Chapter 8

Fly Ash Metal Matrix Composites

Introduction

Metal matrix composites (MMCs) are engineered materials formed by the combination of two or more materials, at least one of which is a metal, to obtain enhanced properties. MMCs tend to have higher strength/density and stiffness density ratios, compared to monolithic metals. They also tend to perform better at higher temperatures, compared to polymer matrix composites.

Though MMCs have been in existence since the 1960s, their commercial applications have been limited due to their higher cost and lack of proper understanding. More recently developed MMCs, especially cast aluminum-fly ash composites, have the potential of being cost effective, ultra light composites, with significant applications (56). Such composites, if properly developed, can be applied for use in automotive components, machine parts and related industries.


Figure 8-1: Brake drum cast with aluminum ash alloy material in Manitowoc, Wisconsin

Aluminum and magnesium are lightweight materials, when compared to iron and steel. However, they do not have the strength requirements necessary for several applications. Metal matrix composites manufactured by dispersing coal fly ash in common aluminum alloys improve mechanical properties such as hardness and abrasion resistance.

Processed fly ash is estimated to cost about $0.10 per pound (including the cost of mixing the ash into the aluminum melt). Aluminum alloy 380 costs approximately $0.70 per pound. An alloy blend containing 40% fly ash would cost about $0.50 per pound, compared to $2.40 to $2.60 per pound for similar conventional aluminum-silicon carbide composites (57).

Preparation of Ash Alloy Metal Matrix Composites

Ash alloy metal matrix composites can be prepared using various techniques. The following methods were studied at the University of Wisconsin-Milwaukee to prepare ash alloys using We Energies fly ash.

- Stir Casting
- Powder Metallurgy
- Pressure Infiltration

Stir Casting

Aluminum-silicon alloys (A356.2 and Al 6061) were used in this work which was conducted at the University of Wisconsin-Milwaukee. In the stir casting process, the alloy is melted at a controlled temperature and the desired quantity of fly ash is added to the molten aluminum alloy. The molten alloy is stirred continuously to create a vortex to force the slightly lighter particles into the melt. Stirring continues to disperse the fly ash particles as uniformly as possible in a short time.

The matrix is then transferred into a preheated and precoated transfer ladle. The material is stirred again and then poured into preheated permanent molds. It is then cooled, cut to shape, and surface cleaned.

Photomicrographs of aluminum alloy (A356.2), with a 10% volume of precipitator fly ash showed that fly ash particles tend to segregate along the aluminum dendrite boundary due to particle pushing. Fly ash particles tend to float to the top of the cast ingots due to their lower density. However, the distribution is reasonably uniform except for the top layer.

Powder Metallurgy

Commercially pure aluminum (99.9%) and We Energies fly ash were used in this work. Oven-dried at 110°C, aluminum and fly ash powders were well-blended by using a rotating drum. The amount of fly ash varied from 5 to 10 percent by weight in the mixtures.

Aluminum fly ash samples were compacted at different pressures (20,000 psi to 60,000 psi) using a uniaxial hydraulic press (58). Aluminum and aluminum fly ash compacts were sealed in a transparent silica tube under pure nitrogen and sintered at 625°C and 645°C for 2.5 and 6 hours at both temperatures.

The green density of the aluminum fly ash powder compacts increased with the increase in compacting pressure and decrease in fly ash content. Fly ash particles did not change shape significantly even when sintered at 625°C for 2.5 hours.

The morphology of aluminum powders changes during compaction due to plastic deformation. When the quantity of fly ash in the composite increased above 10% by weight, the hardness significantly decreased, and thus it was concluded that powder metallurgy did not seem very promising for producing ash alloy composite parts.

