

Applications of Fly Ash in Synthesizing Low Cost Metal Matrix Composites for Automotive and other Engineering Applications

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Abstract

This paper summarizes attempts of incorporating fly ash into aluminum castings to decrease the energy content, material content, cost, and weight of selected industrial components, while also improving selected properties. It is shown that fly ash can be incorporated in aluminum alloy matrix using stir casting and pressure infiltration techniques. The sand and permanent mold castings, which included differential covers, intake manifolds, brake drums and outdoor equipment castings, including post caps demonstrate adequate castability of aluminum melts containing up to 10 vol.% fly ash particles. The potential cost, energy and pollution savings as a result of incorporation of fly ash in aluminum are discussed in the paper.

1. Introduction

The energy consumption of aluminum industry is about 25% of the total energy consumed by metals industry in the United States. In view of increasing cost of primary metals including aluminum, and of energy in recent times, incorporation of low cost and lower energy consuming reinforcements and fillers in metals has become increasingly attractive. If even 1% of aluminum could be replaced by fillers, the total energy saving could be of the order of 5×10^{11} kWh, making aluminum foundries more competitive [1]. Fly ash, a waste by-product generated by combustion of coal in thermal power plants, has been successfully dispersed into cast and wrought aluminum alloys to make aluminum alloy – fly ash (ALFA) composites, which have low density and adequate properties for several automotive applications [1, 2]. Fly ash particles can be either solid (precipitator) or hollow (cenosphere). Cenospheres are beneficial in synthesizing lightweight composites. Over 90 million tons of fly ash is produced each year in thermal power plants and most of it is land filled. Therefore, it is readily available at no cost and requires only the energy needed for beneficiation and transportation.

Figure 1 gives a price comparison of various materials used in making aluminum matrix composites. It shows that the cost of fly ash is much lower than any other reinforcing material as well as the matrix aluminum. Substitution of aluminum with fly ash can decrease the need for energy intensive aluminum, resulting in saving of energy. Fly ash-aluminum composite will also require reduced energy

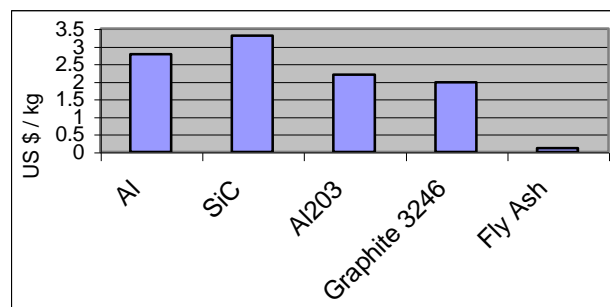


Figure 1. Prices of materials commonly used in making aluminum matrix composites.

for remelting during recycling since the fly ash will not melt and only the aluminum fraction will have to be remelted. Additions of fly ash can make automotive castings lighter, leading to further energy savings during the use of cars and trucks by means of reduced fuel consumption.

The previous research showed that aluminum matrix composites with a variety of reinforcements can be melted and cast using typical aluminum foundry equipment with some modifications. Aluminum-silicon carbide particulate composites have been used most extensively in automotive, electronic packaging, aerospace, and recreation equipment industries [3, 4]. The cast versions of this composite have been used as brake rotors in high-end cars, but the cost needs to come down further before they can be used more widely. Some of the attempts to decrease cost include single step mixing, selective reinforcements, and use of lower grade silicon carbides or lower cost reinforcements.

Prior research at University of Wisconsin-Milwaukee has shown that fly ash can be incorporated in a variety of aluminum alloys using stir mixing (up to 20 vol.%) and pressure infiltration (up to 60 vol.%) techniques (Figure 2) [5]. Addition of fly ash decreases the density and coefficient of expansion of aluminum and increases its wear resistance [6-8]. After successfully synthesizing ALFA composites on laboratory scale, large-scale field trials have been in progress at various industries over the last five years in order to upscale the process of stir casting technique for such composite materials. Figure 3 shows a hollow steel frame incorporating ALFA foam made by Energy industries of Ohio.

