Aluminum Alloy - Fly Ash Composite (Ashalloy) -- Future Foundry Products for Automotive Applications

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Abstract

Synthesis, micro structure and selected properties of cast aluminum alloy - fly ash particle composites have been studied. Several aluminum alloy-fly ash particulate composites were made by dispersing 3 to 20 volume percent of fly ash in Al-Si alloy (A356) using foundry processes. Additions of fly ash particles result in a decrease in the density of aluminum alloy and an increase in their modulus, hardness, and abrasion resistance. These aluminum alloy - fly ash composites appear as attractive foundry products for automotive applications in view of their low cost due to substitution of aluminum by waste fly ash. The mechanisms of formation of solidification micro structures including particle floatation and interaction of fly ash with solidifying interfaces will be discussed. The flow behavior of molten aluminum - fly ash slurries along with the components cast in aluminum - fly ash composites will be presented.

Introduction

Coal fly ash, an industrial solid waste by-product, is produced during combustion of coal by thermal power plants. As of 1990, approximately 80 million tons of waste, including fly ash, bottom ash, boiler slag, and flue gas desulfurization slug was produced each year in the United States, of which 50 million tons is fly ash. Very large amounts of fly ash are generated in thermal power plants and they pose a disposal problem. Research is in progress to find out the various uses of this by-product to eliminate the environmental problem associated with the disposal of fly ash, and to effectively use fly ash to produce new materials. The major quantity of fly ash is being used as an additive to cements. Fly ash is also used as a filler in polymers. In the last decade, fly ash has been dispersed in aluminum alloys and the resulting composite with improved hardness and wear resistance has been cast into various useful shapes.[1,2,3,4] Fly ash cenospheres have very low densities (0.4 - 0.8 g/cm^3), and can be used to produce lightweight metal matrix composites, which may find applications in automotive applications.

In this paper, some of the characteristics of fly ash and casting characteristics of aluminum silicon alloy - fly ash composites have been described. Distribution of fly ash particles in ingot of Ashalloy has been studied. The fluidity of aluminum silicon alloy - fly ash composites as a function of temperature and volume percent of fly ash dispersed in the matrix of aluminum is discussed, along with the description of components cast from Ashalloy composites.

Experimental Procedure

Particle size and size distribution of fly ash

Fly ash used in this research includes precipitator fly ash (solid) and cenosphere fly ash (hollow). Precipitator fly ash is the ash which is collected in electrostatic precipitators and consists of both solid and hollow particles of fly ash. Precipitator fly ash does contain a small fraction of fly ash cenospheres which are hollow. The cenosphere fly ash used in this study was collected on top of ash ponds was generally hollow. These fly ash samples were subjected to sieve analysis after proper sampling from the bulk samples. The sieve analysis data was measured the weight of fly ash retained on a specific sieve size in grams.

Fly ash density

Bulk density and tap density of fly ash were measured according to ASTM standards (B212-89, B527-85). Two different methods were used to measure the true density of precipitator fly ash: (i) using standard volume measurement bottle to measure the volume of a known quantity of fly ash powder. The mass of fly ash particles divided by this volume gives true density. (ii) using a special instrument (AccuPyc 1330 Pycnometer) to measure the true density of fly ash particles automatically. The density of cenosphere fly ash was measured only by instrument (AccuPyc 1330 Pycnometer) because its density is less than that of medium liquid used in method (i) described above.

Synthesis of aluminum alloy - fly ash composites

Aluminum - silicon alloy (A356) was used as the matrix alloy in this research. Requisite quantities of aluminum alloys were melted in an induction furnace, and the melts were degassed with nitrogen and skimmed. Calculated amount of fly ash was added in the vortex created by mechanical stirring of the melt. The melt containing the suspension of fly ash particles was poured into preheated permanent steel molds to produce composite ingots (Ø76 X 300 mm) for further examination.

Measurement of fly ash particle distribution

The samples taken from different locations (5 levels from the bottom to top and 3 samples for each level from surface to center) of the ingot and polished along with longitudinal direction were prepared for optical metallographic examination and image analysis. The measurements of at least 15 fields at the 500 X magnification were done for each sample.

