Development of High Performance Aluminum Composites Using Fly Ash Reinforcement

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Objective:
- Determine the feasibility of converting fly ash waste into valuable materials by utilizing fly ash as the precursor.

Approach:
- Mix fly ash with alkaline silicate solution and cure at moderate temperature to produce geopolymers.
- Fabricate Al-fly ash composites by melting and casting, and powder consolidation followed by equal channel angular processing (ECAP).
- Develop process and performance models.

Payoff:
- Viable solution for fly ash management
- Low cost light weight structural materials
- Fire resistant geopolymers.
Project Objectives

To convert fly ash waste into valuable materials by using the waste as:
- The precursor for fire-proof geopolymer resin (Task 1)
- Reinforcements for aluminum and polymer matrix composites for aerospace and automotive applications (Task 2)
**Project Team**

**WU MASE Department**

Al-Fly Ash Composite Development using Powder Metallurgy Approach

**IIT Bombay**

Al-Fly Ash Composite Development using Ingot Metallurgy Approach and Fabrication of Polymer Fly Ash Composites

**WU EECE Department**

Geopolymer Synthesis Process Modeling

**University of Indonesia**

Synthesis of Geopolymers using Fly Ash as the Precursors
Properties of Al Alloys and Fly Ash

<table>
<thead>
<tr>
<th>Property</th>
<th>Al Alloys</th>
<th>Precipitator Fly Ash</th>
<th>Cenosphere Fly Ash</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm(^3))</td>
<td>2.7</td>
<td>2.2 - 2.45</td>
<td>0.7</td>
</tr>
<tr>
<td>Shear Modulus (GPa)</td>
<td>35 - 40</td>
<td>98 - 126</td>
<td>13 - 17</td>
</tr>
<tr>
<td>Hardness (kg/mm(^2))</td>
<td>80 - 100</td>
<td>160 - 400</td>
<td>230 - 260</td>
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</tbody>
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Beneficial Effects of Particulate Reinforcement and Grain Refinement

Trends and Speculations

Particulate and whisker reinforcement is a cost effective method to produce significant increases in strength, and moderate increases in modulus. But ductility and toughness reduction are problems.

- An equiaxed fine grain size microstructure results in increased strength, ductility, and toughness- Applicable to many alloys and intermetallics.
- By combining grain refinement and particulate reinforcement it may be possible to produce a good combination of strength, ductility, and toughness.

How to produce these microstructures?
Equal Channel Angular Extrusion (ECAE) Process

Conventional Extrusion

Equal Channel Angular Extrusion
Grain Refinement of an Aluminum Alloy by ECAE Processing

1 Pass +550°C Ann.

2 Passes +550°C Ann

3 Passes +550°C Ann

4 Passes +550°C Ann
Powder Metallurgy Approach

- Powdered Al is mixed with fly ash
- Mixture is consolidated by:
  - Cold pressing at $\approx 340$ MPa
  - Hot pressing at $\approx 90$ MPa and $500^\circ$C for 90 minutes
- Mechanical properties of consolidated billet are enhanced through equal channel angular extrusion
Materials

- Aluminum-2124 & Aluminum-6061 alloy powders
- Cenosphere class & precipitator class fly ash
- Morphology
- Chemical composition
- Particle/powder size
- Mechanical properties
Fly Ash Morphology

Precipitator Class Fly Ash (PFA)
Density: 2.2-2.5 gcc
Solid, angular, nodular

Cenosphere Class Fly Ash (CFA)
Density: 0.4-0.7 gcc
Hollow, porous walls, highly spherical

“Porous” Fly Ash
Mentioned by Sudarshan & Surappa; not otherwise documented
Powder Metallurgy Approach

1. Powdered Al is mixed with fly ash

2. Mixture is consolidated by cold and hot pressing

3. Consolidated billet properties are enhanced through equal channel angular extrusion

4. Fully extruded billet is produced
Equal Channel Angular Extrusion

- Process carried out at WashU’s facilities
- Imparts uniform strain in the material while maintaining the original geometry
- Refines grain size for improved mechanical properties
- Process is modeled using finite element analysis
ECAE Processed Material

Billet

Longitudinal Cross Section

Microstructure of hot pressed billet

Microstructure of ECAE Processed billet
Modulus and Strength of Composites

- **Rule of Mixtures Model**
  - Isostrain - Upper limit
  - Isostress - Lower limit

- **Mori-Tanaka Model**
  - Anisotropy of materials

- **Shear Lag Model**
  - Based upon fibre-reinforcement theory

- **Other Models**
  - Predict strengthening regardless of particle stiffness value

\[ E_c = E_m V_m + E_p V_p \]
\[ E_c = \frac{(E_m E_p)}{E_p V_m + E_m V_p} \]
Higher Strengths in ST condition

Similar strengths at moderate temperature in ST&A condition

Lower strengths at room and high temperatures in ST&A condition
- Substantially higher values in ST condition
- Similar values at room temperature in ST&A condition
- Slightly higher at moderate temperature in ST&A condition
- Lower values at high temperature in ST&A condition
- Increases in ST and ST&A conditions at room and moderate temperatures
- Decreases in ST and ST&A conditions at high temperatures
Ingot Metallurgy Processing of aluminum fly ash metal matrix composites

- Melting of Aluminum alloy grade AA2024 & AA6061 above the liquidus temperature 800°C
- Addition of 1% Mg in the form of pallets to increase wettability of fly ash
- Preheating of reinforcement Fly ash grade P60 up to 650°C for 4 hrs
- Continuous feeding of fly ash P60 particle in the melt at 5gm/ min
- Vigorous agitation at speed of 550 rpm
- Stirring during and after completion of particle feeding for 15 - 20 min
- Casting in preheated metallic mould 200-300°C
- Hot rolling and Extrusion at BARC
- Sampling for Mechanical and corrosion testing of MMC
Ingot Metallurgy Processed Aluminum-Fly Ash Composites

steady increase in yield strength as the percent fly ash increases

steady increase in ultimate strength as the percent fly ash increases
Concluding Remarks

- Fly ash is an aluminosilicate
  - PFA is solid, angular, & density = 2.2-2.5 gcc
  - CFA is hollow, spherical, & density = 0.4-0.7 gcc
- Cenosphere fly ash crushes under compacting pressure of 345 MPa
- Powder consolidation followed by ECAE is an effective method for the fabrication of Al-fly ash composites
- 6061Al-fly ash composites have superior density and cost normalized yield and ultimate tensile strengths.
- Ingot metallurgy processing has been successfully used to produce Al-fly ash composites with up to 10 vol.% fly ash.
- IM processed Al-fly ash composites have higher strengths and modulus values than the base alloys.
Strengthening Contributions in Al-fly ash composites

- Al-cu-Zn-Mg solid solution strengthening due to dislocation-solute atom interactions
- Precipitation strengthening due to shearing of coherent $T'$ precipitates by dislocations.
- Rule of mixture strengthening from fly ash reinforcements.
- The overall strengthening is determined by the superposition of various strengthening contributions.
Future Plans

- Testing per ASTM specifications:
  - Tensile
  - Fracture toughness
  - Forgeability and formability

- Investigate lower strength matrix composition Aluminum alloys

- Investigate different volume fractions of fly ash reinforcements