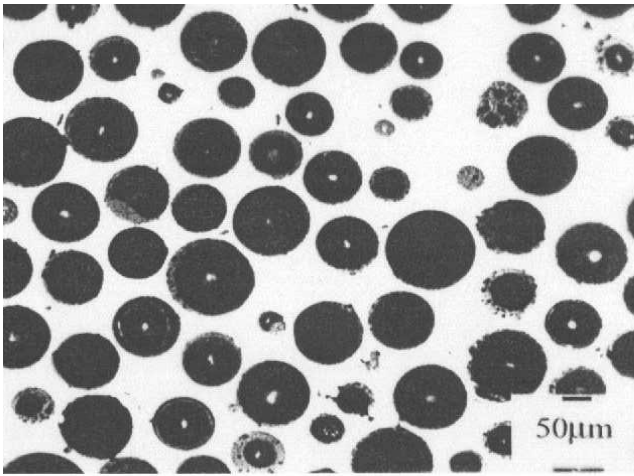


Fig. 2 Microstructure of an aluminum-fly ash syntactic foam.



Fig. 3 Aluminum foam used as reinforcement in steel frame (courtesy R. Purgert).

In addition to the work on sand and permanent mold casting described in this paper, motor mounts have been squeeze cast and mounting brackets have been pressure die cast from ALFA composites. ALFA ingots have also been made and successfully extruded demonstrating the possibility of using wrought version of these composites.

This paper primarily describes the possibility of saving energy and materials, leading to a cost reduction in aluminum castings by incorporation of fly ash. Among other material systems, fly ash has already been incorporated in rolled and extruded aluminum alloys, and in cast copper, lead, magnesium, and zinc alloys, and this concept can be extended to several other materials.

2. Process

Aluminum alloys A356 and 319 were used as base alloys and fly ash particles collected from Wisconsin Electric (WE) and Dayton Power & Light (DPL), Ohio, were used in this work. The EDX analysis shows that the major components in the fly ash are Al_2O_3 , SiO_2 , and mullite as presented in Table I [9]. Figure 4 shows a scanning electron micrograph of $\sim 100 \mu m$ WE fly ash.

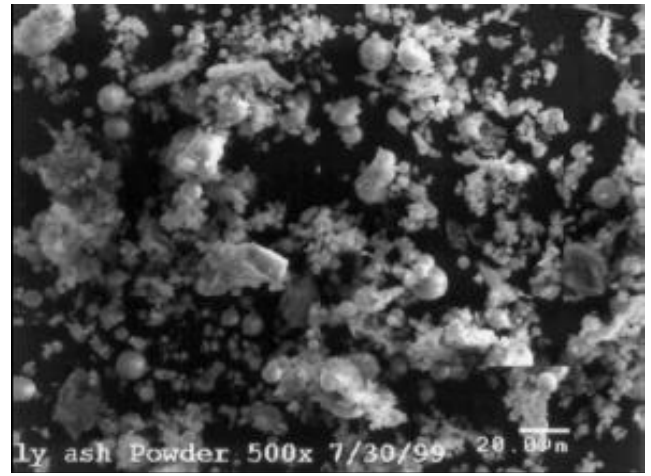


Figure 4. Scanning electron micrograph of WE class F fly ash.



Figure 5. Typical melting and stirring setup for manufacturing aluminum matrix composites

The pictures show that some fly ash particles are spherical, while some others are irregular in shape. Frequently there are large aggregates of fine fly ash. The fly ash was stirred into the aluminum alloy melt using an impeller designed to create a vortex to effectively pull the lighter fly ash into the melt. An argon gas cover was used to prevent the incorporation of oxides into the melt. Figure 5 shows a typical industrial melting and stirring setup used for these experiments. The tensile bars containing different amounts of fly ash were cast using a permanent mold. The volume percentage of fly ash in samples used in this paper is the nominal composition based on the weight of fly ash added to the melt, assuming that most of fly ash was retained in the melt. A qualitative confirmation of this assumption was obtained by microscopically examining the castings. The resulting castings were cut and polished for density measurements, microstructural analysis and mechanical property measurements. Tensile bars of the A356-fly ash composite were heat treated (T6) before tensile test.

