and abrasion resistance. It also improves the machinability, damping capacity, coefficient of friction etc. which are needed in various industries like automotive etc.
4. As the production of Al is reduced by the utilization of fly ash. This reduces the generation of greenhouse gases as they are produced during the bauxite processing and alumina reduction.

Chemical Reaction Between Al And Fly Ash

The thermodynamic analysis indicates that there is possibility between the reaction of Al melt and the fly ash particles. The particles contain alumina, silica and iron oxide which during solidification process of Al fly ash composites or during holding such

composites at temperature above 8500°C, are likely to undergo chemical reactions, reported by P.K.Rohatagi and Guo. The experiments indicate that there is a progressive reduction between SiO₂, Fe₂O₃ and mullite by Al and formation of Al₂O₃, Fe and Si. The wall of cenosphere fly ash particles progressively disintegrates into discrete particles into the reaction progress.

EXPERIMENTAL PROCEDURE

First of all, 400 gm of commercially pure aluminium was melted in a resistance heated muffle furnace and casted in a clay graphite crucible. For this the melt temperature was raised to 993K and it was degassed by purging hexachloro-ethane tablets. Then the aluminium-fly ash (5%, 10%, 15%, and 20%) composites were prepared by stir casting route. For this we took 400 gm of commercially pure aluminum and then (5, 10, 15, 20) wt% of fly ash were added to the Al melt for production of four different composites. The fly ash particles were preheated to 373K for two hours to remove the moisture. Commercially pure aluminium was melted by raising its temperature to 993K and it was degassed by purging hexachloro ethane tablets. Then the melt was stirred using a mild steel stirrer. Fly-ash particles were added to the melt at the time of formation of vortex in the melt due to stirring. The melt temperature was maintained at 953K- 993K during the addition of the particles. Then the melt was casted in a clay graphite crucible. The particle size analysis and chemical composition analysis was done for fly ash. The hardness testing and density measurement was carried out Al-(5, 10, 15, and 20) wt% fly ash composites. The hardness of the samples was determined by Brinell hardness testing machine with 750 kg load and 5 mm diameter steel ball indenter.

The detention time for the hardness measurement was 15 seconds.

The wear characteristics of Al-fly ash composites were evaluated using wear testing machine. For this, cylindrical specimens of 1.1 cm diameter and 2.1 cm length were prepared from the cast Al-fly ash composites. Test was performed at under different loads and rpm for 10 minutes. The SEM was done for all the samples.

WORKS DONE

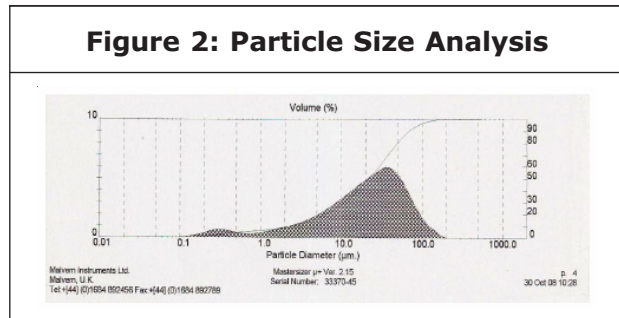
1. Commercially pure Al was melted and casted.
2. Al-(5%, 10%, 15%, and 20%) fly ash composite was fabricated by stir casting method.
3. Particle size analysis was done for fly ash used.
4. Hardness measurement was carried out for Al-fly ash composite samples.
5. The wear characteristics of Al-fly ash composite samples were evaluated and compared.
6. SEM analysis was done for all the Al-fly ash composite samples, Fly-ash and worn surfaces.