Measurement of fluidity

The fluidity of A356 - fly ash composite was measured by casting fluidity spirals in permanent steel molds. The steel mold was heated to 200 C by means of heating cartridges embedded in the mold. A refractory pouring cap coated with boron nitride was used to maintain constant velocity and laminar flow of the composite slurry.

The composite was heated to about 10 C above the required pouring temperature. The melt was skimmed and stirred before pouring. Fluidity tests were carried out at pouring temperatures of 700, 750, 800, 850 C for each composite with different fly ash content. The lengths of fluidity spirals were measured to get an idea of the type of castings which can be made from melts of aluminum - fly ash suspensions.

Examination of A356 - fly ash composite

The densities of A356 - fly ash composites containing different amount of fly ash were calculated by measuring the volume of a known weight of composite. The mass of the composite divided by this measured volume was used to estimate the density.

The hardness and elastic modulus of A356 - fly ash composites containing different amount of fly ash were experimentally determined.

Results and Discussion

Fly ash characterization

The chemical composition of precipitator fly ash is given in Table I. The size distribution of precipitator fly ash, shown in Figure 1, indicates that more than 80 percent by weight of this fly ash is between 45 to 106 μm, with a median size of about 63 μm. The results of sieve analysis for fly ash cenospheres are shown in Figure 2. The bulk of the particles of cenospheres are in the size range of 63 to 105 μm with the median size around 90 μm. Figure 3 (a) & (b) show the

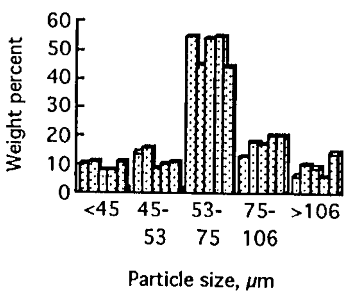


Figure 1. Results of sieve analysis of precipitator fly ash, five separate measurements.

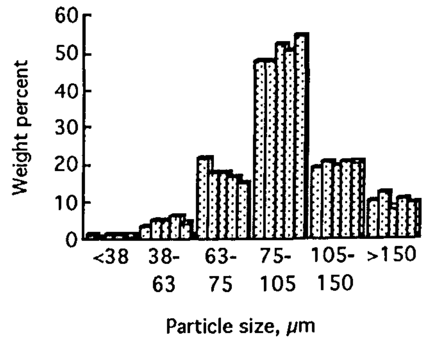
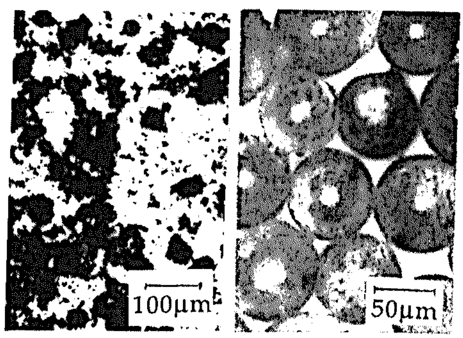


Figure 2. Results of sieve analysis of cenosphere fly ash, five separate measurements



(a) (b)
Figure 3. Optical photomicrograph of fly ash (a) Precipitator fly ash, (b) Cenosphere fly ash

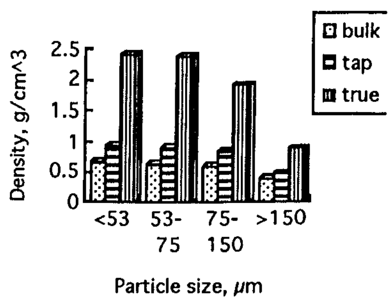


Figure 4. The densities of different sizes of precipitator fly ash particles

Table I. Chemical constituents of precipitator fly ash

Composition	SiO_2	Al_2O_3	Fe_2O_3	CaO	SO_3	MgO	K_2O	Na_2O	P_2O_5	TiO_2
%	38.5	17.1	25.1	4.0	1.9	1.1	2.5	0.5	0.5	1.5