3. Characterization of Composite Castings

3.1 Density Measurements

Figure 6 shows the results of density measurements of A356-WE fly ash composite castings (permanent mold).

Table I. Chemical composition of as received cenosphere fly ash particles.

Compound	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	SO ₃	MgO	K ₂ O	Na ₂ O	TiO ₂
Wt %	61.0	25.80	4.99	0.82	0.31	1.58	3.59	0.74	1.00

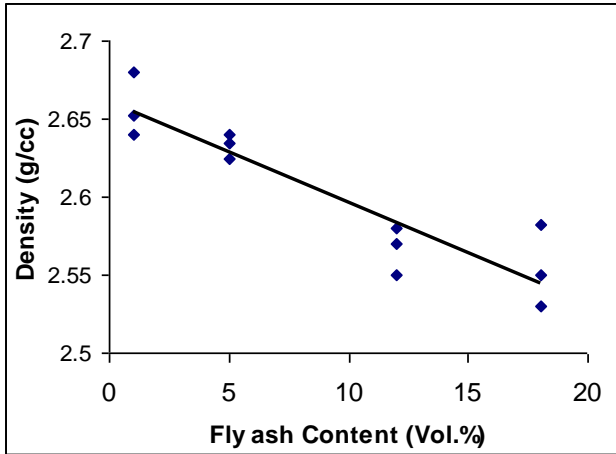


Figure 6. Density measurements of A356– fly ash composite castings (permanent mold and in as cast condition) as a function of fly ash content.

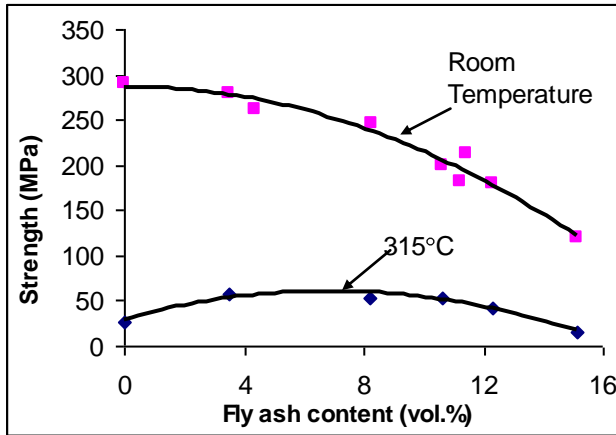


Figure 7. Tensile strength of A356–fly ash composite castings as a function of fly ash content at room temperature and high temperature (315°C).

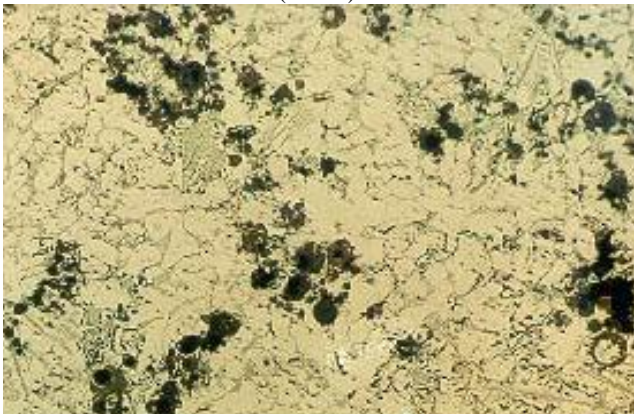


Figure 8. Photomicrograph of A356-10 vol% fly ash composite casting (permanent mold, as cast condition); Dark particles are Fly Ash.

It can be seen that the density decreases as fly ash content increases; this could lead to a decrease in the weight of components.

