

# Mechanical Behavior of Aluminium Matrix Composite Reinforced with Untreated and Treated Waste Fly Ash

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## Abstract

**Background/Objectives:** To fabricate Aluminium Matrix Composites (AMCs) using liquid stir casting technique, in which waste fly ash obtained from thermal power plant is to be applied as reinforced material. **Method/Statistical Analysis:** In one type, 14.3% (by volume) of the reinforcement material was directly employed as received from the power plant and in the other type, 13.2% (by volume) fly ash was thermally treated and reinforced with the Al-Si alloy matrix material. **Results/Findings:** The Energy dispersive X-ray analysis (EDAX) analysis and X-ray studies have revealed nearly complete conversion of  $\text{SiO}_2$  to  $\text{SiC}$  by thermal reduction in a plasma reactor. Particle sizes obtained were in the range of  $2\mu\text{m}$ - $40\mu\text{m}$  with different shape and aspect ratios. Mechanical properties like hardness, compression strength and tensile properties such as UTS, YS are more for AMC prepared with thermally treated fly ash in comparison to AMC prepared with untreated fly ash and Al-Si alloy. **Conclusion/Application:** A novel in-situ ternary ceramic mixture composite of  $\text{Al}_2\text{O}_3$ - $\text{SiC}$ -C is fabricated by carbothermal reduction of fly ash in a plasma reactor.

**Keywords:** Aluminium Matrix Composite, Mechanical Property, Microstructure, Treated Fly Ash

## 1. Introduction

In the past 5 decades, the researchers and design experts have supposed their research to prominence on finding lightweight, environmental friendly, low-cost, high quality, and good performance materials<sup>1</sup>. In accordance with this trend, MMCs have been attracting growing interest among researchers and industrialists. Metal Matrix Composites (MMCs) are the forerunners amongst different classes of composites. Over the past two decades Metal Matrix Composites (MMCs) have been altered from a topic of scientific and intellectual interest to a material of broad technological and commercial implication<sup>2</sup>. In recent years Aluminium based MMCs have received increasing attention as engineering materials because of their lightness, higher specific strength and wear resistance. Choice of a suitable combination of matrix with reinforcement materials has become an interesting area for manufacturing science in MMCs<sup>3</sup>.

Aluminium-silicon alloys, as a matrix material, are chosen for their good strength-to-weight ratio, ease of fabrication at reasonable cost, good thermal conductivity, high strength at elevated temperature, excellent corrosion resistance as well as good castability and wear resistance properties. Thus, these alloys are suitable for aerospace, automotive and military applications. Majority of eutectic or near eutectic Aluminum-silicon alloys are used to produce pistons and are, therefore, known as 'piston alloy', which provides the best overall balance of properties<sup>4</sup>. The traditional material such as cast iron as engine component is replaced by lightweight Al-Si alloy castings which help in savings fuel and reduces vehicle emissions. However, the main weaknesses of aluminium alloys lie in a fact that they exhibit low wear resistance and creep resistance. Therefore, ceramic particles are added to reinforce aluminium alloy matrices to overcome these problems<sup>5-12</sup>.  $\text{Al}_2\text{O}_3$  and  $\text{SiC}$  powder are two commonly used reinforcing agents in Aluminium Metal Matrix Composites (AMCs)

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and the addition of these reinforcements to aluminium alloys has become the subject area for research work<sup>13,14</sup>. In the automotive and aircraft industries,  $\text{Al}_2\text{O}_3$  or SiC reinforced aluminium alloy matrix composites are applied for pistons, cylinder heads, etc., where the tribological properties of the material are very important<sup>15-21</sup>. Therefore, the development of AMC is emphasized for meeting the requirements of various industries. The mixtures of hard second phase particles in the alloy matrix to produce AMC is also considered to be beneficial and economical<sup>22-25</sup>. Fly ash particles are potential discontinuous dispersoids used in metal matrix composites, since they are low-cost and low-density reinforcement available in large quantities as a waste by-product in thermal power plants. The fly ash contains the most important chemical constituents like  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{Fe}_2\text{O}_3$  and  $\text{CaO}$ <sup>26-29</sup>. The fly ash reinforced AMCs are also termed as 'Ash alloys'<sup>30</sup>. With the increase in the content of fly ash in Al or its alloys, the mechanical properties such as hardness, modulus of elasticity, 0.2% proof stress, tensile strength, compression strength and impact strength are enhanced<sup>31</sup>. It was also reported that addition of fly ash in narrow range has enabled superior mechanical properties of AMC as compared to AMC prepared with wider size range fly ash particles. The ductility of the composite decreases with increase in the weight fraction of reinforced fly ash and decreases with increase in particle size of the fly ash. However, for composites with more than 15% weight fraction of fly ash particles, the tensile strength is reported to be decreasing<sup>32</sup>.