photomicrographs of precipitator fly ash clusters and near spherical cenosphere fly ash particles, respectively. Figures 4 and 5 show the densities of different sizes of precipitator fly ash and cenosphere fly ash, respectively. The true density value of precipitator fly ash is in the range of 0.90 to 2.41 g/cm^3. The true densities of different size particles are shown in Figure 4, indicating a behavior pattern similar to bulk density and tap density that as the particle size increased the density decreased. The true density of cenosphere fly ash is as low as 0.58 g/cm^3. The wall thickness of the cenosphere was in the range of microns and the ratio of the wall thickness to diameter of the cenosphere was in the range of 4-6%.

Distribution of fly ash particles in ingot

An important feature of the aluminum alloy - fly ash composite casting is the distribution of fly ash particles in the casting. The results of the measurements of particle distribution showed that the volume fraction of particles in ingot varied with different locations within ingot. Figure 6 shows the distribution of precipitator fly ash particles in Ø76 X 300 mm ingot of A356 - 5vol% precipitator fly ash composite. As the distance from the bottom of the ingot increases, the volume fraction of the fly ash increases. It is noted that a reasonably uniform distribution of fly ash particles is obtained in most portions of the composite ingot, except at the very top and the very bottom portion of the ingot. Also, it can be seen from Figure 7(a) that fly ash particles were reasonably uniformly distributed throughout the ingot on the macro scale.

However, examination under the optical microscope shows that the precipitator fly ash particles tend to segregate at interdendritic region as shown in Figure 7 (b). According to the results of Zubko's[5] work and Surappa and Rohatgi's research[6], the particles at the solid / liquid metal interface during solidification will be pushed ahead of the advancing interface if,

$$K_p / K_l < 1 \quad \text{or} \quad (K_p\, C_p\, \rho_p / K_l\, C_l\, \rho_l)^{0.5} < 1 \tag{1}$$

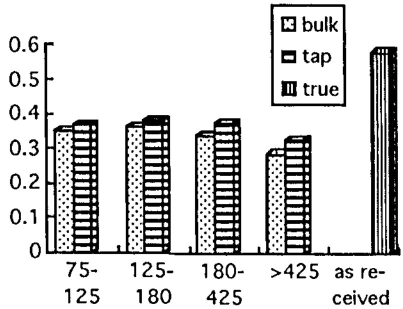


Figure 5. The densities of different sizes of cenosphere fly ash particles

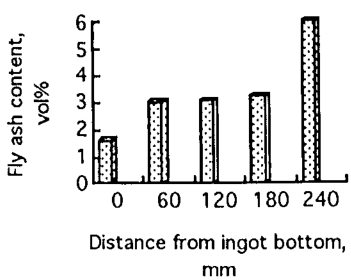
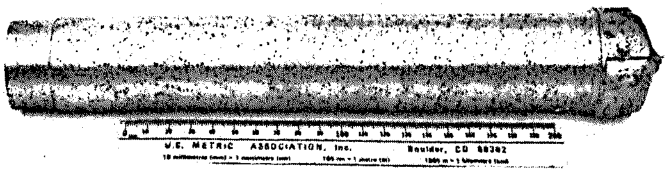


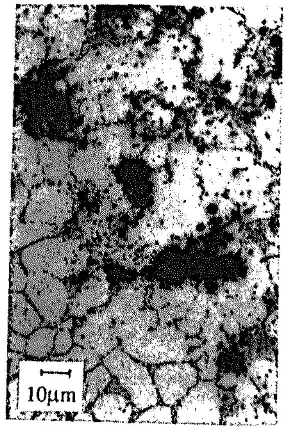
Figure 6. Fly ash particle distribution along the height of ingot of 76 mm dia permanent mold cast, A356 - 3vol% precipitator fly ash composite

where, K_p = thermal conductivity of particle,
K_l = thermal conductivity of liquid metal,
C_p = heat capacity of particle,
C_l = heat capacity of liquid metal,
ρ_p = density of particle,
ρ_l = density of liquid metal.