3.2. Tensile Tests

The values of tensile strength of castings measured both at room temperature and at 315°C are given in Figure 7. The tensile strength (room temperature) of castings which contain up to 8 vol% fly ash are similar to that of the base alloy. The tensile strength at high temperature (315°C) of composite castings containing 3 to 12.5 vol% fly ash is 45 to 62 MPa which is much higher than that of base alloy (27.5 MPa) at 315°C, as shown in Figure 7. The high temperature tensile strength decreases slightly with increasing fly ash content from 3 vol% to 12.5 vol%. The room temperature strength of the unreinforced A356 alloy is compared with that of the Al-8 vol% fly ash composite. It can be observed that the measured value of strength on A356 samples made in this study (25.9 MPa) is very close to the value (26.2 MPa) listed in the handbook, verifying that appropriateness of the casting and testing procedures used in this study. Additions of 8 vol% fly ash decrease the room temperature tensile strength of A356 by a magnitude of 28.9 MPa; additions of fly ash lower than 8 vol% result in even lower decrease in strength values. Research is in progress to modify the process and add suitably pretreated finer fly ash to improve even the room temperature strength of the base aluminum alloys as a result of fly ash addition. These composites containing low volume fraction are presently recommended for nonstructural components where most loads are the self weight of the components, and the lower weight, cost, thermal expansion and higher abrasion resistance would be an advantage. These components could include

- Intake manifolds, covers, differential housing and unloaded brackets for automotive, motorcycles and watercrafts
- Highway and runaway signs
- Extrusions for home accessories such as door knobs, handles, and appliance covers
- Yard tool covers (lawn movers, edgers, etc.)
- Sliding tracks for homes Industrial furniture and covers
- Chair support brackets, patio furniture and statuary
- External lamp posts and in-home consumer products

3.3. Microstructure Analysis

Micrograph of a typical composite casting containing 10 vol% fly ash is shown in Figure 8; the dark spherical particles represent fly ash and the lighter colored dendritic matrix is alloy 356. For the most part, the fly ash particles were well dispersed in the matrix, and only a few small clusters of fly ash were observed. As the synthesis technology for ALFA composites improves, the occurrence of such clusters will be further reduced.

4. Sand Casting of A356 - Fly Ash Composites

Figure 9 shows four different components of A356– fly ash composite cast using sand molds. The sand mold castings including intake manifolds, motor mounts,



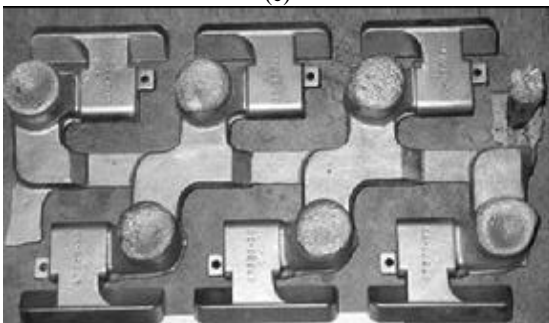
(a)



(b)



(c)



(d)

Figure 9. The sand mold castings of A356-fly ash composite (a) intake manifold, (b) brake drum (c) motor mount, (d) differential cover casting

differentials and brake drums, demonstrate that it is feasible to make complex shaped sand castings from these composite. However, process improvements are needed to eliminate the porosity and formation of fly ash clusters at higher volume percentage of fly ash. Suitable changes in melting, mixing, and casting practice or providing chills can ensure that an acceptable distribution of fly ash is obtained.

4.1 Sand Casting of Post Caps as a Demonstration

Figure 10 shows a single mold cluster of four protective post cap castings for playground equipment produced from A356-fly ash composite using sand casting. The principle function of post cap castings is to prevent the rain water from getting into hollow cylindrical posts; the sand cast post caps weighing 0.64 kg are sand blasted. The open end part of the post cap is turned to provide chamfer and three holes are drilled for bolting the cap to the posts. The post caps are then spray painted in different colors to give them an attractive appearance. The ALFA post cap castings were successfully cut, and the gates and risers could be removed using the conventional band saw equipment utilized for base aluminum alloy castings. Holes could be drilled in the post cap castings using black oxide coated screw machine length high speed steel drills. The open end of the post cap could be turned using a coated Cermet insert. However, in view of the higher wear rate of the drills and tools while machining ALFA castings, as compared to base Al-alloy castings, it is recommended that poly crystalline diamond tooling be used to machine large batches of ALFA castings. While machining of ALFA composites was more difficult, as compared to the base Al-alloys, it was much easier than machining of Al-SiC composites. The ALFA post caps could be successfully painted with spray-on polymer based paint similar to the base Al-alloy's post cap castings.