RESULTS AND DISCUSSION

Chemical Analysis of Fly Ash

Compounds	Percentage (%)
SiO ₂	67.2
Al ₂ O ₃	29.6
Fe ₂ O ₃	0.1
CaO	1.4
MgO	1.7

Particle Size Analysis of Fly Ash



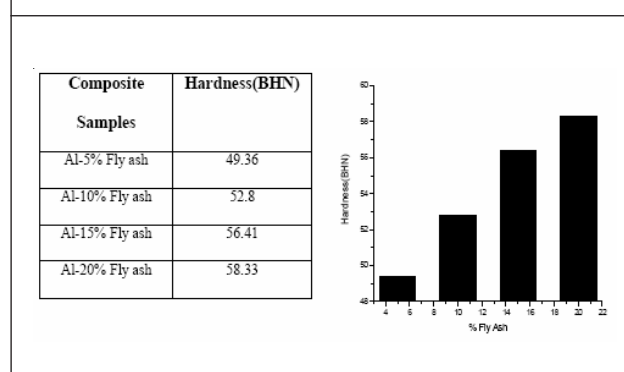
The size, density, type of reinforcing particles and its distribution have a pronounced effect on the properties of particulate composite. Size range of fly ash particles is reported in the above figure. The size range of the particles is very wide i.e. 0.1 micron to 100 micron. The size ranges of the fly ash particles indicate that the composite prepared can be considered as dispersion strengthened as well as particle reinforced composite.

As is seen from the particle size distribution there are very fine particles as well as coarse ones (1-100 µm). Thus the strengthening of composite can be due to dispersion strengthening as well as due to particle reinforcement. Dispersion strengthening is due to the incorporation of very fine particles, which help to restrict the movement of dislocations, whereas in particle strengthening, load sharing is the mechanism. Strengthening of matrix may occur because of solid solution strengthening.

Hardness Measurement

The above table shows that incorporation of fly ash particles in Aluminium matrix causes reasonable increase in hardness. The strengthening of the composite can be due to dispersion strengthening as well as due to particle reinforcement. Thus, fly ash as filler in Al casting reduces cost, decreases density and increase hardness which are needed in various industries like automotive etc.

Figure 3: Hardness



Wear Behaviour

In the graphs below the colour coding is as follows:-

1. Blue for Al-5% Fly ash
2. Red for Al-10 % Fly ash
3. Black for Al-15% Fly ash
4. Green for Al-20% Fly ash

Figure 4(a): Wear Behavior of MMCS with Different % of Fly Ash at 20N Load and 240rpm

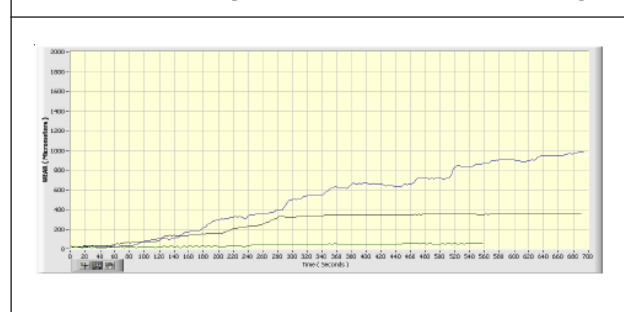


Figure 4(b): Variation of Frictional Force with Different % of Fly Ash at 20N Load and 240 rpm

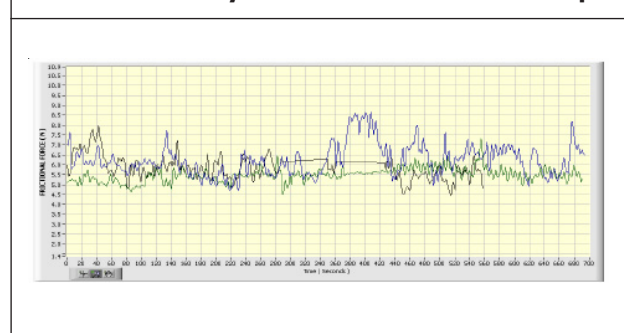


Figure 4(c): Wear Behavior of MMCS with Different % of Fly Ash at 50N Load and 240rpm

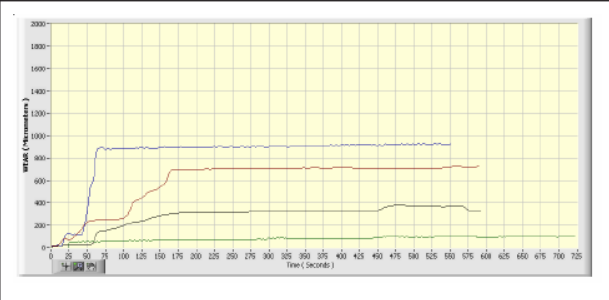


Figure 4(g): Wear Behavior of for Al-(5%) Fly Ash Composite at 240 rpm and at 20N (red line) and 50N(blue line) load