Using the properties of the components of fly ash from Table II, the fly ash particles are expected to be pushed by the solid / liquid metal interface according to either of the above criterion. This is also observed in the present experimental work.



(a)



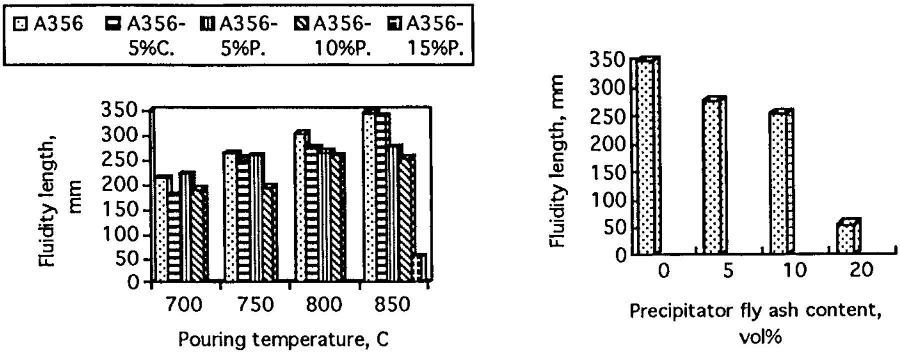
(b)

Figure 7. Optical photographs of A356 - 10 vol% precipitator fly ash composites; (a) composite ingot, (b) micro structure of the composite showing fly ash particles segregating at the interdendritic boundaries due to particle pushing and absence of nucleation.

Table II. Components generally found in fly ash and their properties compared to the properties of Al[7,8,9]

Item	Composition	Density (g/cm^3)	Thermal conductivity (W/cm K)
Mullite	$3Al_2O_3,2SiO_2$	3.156	<0.059
Quartz	SiO_2	2.65	<20
Magnetite ferrite	Fe_3O_4, $(Mg,Fe)_3O_4$	4.9-5.2	
Hematite	Fe_2O_3	4.9-5.3	
Anhydride	$CaSO_4$	2.6-3.0	
Alumina	α-Al_2O_3	3.6–4.0	<0.13
Aluminum	Al	2.7	222

Figure 8 shows fluid spiral lengths of A356 - cenosphere fly ash and A356 - precipitator fly ash composites poured at different temperatures. The fluid spiral length is plotted as a function of temperature in Figure 8(a) and that as a function of precipitator fly ash content in Figure 6(b). The spiral length increases with increasing in temperature from 700 C to 850 C. It is noted from Figure 8(b) that the length of fluidity spiral of the composite does not significantly decrease with



(a) (b)

Figure 8. The fluidity of A356-fly ash composite slurry; (a) variation of fluidity with different pouring temperature for each composite containing different amount of fly ash particles, (b) variation of fluidity of A356-precipitator fly ash composites with different fly ash contents at pouring temperature of 850 C.

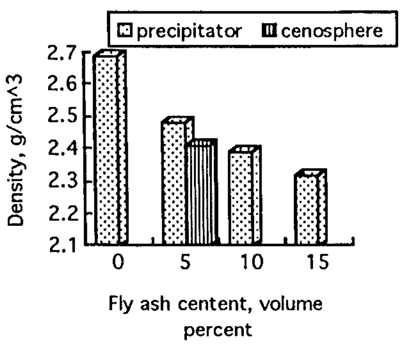


Figure 9. Densities of A356 - fly ash composites.

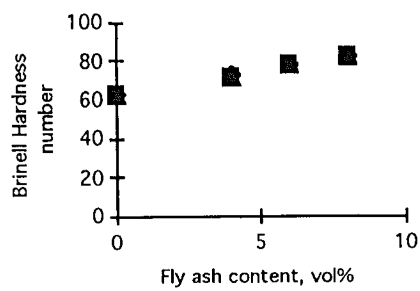


Figure 10. Hardness of A356 - precipitator fly ash composites.(using force of 3000 kg)

fly ash contents up to 10 vol%. However the composite containing 20 vol% of precipitator fly ash exhibits a relatively low fluidity.