4.3 Other Casting Techniques

Motor Mount castings produced using direct squeeze casting (Figure 11) at Thompson Aluminum at 69 MPa pressures showed improved particle wetting and adequate tensile strength of the order of 262 MPa. Mounting brackets have also been made by pressure die cast aluminum-fly ash melts containing up to 10 vol% fly ash.

5. Energy, Materials and Pollution Savings Resulting from Use of ALFA Composites

5.1 Lower Material and Energy Costs for Parts Manufacture

ALFA composites provide significant savings to foundries and auto parts makers, which can be passed on to consumers. Power companies also benefit by avoiding ash disposal and monitoring costs. Fly ash is a by-product that costs 11-22 cents/kg after beneficiation compared to \$2.78/kg of aluminum and about \$3.3-6.6/kg for silicon carbide. However there will be some incremental cost of mixing fly ash in terms of equipment and consumables, pretreatments of the melt and the fly ash, and higher machining costs.



Figure 10. Four post cap casting made from Aluminum 319-10 vol% fly ash melt with gating.



Figure 11. Automotive motor mounts of Al-fly ash made by squeeze casting.

The manufacturing process to make ALFA castings on industrial scale is still evolving and it is not possible to offer a quantitative cost figure, other than to state that ALFA castings are likely to be very attractive because the significantly lower cost of fly ash outweighs the small cost increment in processing. Savings in manufacturing costs will be roughly proportional to the volume percent fly ash that replaces aluminum. Materials savings calculations assume a price of average \$2.77/kg for aluminum alloys and \$0.11/kg fly ash, with an approximate fixed cost of \$0.11/kg for equipment and labor to introduce ash into the melt. Thus, the cost of an ALFA part containing 20 vol.% ash will be \$2.51/kg. Similarly, a part containing 40 vol.% ash will cost about \$2.24/kg. Moreover, by requiring fewer aluminum ingots per casting, ALFA composites reduce the energy required to produce and transport the raw material, and melt the aluminum.

5.2 Avoided Ash Disposal Costs

Power plants generate about 90 million tons of fly ash per year, most of which is land filled at a cost approaching \$1 billion. These disposal costs are rising rapidly as landfill sites grow scarce. By selling ash as filler, the power companies would not only avoid disposal costs, but bring in revenue. The fly ash can be collected and processed within the market value of \$100/ton. The potential U.S. market for fly ash in ALFA composites (all industries) is estimated at more than 1 million tons of ash annually.

5.3 Calculations of Possible Energy Savings due to use of ALFA Composites

The energy savings and environmental benefits through the manufacture of ALFA composites can be obtained from reductions in aluminum utilization due to displacement of part of Aluminum by the fly ash and use of automotive parts with aluminum-fly ash parts, in automotive applications. Compared to the total energy consumption of 14.56×10^{10} kWh in primary aluminum production in the US, a 20% reduction in the requirement of aluminum will lead to a saving of about 2.77×10^{10} kWh.

The second savings will come from the reduced weight of passenger cars as a result of the use of the ALFA composites. It is estimated that a reduction of about 70 kg in the weight of each car can be achieved. The energy saving due to replacement of currently used automotive parts by ALFA in US automotive sector can be estimated by the following calculations. 1% reduction in weight translates into about 0.6% reduction in fuel consumption. Assuming that the usage per car per year is about 19,300 km, and fuel consumption is about 10 km/l, reduction in 70 kg through the use of ALFA composites will lead to reduction in fuel consumption by 6.66×10^8 liters (or 0.59×10^{10} kWh) per year for 11 million cars.

The total energy saving due to these two means adds up to be 3.36×10^{10} kWh. The energy saving due to the process development can be calculated as follows: the US metal casting industry's annual energy usage is estimated to be 7.32×10^{10} kWh. Most of the energy is used for major operations such as melting, molding and heat treating. Annual energy use in nonferrous casting industry is about 1.25×10^{10} kWh. Assuming 0.1% saving in energy due to development of ALFA composites (which will reduce the amount of aluminum remelted and cast), the energy saved can be as high as 1.25×10^9 kWh.