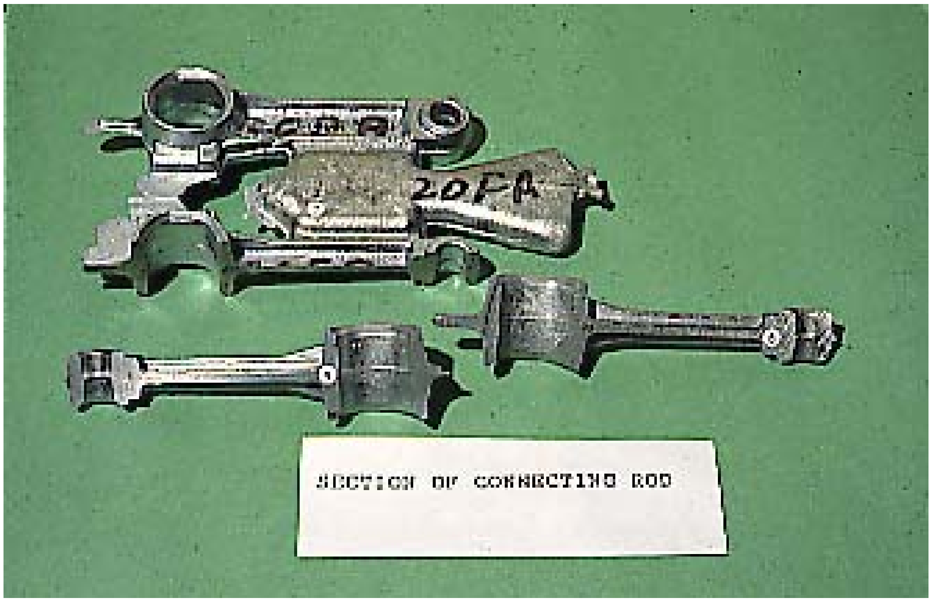

Figure 8-2: Connecting rods produced at the University of Wisconsin-Milwaukee with aluminum ash alloy material.

Pressure Infiltration

Commercial aluminum-silicon alloy (A356.2) and We Energies fly ash were used in this study. Preforms were prepared by mixing cenospheres and precipitator ash with MAP (mono-aluminum phosphate). The slurry was poured into a mold, dried at 204°C for 24 hours and then cured at 815°C for five hours. The preforms were placed in a graphite die followed by preheating at 815°C for two hours. The aluminum alloy was poured into the die at 840°C. A pressure of 1,500 to 2,500 psi was applied on top of the molten alloy for a period of 10 minutes.

When higher percentages of fly ash are used in ash alloy materials, the pressure infiltration casting technique is preferred. The distribution of fly ash particles is uniform in the pressure-infiltrated casting. The volume percentage of fly ash in the composite can be controlled by controlling the porosity in the fly ash preform, which can again be controlled by adjusting the quantity of foaming agent in the preform. The pressure infiltration method gave better castings than the other techniques developed earlier.

Properties of Ash Alloy

In order to determine the suitability of fly ash composites in the manufacture of various automobile and other components, abrasive wear behavior and forging characteristics of composites containing We Energies fly ash were also studied at the University of Wisconsin-Milwaukee.

Abrasive Wear Behavior

Standard Al - 7Si casting alloy (A356) and We Energies fly ash were used in wear tests in the laboratory. Composites were prepared in the lab by stir casting containing 3% fly ash by volume, and composites were also prepared by the squeeze casting technique containing 56 % fly ash by volume. Wear tests were carried out on a FALEX machine. The details of the test procedure can be obtained from reference 50.

The study concluded that:

1. Fly ash improves the abrasive wear resistance of aluminum alloy. Specific abrasive wear rate of aluminum alloy with 3% fly ash composites was decreased with increasing load and increasing sliding velocity.
2. The aluminum alloy - 3% fly ash composite showed better resistance than base alloy up to 24N.
3. Specific abrasive wear rates of the composite (aluminum alloy with 3% fly ash by volume) decreased with decreasing size of the abrading particles.
4. Friction coefficients of the above composites decreased with increasing time, load and size of the abrading particles.
5. Observation of wear surface and wear debris shows that fly ash particles in the composite tend to blunt the abrading SiC particles, thus reducing the extent of ploughing.

Forging Characteristics

The hot forging behaviors of Al 6061- fly ash composites were compared with that of the Al 6061 matrix alloys, Al 6061-20% (by volume) SiC and Al 6061 - 20% Al_2O_3 composites made by Duralcan and Comalco, respectively.

The Al 6061 - fly ash composites were made at the University of Wisconsin-Milwaukee using sieved precipitator fly ash particles obtained from We Energies and cenospheres from another source. The fly ash composites were made using the stir casting and squeeze casting techniques. Table 8-1 is a list of alloys and samples tested in the laboratory.