From foregoing discussion, it is evident that use of a waste material such as fly ash in Al and its alloy is beneficial and has dispensed with the use of costly ceramic particles such as SiC or  $\text{Al}_2\text{O}_3$  in to Al or its alloy matrices. In the present investigation, a novel in-situ ternary ceramic mixture composite of  $\text{Al}_2\text{O}_3$ -SiC-C is fabricated by carbothermal reduction of fly ash in a plasma reactor. The experimental results on the mechanical behavior of the newly developed AMCs are presented and described in this paper.

## 2. Materials and Methods

### 2.1 Thermal Treatment of Fly Ash

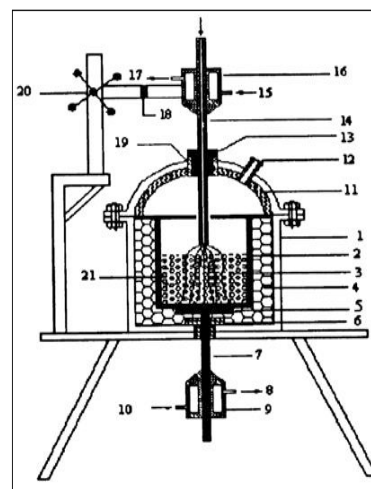
The waste fly ash material, obtained from thermal power plant, is screened below 240 mesh size. The average size of screened fly ash material is determined by mechanical sieve analysis. Judicious amount of activated carbon

is added to the fly ash for converting  $\text{SiO}_2$  to SiC before treating it in a plasma reactor. The total mixture is then thermally treated in a plasma reactor under neutral argon atmosphere as shown in Figure 1. Untreated and treated fly ashes are then analyzed by Scanning Electron Microscope (SEM), Energy Dispersive X-ray Spectroscopy (EDS) and are also characterized by X-Ray Diffraction (XRD) analysis.

### 2.2 Fabrication of Aluminium Matrix Composites

After cleaning Al-Si ingot, it is cut to proper size, weighed in requisite quantities and is charged into a vertically aligned pit type bottom poured melting furnace as shown in Figure 2. Fly ashes are preheated to  $650^\circ\text{C} \pm 5^\circ\text{C}$  in a plasma reactor before mixing with the melt of Aluminium-silicon alloy. This activity is performed to facilitate the removal of any residual moisture in the as received fly ash as well as to improve wettability.

The molten metal is stirred with a Boron Nitride (BN) coated stainless steel rotor at speed of 600-650 rpm.



**Figure 1.** Schematic view of the plasma reactor. (1) M.S. Casting, (2) Graphite Crucible, (3) Plasma, (4) Bubble Alumina, (5) Graphite Base, (6) Alumina Bush, (7) Bottom Electrode (graphite), (8) Water Outlet, (9) Copper Connector, (10) Water Inlet, (11) Magnesia Lining, (12) Exhaust, (13) Graphite Bush, (14) Top Electrode (graphite), (15) Water in, (16) Copper Connector, (17) Water out, (18) Electrical Insulation, (19) Alumina Bush, (20) Rack and Pinion, and (21) Charge.



**Figure 2.** Bottom pouring furnace used in the work.

A vortex is created in the melt by using a stirrer, where preheated fly ash is poured centrally in to the vortex. The rotor is moved down slowly, from top to bottom by maintaining a clearance of 12mm from the bottom. The rotor is then pushed back slowly to its initial position. The pouring temperature of the liquid is kept around 700°C. Casting is made in a rectangular metal mould of dimension 250 x 20 x 45 mm<sup>3</sup>. For comparison purpose, two types of composites are prepared, one with untreated fly ash and the other with treated fly ash.

### 2.3 Optical and Mechanical Tests

Metallographic samples are cut from the central part of the ingot. The samples are examined under an optical Microscope (model: XJL-17). The cast AlSi-fly ash samples are taken for examination in SEM (model: JEOL-JSM, 6480LV) attached with EDX. The test samples shown in Figure 3 are obtained from the cast composites by machining operations.