5.4 Calculations of Environmental Benefits

The estimated air emissions resulting from production of primary aluminum are listed in Table II. It is shown that the major air emissions from aluminum production are SO_x and CO₂. If 20% less aluminum is produced in the US due to the use of ALFA composites, the air emissions will be reduced as shown in Table II. In addition, the reduction in weight of transportation components will lead to further environmental benefits due to reduced energy consumption. In cars alone the total fuel saving of 6.66×10^8 liters/year will lead to considerable reductions in emissions as shown in Table III.

5.5 Energy Savings in individual Parts

In Table IV and V calculations are shown for energy consumption for one kg of Aluminum castings, and one kg Aluminum equivalent volume of ALFA composite. It assumes that the volume of the base Aluminum alloy casting, and the volume of the ALFA casting are similar. The calculations show that 4.52 kWh of energy is reduced per kg equivalent of finished ALFA composite product.

It then calculates the energy savings in 2000 of post caps shown in Figure 10, with each part made out of 0.64 kg of base Aluminum alloy. Two additional calculations are made for energy savings. These include energy savings from (a) 255,000 kg of Aluminum replaced by ALFA composites and

Table II. Combustion emissions associated with primary aluminum production in the United States in thousand metric tons (1995).

Emissions due to	SO _x	NO _x	CO ₂	CO	Particle	VOCs	Organics
Primary aluminum production in the USA	216.22	88.47	23,298.39	7.76	62.24	0.66	14.51
20% savings due to a reduction in primary aluminum production	43.24	17.69	4,659.68	1.55	12.45	0.13	0.90

Table III. Emission saved due to a reduction in weight in cars.

Gas	Hydrocarbon	CO	NO _x	CO ₂
Reduction in Emission (tons)	125	34,096	1,406	1,895,975

Table IV. Energy consumption for one kg of aluminum in a finished casting

Description	Energy	Comment
Energy to provide 1 kg of primary aluminum ingot	37.26 kWh/kg	From table 4-3 of DOE Aluminum Industry Energy and Environmental Profile
Theoretical Energy to melt Al needed to produce 1 kg of finished casting with 35% casting to melt ratio	1.60 kWh	Assumes melting 1.3 kg of Aluminum by heating from 21°C to 704°C with a 50% combustion heat transfer efficiency
Total energy/kg of finished product	38.86 kWh	Addition of above numbers

Table V. Energy consumption for 1 kg equivalent volume of ALFA composite

Description	Property	Comment
Energy to provide 0.9 kg of primary aluminum ingot	33.54 kWh/0.9 kg	From table 4-3 of DOE Aluminum Industry Energy and Environment Profile
Density of fly ash	2.2 g/cc	From Mark's Handbook for Mechanical Engineers
Density of Aluminum	2.7 g/cc	From Mark's Handbook for Mechanical Engineers
Weight of fly ash that displaces 0.1 kg of Aluminum = $0.1 \text{ kg} \times (2.2/2.7)$	0.0815 kg of Fly Ash	Calculated based on density ratio
Specific heat of Aluminum	$2.51 \times 10^{-4} \text{ kWh}/(\text{kg} \times ^\circ\text{C})$	From Mark's Handbook for Mechanical Engineers
Latent heat of melting for Aluminum	0.11 kWh/kg	From Mark's Handbook for Mechanical Engineers
Energy to bring 0.9 kg of Aluminum from 21°C to 704°C = $0.9 \times (2.51 \times 10^{-4} \times 683) + 0.9 \times 0.11 \text{ kWh/kg}$	0.253 kWh	Calculation
Energy to bring 0.037 kg of fly ash from 21°C to 704°C = $0.037 \times 0.00023 \times 683/0.50$	0.0117 kWh	Calculation using a 50% combustion heat transfer efficiency
Total energy to bring equivalent volume of ALFA to 704°C = $1.3 \times (0.253 + 0.0117)$	0.344 kWh	Total for the same volume as 1 kg of monolithic Aluminum
Total energy to produce the equivalent finished volume as 1 kg of aluminum = $0.344 + 33.54$	33.884 kWh	Calculation
Theoretical energy reduced per kg equivalent of finished ALFA product	4.98 kWh	Subtraction of before and after numbers
Total energy saved in 2000 part post cap demonstration	9960 kWh	Equivalent to six months production for this single part
Total energy savings potential for 255,000 kg of annual outdoor non-structural applications	1.27kWh	Potential application in the outdoor equipment industry
Total energy saving potential to use ALFA composites in 10% of 225,000 tons of annual automotive Applications	$92.25 \times 10^6 \text{ kWh}$	Potential application expected in the automotive industry