Influence of particle dispersions on fluidity of melt has been studied and was explained on the basis of the variation in viscosity of the base alloy as a result of suspension of particles.[10,11]

The relative viscosity of the melts containing dispersed fly ash particles is expected to increase with the volume percent of fly ash according to the following equation:[12,13,14]

$$\mu_r = \mu\,(1 + 2.5\, f_p + 10.05\, f_p^2) \qquad (2)$$

where, μ_r = relative viscosity of composite, Ns/m^2,

μ = viscosity of base alloy, Ns/m^2,
f_p = volume fraction of particles.

The increase in the viscosity of the molten aluminum alloys due to the presence of suspended fly ash particles, and change in the other thermophysical properties as a result of additions of fly ash leads to the net decrease in fluidity. However despite decreases in the fluidity measured in this study, the fluidity of Al - fly ash composite melts is adequate to make a variety of cast components of the type used in automotive, small engine, and electromechanical machinery applications (Figure 12).

The results of density measurements on the A356 - fly ash composites are shown in Figure 9. Low density fly ash used as a filler in metal can produce lightweight metal matrix composites. Addition of cenosphere fly ash into the aluminum alloy significantly decreases the density of the material as shown in Figure 9.

Figure 10 shows the Brinell hardness number of A356 - precipitator fly ash composites (without heat treatment). A slight increase in the hardness of the composites was noticed with increase in the fly ash content of the composite. The matrix hardness without any fly ash addition was about 65 HB, and the hardness increased to about 82 HB with the addition of about 8 vol% fly ash; higher volume percentages of fly ash will give greater increases in the hardness of these composites. Additions of fly ash also lead to an increase in abrasion resistance of the matrix aluminum alloys[3].

Figure 11 shows the increase in the tensile elastic modulus of Ashalloy as the volume percentage of fly ash increased from 3% to 10%. A higher elastic modulus, which indicates greater stiffness, means that in cases where stiffness is the principal design criterion, components with smaller cross sections can be fabricated. This means reduced component mass, which may offer additional advantages in rotating parts.

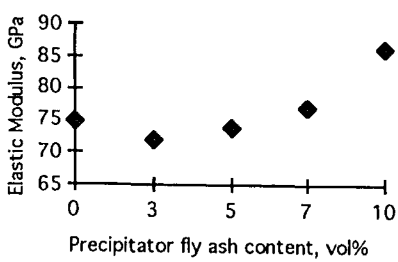


Figure 11. The tensile elastic modulus of Ashalloys increases as the fly ash content increases.

Figure 12. Photograph showing castings made from Al alloy - 10 vol% precipitator fly ash 'Ashalloy' composites including pistons, cylinder liner, and connecting rods.

Conclusions

1. Solidification processing techniques have been successfully developed to produce aluminum alloy - fly ash composites. Fly ash particles were successfully dispersed in the matrix

of aluminum alloy by stir casting technique and quite uniform macroscopic distribution of fly ash particles was observed in small castings made in this study.

2. On the microscopic scale, fly ash particles tend to segregate at inter - dendrite region due to the differences of the thermal properties between fly ash particles and aluminum alloy matrix. These result in the absence of nucleation of α-aluminum phase on the surface of fly ash particles and the pushing of fly ash particles or their clusters, by advancing solid - liquid fronts during freezing of castings.

3. The fluidity of the A356 - fly ash composite decreases with an increase in the fly ash dispersed in the melts, but remains adequate to make a variety of castings.

4. Low density fly ash (such as cenosphere fly ash) used as a filler in metal can significantly decrease the density of the material.

5. Addition of precipitator fly ash into the aluminum alloy increases the hardness of the composites. The matrix hardness without any fly ash addition was about 65 HB, and the hardness increased to about 82 HB with the addition of about 8 vol% fly ash.

6. Elastic modulus of Ashalloy increases as the volume percentage of fly ash increased from 3% to 10%.

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