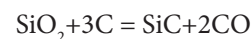
Tensile tests are conducted using a Hounsfield computerized tensile testing machine of capacity 20 KN. The

mechanical properties such as tensile strength, % elongation are recorded. The tensile test data are taken from an average of three independent test results for each material. To understand the effect of addition of fly ash on the mechanical behavior of the AMCs, the compression test is carried out on the eutectic alloy and its composites. The test sample geometry of Ø 20mm x H20mm is taken for the compression test by using a universal testing machine. Stress values are calculated for the three materials of similar geometry, after loading 50% of their heights. The compression test results are based on an average of three independent test values of each material. The hardness test is performed in a digital display Vickers Micro hardness tester (model: HVS-1000). The specimens used are highly finished surfaces. Micro hardness testing machine gives an allowable range of load for testing with a diamond indenter. The impact strength of AMC is measured by Charpy test. The specimen standard of charpy test is shown in Figure 4.

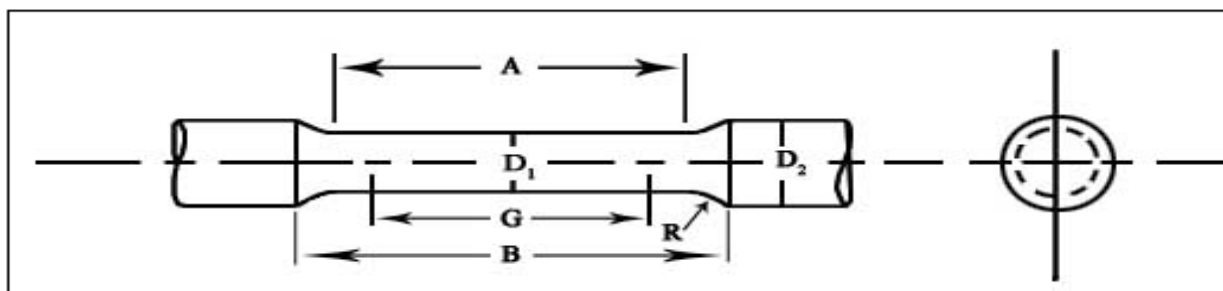
## 3. Result and Discussion

### 3.1 Characteristics of Fly Ash

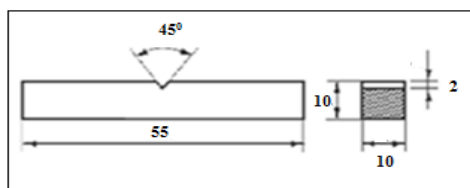
Chemical analysis of as received fly ash (Table 1.) shows presence of compounds such as Al<sub>2</sub>O<sub>3</sub>, SiO<sub>2</sub>, and Fe<sub>2</sub>O<sub>3</sub> as major constituents. The conversion of as received fly ash to a ternary mixture of Al<sub>2</sub>O<sub>3</sub>-SiC-C has been achieved in a plasma reactor (Figure1). The conversion reaction is shown below:



SEM micrographs show distribution of particles before and after treatment. Figures 5(a) and 5(b) shows distribution of particles for the untreated fly ash sample at two different magnifications. The corresponding SEM micro-



**Figure 3.** Tensile testing sample.



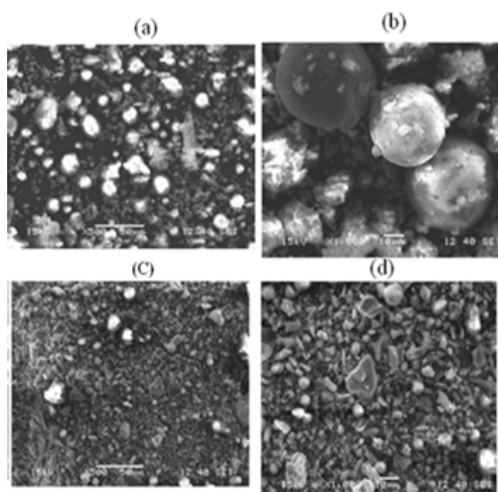
**Figure 4.** Charpy test V-notch specimen standard.

**Table 1.** Chemical composition of fly ash

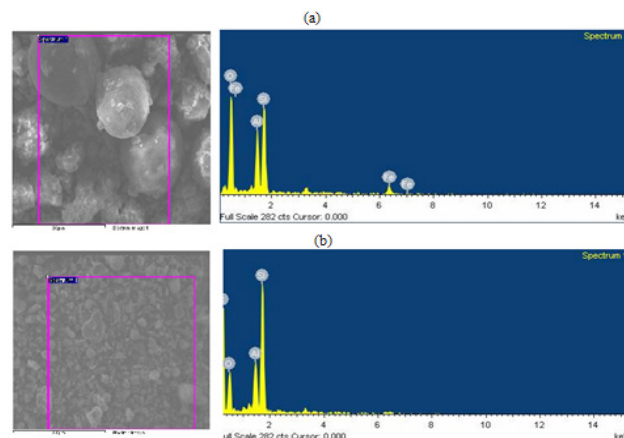
| Compound | SiO <sub>2</sub> | Al <sub>2</sub> O <sub>3</sub> | Fe <sub>2</sub> O <sub>3</sub> | CaO  | MgO  | Na <sub>2</sub> O | K <sub>2</sub> O |
|----------|------------------|--------------------------------|--------------------------------|------|------|-------------------|------------------|
| Wt. (%)  | 63.34            | 24.60                          | 4.97                           | 1.23 | 0.56 | 0.11              | 0.64             |