(b) 10% of 225,000 tons of Aluminum annually in automotive sector displaced by ALFA through the use of composites.

6. Conclusions

The research demonstrates the ability to successfully produce selected prototype castings of ALFA composites. The use of these castings has a potential to reduce the cost and weight of automotive parts, in addition to providing a high value use of fly ash. The potential reduction in cost and energy content of individual parts, energy consumption and emissions due to replacement of 20% aluminum by fly ash, and energy consumption and emissions due to reduced weight of cars, are calculated in the paper. All these values show substantial benefit of using ALFA composites, suggesting the possibility of conserving materials and energy, and reducing pollution.

The density and coefficient of thermal expansion of castings decrease, and their hardness and wear resistance increase as their fly ash content increases. Tensile strength of castings (T6) which contain less than 8 vol% fly ash appears to be similar to that of the base alloy. ALFA composites should initially be explored for nonstructural applications where most of the loads are self-weight of the components, and lower weight, cost and expansion would be an advantage. As the processing technology improves and more property data including fatigue becomes available, ALFA can be explored for other applications.

REFERENCES

1. P.K. Rohatgi and R.Q. Guo; "Opportunities of Using Fly Ash Particles for Synthesis of Composites," Proceedings of the 59th Annual American Power Conference, Chicago, pp. 828- 833 (1997).
2. R.Q. Guo, P.K. Rohatgi, and S. Ray; "Casting Characteristics of Aluminum – Fly Ash Composites,"

- Trans. Am. Foundrymen's Soc., 104, pp. 1097-1101 (1996).
3. G.E. Kiourtsidis, S.M. Skolianos and G.A. Litsardakis. Aging response of aluminium alloy 2024/silicon carbide particles (SiCp) composites. *Materials Science and Engineering A*, 382, 1-2, 2004, 351-361.
4. M.S. El-Gallab and M.P. Sklad. "Machining of aluminum/silicon carbide particulate metal matrix composites: Part IV. Residual stresses in the machined workpiece." *Journal of Materials Processing Technology*, 152, 1, 2004, 23-34.
5. P.K. Rohatgi, J.K. Kim, N. Gupta, Simon Alaraj and A. Daoud. "Compressive characteristics of A356/fly ash cenosphere composites synthesized by pressure infiltration technique." *Composites Part A*, 37, 3, 2006, 430-437.
6. P. K. Rohatgi, N. Gupta, and Simon Alaraj. "Thermal Expansion of Aluminum–Fly Ash Cenosphere Composites Synthesized by Pressure Infiltration Technique." *Journal of Composite Materials*, 40, 2006, 1163 - 1174.
7. P.K. Rohatgi, H. Iksan, R.Q. Guo, and X. Qiu, "Thermal Expansion of Aluminum-Fly Ash Composites," Proceedings of the 60th Annual American Power Conference, Chicago, April, 1998.
8. P.K. Rohatgi, R.Q. Guo, P. Huang, and S. Ray; "Friction and Abrasion Resistance of Cast Aluminum Alloy – Fly Ash Composites," *Metall. Mater. Trans. A*, 28A, pp. 245-250 (1997).
9. R.Q. Guo and P.K. Rohatgi; "Chemical Reactions between Aluminum and Fly Ash during Synthesis and Reheating of Al – Fly Ash Composite," *Metall. Mater. Trans. B*, 29B, pp. 519-525 (1998).