Table 8-1: Alloy Samples Tested in the Laboratory

No.	Type	Description
1.	Al 6061	Matrix alloy only
2.	Al 6061	20% SiC (14-20 um) Duralcan)
3.	Al 6061	20% SiC $A1_2O_3$ (14-20 um) (Comalco)
4.	Al 6061	5% Cenosphere fly ash (100 um)
5.	Al 6061	10% Cenosphere fly ash (100 um)
6.	Al 6061	10% Precipitator fly ash (44 - 75 um) squeeze cast
7.	Al 6061	20% Precipitator fly ash (44 - 75 um) squeeze cast
8.	Al 6061	30% Cenosphere fly ash (110 um) squeeze cast

Three-inch thick blocks were cut from the ingots and slightly turned to clean up imperfections. The blocks were then coated with either boron nitride or graphite paste to lubricate the ends.

The pieces were then forged in a 150-ton (1.34 MN) hydraulic press at a forging rate of 0.5 in/minute, under a vacuum of 13MPa (97508 torr). The forgings were made at The Ladish Co., Inc., in Milwaukee, Wisconsin. Table 8-2 lists the defects found in each forging.

The study at the University of Wisconsin-Milwaukee led to the following conclusions:

1. The A1 6061 fly ash composites containing 5% or 10% fly ash performed similar to the A1 matrix alloys containing no fly ash during forging.
2. All castings had porosity which affected forgeability.
3. The A1 6061 alloy containing 5% and 10% fly ash forged without cracking. Under similar conditions, A1 6061- 20% SiC and A1 6061- 20% $A1_2O_3$ showed peripheral cracking. A1 6061- 20% fly ash composite showed some cracking. This may be due to non-uniform distribution of fly ash.
4. A1 6061- fly ash composites, had significant segregations in the forgings due to segregations in the billets. Despite the non-uniformity in the microstructure, these composites can be forged.
5. The fly ash particles remained integrated to the alloy particles, showing good microstructure and no debonding. However, during forging some cenospheres collapsed leading to a layered structure of aluminum and collapsed cenospheres.

The University of Wisconsin-Milwaukee study suggests that We Energies fly ash can be used to make composites suitable for forging. However, additional work is being conducted to perfect this technology.

Table 8-2: Defects of Forging Samples Tested

Serial No.	Material	Forging Temperature F (C)	Initial Dimension Height/Dia. (mm)	Forged Thickness	Remarks
4199 4201	Matrix alloy Al 6061	800 (427) 800 (427)	74.7/50.3	9.91	No cracking
4202 4203 4205 4206 4211	Duralcan Al 6061-20 Vol % SiC (14-20 µm)	800 (427) 800 (427) 800 (427) 800 (427) 800 (427)	69.9/50.5 72.6/50.5 72.6/50.3 74.4/50.5 68.1/50.3	10.9 10.7 11.2 11.4 11.4	All five forgings cracked quite severely under a strain greater than 80% forging strain
4207 4208 4209 4210	Comalco Al 6061-20 Vol % Al_2O_1 (14-20 µm)	800 (427) 800 (427) 800 (427) 800 (427)	73.9/50.0 73.7/50.0 81.2/50.5 68.8/50.5	10.9 10.7 11.7 11.4	All four forgings cracked, more or less similarly to the Duralcan forgings
4189 4190 4198	UWM Al 6061-5 Vol % cenosphere fly ash (110 µm)	900 (482) 900 (482) 800 (427)	76.2/49.3 73.7/50.3 76.2/50.0	9.14 9.14 10.2	All three forgings are crack free
4186 4188	UWM Al 6061-10 Vol % cenosphere fly ash (110 µm)	900 (482) 900 (482)	76.7/50.3 75.9/50.0	10.9 9.65	Both forgings are crack free
4194	UWM Al 6061-10 Vol % precipitator fly ash, squeeze cast (44-75 µm)	800 (427)	75.4/50.5	8.89	No transverse edge crack
4191	UWM Al 6061-20 Vol % precipitator fly ash, squeeze cast (44-75 µm)	900 (482)	45.7/50.5	11.9	A little cracking. However, the strain was about 75%

Cenospheres

Cenospheres are hollow, gas-filled glassy microspheres, which normally represent a small portion of fly ash. Cenospheres are formed when CO_2 and N_2 fill the semi-molten material in a coal-fired boiler.