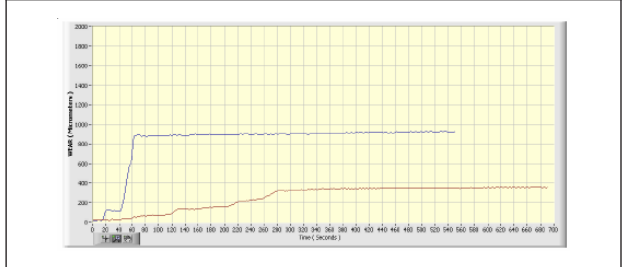


Figure 4(d): Variation of Frictional Force with Different % of Fly Ash at 50N Load and 240 rpm

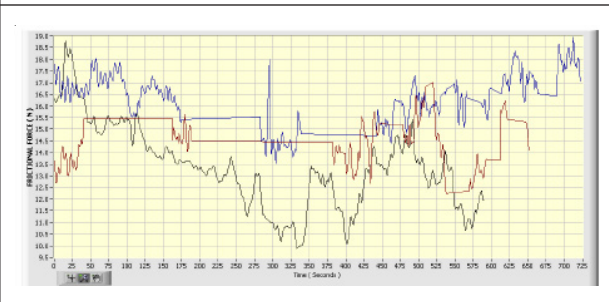


Figure 4(h): Variation of Frictional force for Al-(5%) Fly Ash at 240 rpm and at 20N (red line) and 50N(blue line) Load

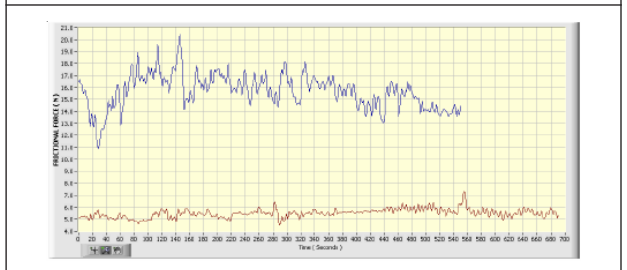


Figure 4(e): Wear Behavior of Al-(20%) Fly Ash composite at 20N Load at 240 rpm(red line) and 500rpm(blue line)

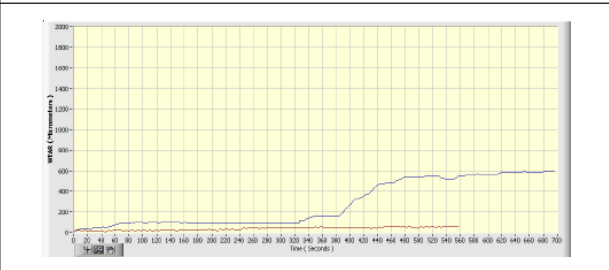
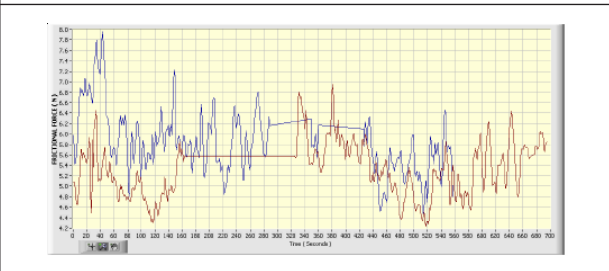


Figure 4(f): Variation of Frictional Force for Al-(20%) Fly Ash Composite at 20N Load at 240 rpm(red line) and 500 rpm(blue line).



The figures [4(a), 4(b)] shown above, clearly indicates that the wear rate has improved significantly and frictional force has decreased with the increase in the percentage of fly-ash.

The figure [4(c), 4(d)] shows the variation of wear rate and frictional force with time at different percentage of fly ash at 240 rpm. It shows that the wear rate has increased and the frictional force has decreased with increase in percentage of fly ash.