graphs for treated fly ash samples are shown in Figures 5(c) and 5(d) at the same magnification. For the untreated sample the shape of the particles are spherical with size ranging between 2 $\mu$ m to 40 $\mu$ m. For treated fly ash sample, the morphology, shape and size of particles have altered. It is observed that there are rod shaped particles with varying aspect ratios, 3-6 (on an average) and number of irregular shaped particles. The change in size and morphology of particles due to thermal treatment is thought to be an important proposition since the addition of converted fly ash with such morphology and distribution is expected to enhance of mechanical properties of Al-Si based composites.

EDAX analyses are shown in Figures 6(a) and 6(b) for both untreated and treated samples respectively. The



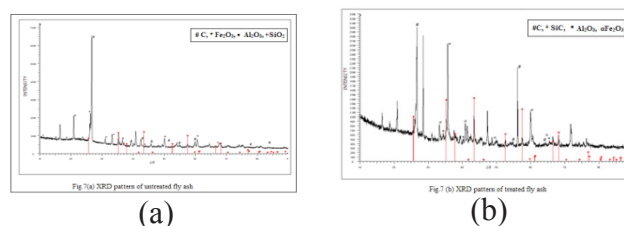
**Figure 5.** SEM micrograph of fly ash. (a) untreated form at 500X, (b) untreated form 1000X, (c) Plasma treated form at 500X and (d) Plasma treated form at 1000X.



**Figure 6.** (a) SEM micrograph and EDX analysis of untreated fly ash, (b) SEM micrograph and EDX analysis of treated fly ash.

elemental analysis of the untreated fly ash sample shows the presence of Al, Si, and O. However for treated fly ash sample EDAX analysis shows the presence of elements i.e. Si, Al, O and C.

Figures 7(a) and 7(b) shows diffraction pattern obtained from untreated and treated fly ash respectively. For untreated sample, phases identified are Al<sub>2</sub>O<sub>3</sub>, SiO<sub>2</sub>, and Fe<sub>2</sub>O<sub>3</sub> etc [Figure 7(a)]. This corroborates chemical analysis shown in Table 2. Figure 7(b) shows the diffraction pattern of treated fly ash. Peaks are identified as Al<sub>2</sub>O<sub>3</sub>, SiC, C and SiO<sub>2</sub> peaks (less prominent), ensuring conversion of SiO<sub>2</sub> to SiC in major quantities. Together with the EDAX analysis, XRD pattern of treated fly ash [Figure 7(b)] indicates that at a very high temperature under neutral atmosphere, the SiO<sub>2</sub> has converted to SiC during plasma synthesis, with some amount of carbon left in the product. The in situ composite thus prepared has three major constituents, i.e SiC-Al<sub>2</sub>O<sub>3</sub>-C. The presence of sharp carbon peaks in XRD patterns indicates the presence of unreacted carbon in the form of a crystalline phase, presumably of graphite. As a result of chemical formation of in situ phases such as SiC, Al<sub>2</sub>O<sub>3</sub> and graphite,



**Figure 7.** XRD Pattern of (a) untreated fly ash and (b) treated fly ash.



the physiochemical properties are expected to improve properties of AMC prepared with the treated fly ash.

The aluminium silicon alloy based metal matrix composites is then made by using untreated and treated fly ash. In the present investigation, it is anticipated that both the composites i.e. Al-Si with untreated fly ash and treated fly ash will have the same vol% of the dispersed phases. However, within the experimental limitation, it was possible to have 14.2 and 13.3 vol% of particulates in the untreated and treated composites respectively.

### 3.2 Preparation of Al-Si Alloy Based Metal Matrix Composite

Matrix used: Eutectic Al-Si (LM6) alloy.

Reinforcement used: As received fly ash (untreated) and thermally treated fly ash.

The chemical analysis of the alloy is given in Table 2.