Cenospheres are generally less than one percent of the total mass of CCPs produced. They are generally gray to buff in color and primarily consist of silica and alumina. Cenospheres have valuable applications as fillers in the manufacture of paints, plastics, ceramics, adhesives and metal alloys. Cenospheres are also excellent insulators, which is a direct result of their low density (59).

We Energies, along with the Electric Power Research Institute (EPRI) and several other agencies, have been funding research projects aimed at developing technology for manufacturing ash-alloy automobile components.

We Energies and EPRI have patented a manufacturing method of ash-alloy (U.S Patent 5,897,973). The first step in the method is to prepare a solid, porous, reinforcing phase preform combined with an aqueous medium comprising a binder, such as sodium silicate and polyvinyl alcohol. The ratio of reinforcing phase to aqueous medium ranges is from 1:1 to 3:1. The ratio of binder to water in the aqueous medium generally ranges from 1:1 to 1:9, more usually 1:1 to 1:2. Following introduction into the mold, the slurry produced by the combination of the aqueous medium and reinforcing phase is dried to produce a porous, reinforcing material preform at temperatures ranging from 194ºF to 482ºF for one hour or two. The molten metal is then infiltrated into the porous preform by pressure ranging from about 2000 to 2500 psi. After infiltration, the resultant metal matrix composite is cooled using air drying or low temperature.

Ash alloys containing a volume of over 40% hollow cenospheres are extremely light. It is possible to develop magnesium composites with the density of plastics by proper addition of cenospheres and the use of controlled processes.

Advantages of Using Ash Alloys

The significance of developing and marketing ash alloys can be fully understood only if we consider the overall benefit to various industries and to the environment. The process of developing an ash alloy matrix with excellent properties is very involved, expensive and lengthy. The following are a few of the benefits that will have a significant impact on the community:

1. **Economics:** Ash alloys are at least 10-30% lower in cost than other alloys available in the market. Hence foundries and auto part manufacturers can potentially realize significant savings which can be shared with consumers.

2. **Reduced Energy Consumption:** With a projected annual displacement of 225,000 tons of aluminum with ash, the savings in energy costs for aluminum production is about $156 million annually.
3. **Availability of Lightweight Material:** The U.S. auto industry has a goal to reduce vehicle weight. Ash alloys are significantly lighter when compared to steel.
4. **Improved Gas Mileage:** Due to the projected significant weight reductions, the gas mileage of U. S. vehicles will improve and the savings will be significant. The Department of Energy's Light-Weight Materials Program has predicted that a 25% weight reduction of current vehicles would result in a 13% (750,000 barrels/day) reduction in U.S. gas consumption.
5. **Avoided Ash Disposal Cost:** Electric utilities generate approximately 60 million tons of coal fly ash per year, which are landfilled. If fly ash can be sold as a metal matrix filler, utilities would avoid disposal costs and simultaneously generate revenue from the sale of ash. The anticipated market value of processed fly ash is $100/ton.
6. **Reduced Greenhouse Gases:** Greenhouse gases are produced during the two stages of aluminum production; bauxite processing and alumina reduction. Carbon dioxide (CO_2) and perfluorocarbons (PFCs) are generated in significant amounts during these processes. Decreasing the production of aluminum or other metals by fly ash substitution will significantly reduce the production of these gases. CO_2 emissions would also be reduced by approximately 101 million tons per year.
7. **U.S. Competitiveness:** The U.S. auto parts manufacturers are losing market share to overseas competitors who benefit from low-cost labor. The competitive edge of the United States is its research and development facilities and technical expertise. Development and commercial use of a superior ash alloy matrix at less than half the cost of conventional materials can boost the competitive edge of U.S. parts manufacturers.

These benefits are not limited to the automotive industry. The commercial applications of lighter weight materials, if properly exploited, can benefit foundries, manufacturers, transportation, construction, electrical and consumer goods industries.