The figure [4(e), 4(f)] shows the variation of wear rate and frictional force with time of Al-20% fly ash at 20N load at 240 and 500 rpm. It shows that the wear rate has increased with the increase in rpm at constant load. The reason being the oxide particles are removed giving rise to three body wear and wear rate increases with increase in sliding velocity.

The figure [4(g), 4(h)] shows the variation of wear rate and frictional force with time of Al-5% fly ash at 20N and 50N load at 240 rpm. It shows that the wear rate has increased with the increase in load at constant rpm. Al-fly ash composites also have an increasing trend of wear with applied load due to deformation generation of cracks within the oxide film that may act as a three body wear on removal of the particles increasing the wear rate drastically at high loads. The addition of fly ash acts as a barrier to the movement of dislocations and thereby increases hardness of the composite. Thus addition of fly ash particles to the aluminium melt significantly increases its abrasive wear resistance. The improvement in wear resistance is due to the hard alumino-silicate constituent present in fly ash particles.

From the view of material, influencing factors on friction force are mechanical properties of the matrix, hardness, chemical stability of the particles, composition and strength of the interface. Interaction between these and tribological parameters (such as load and speed, environment and the properties of the counter faces materials) are responsible for the overall response.

SEM ANALYSIS

SEM photographs were taken to analyze the fly ash particles and surfaces of Al-(5%, 20%) fly ash composites.

Figure 5(a): SEM Micrograph of Fly Asash Particles

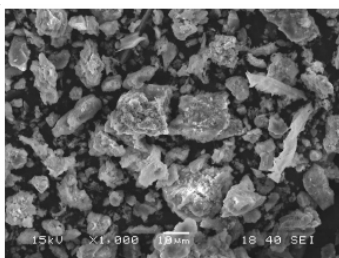


Figure 5(b): SEM Micrograph of Al-5% Fly Ash Composite

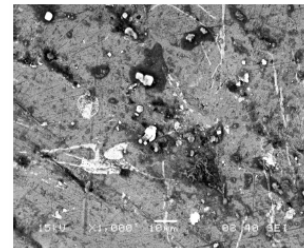
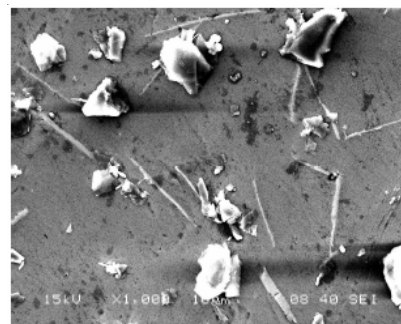
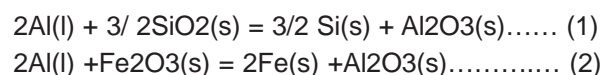


Figure 5(c): SEM Micrograph of Al-20% Fly Ash Composite



The figure 4.5(a) shows that the fly ash particles consist of precipitator particles. The figure [4.5(b),(c)] shows that with increase in percentage of fly ash there is increase in incorporation of fly ash in the composites.

Thermodynamic analysis indicates that there is a possibility of chemical reaction between aluminium melt and fly ash particles. As these fly ash particles consist of alumina, silica and iron oxide, they are likely to undergo chemical reduction during their contact with the melt, as follows:



The elements (Si and Fe) formed by reduction reaction would alloy with the matrix. Gibbs free energy and the heats of reactions are highly exothermic in nature. As a result of this reaction (Eq.(1)) greater amount of eutectic silicon is seen in the composites.

CONCLUSION

1. From the study it is concluded that we can use fly ash for the production of composites and can turn industrial waste into industrial wealth. This can also solve the problem of storage and disposal of fly ash.
2. Fly ash upto 20% by weight can be successfully added to Al by stir casting route to produce composites.
3. The hardness of Al-fly ash composites has increased with increase in addition of fly ash.
4. Both the frictional forces and the wear rates has decreased significantly with the incorporation of fly ash in Al melt.
5. Strengthening of composite is due to dispersion strengthening, particle reinforcement and solid solution strengthening.

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