### 3.3 Mechanical properties

Figure 8 shows hardness values for three materials i.e. Al-Si (Eutectic), AMC with untreated fly ash (14.2%) and AMC with treated fly ash (13.3%). The average value of hardness recorded is found to be the highest for AMC prepared with the treated fly ash. The tensile properties are measured and shown in Figure 9.

The Stress-Strain diagram shows that the % elongation, tensile strength and fracture strength are recorded to be the highest for AMC prepared with the treated fly ash as

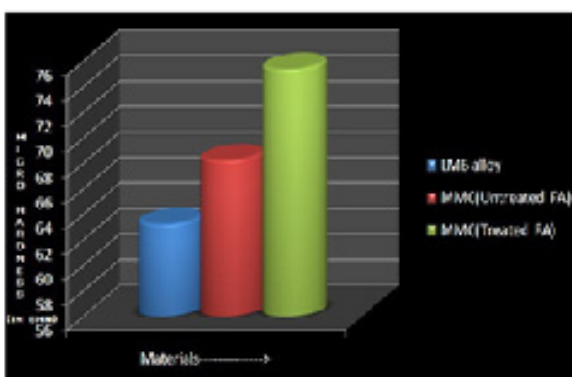


Figure 8. Comparison of hardness data.

compared to the other two materials. The area under the stress-strain curve for AMC prepared with treated fly ash sample is more in comparison with the other two materials. Result of compression test Figure 10 has also shown the highest strength value for AMC prepared with treated fly ash in comparison to Al-Si alloy and AMC prepared with untreated fly ash. The largest value obtained under static as well as dynamic test conditions for AMC prepared with treated fly ash material is attributed to the microstructural changes, caused due to carbothermal reduction and formation of SiC from  $\text{SiO}_2$ . The insitu structure has enabled improvement in the properties because of change in morphology of the microstructure i.e., spherical shape to rod shaped as well due to fineness of the reinforcing particles.

## 4. Conclusion

A novel in situ ceramic composite consisting of  $\text{Al}_2\text{O}_3$ -SiC-C has successfully been prepared from waste fly ash material, obtained from thermal power plant. Fly ash containing  $\text{SiO}_2$  is converted to SiC in major quantities by thermal reduction. SEM, EDAX and XRD analyses have confirmed successful conversion of  $\text{SiO}_2$  to SiC in major quantities with some unreacted C, presumably of graphite. AMCs prepared with untreated and treated fly ash have 14.2 % and 13.4% volume fly ash in the matrix, respectively. Mechanical properties such as hardness, tensile properties (UTS) and compression strength are more for AMC prepared with treated fly ash in comparison to the other two materials i.e. AMC prepared with untreated fly ash and Al-Si alloy.

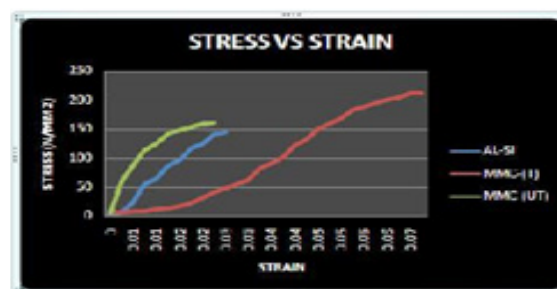
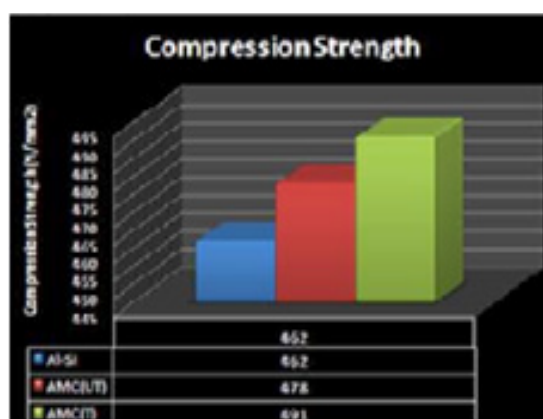


Figure 9. Comparison of tensile strength data.

Table 2. Composition of Al-Si alloy [wt. %] designated as a base alloy

| Si      | Co     | Fe     | Cu     | Mn     | Ti     | Zn     | Ni     | Sn     | Cr     | Ca     | V      | Al      |
|---------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|---------|
| 12.2491 | 0.0174 | 0.4353 | 0.0800 | 0.1601 | 0.0672 | 0.0944 | 0.0264 | 0.0632 | 0.0199 | 0.0082 | 0.0146 | 86.7654 |



**Figure 10.** Comparison of compression strength data.

## 5. Acknowledgement

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