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Incorporation of High-Ca Fly Ash Particles into A356 Al by Stir Casting Technique and Characterization of the Fabricated Composites

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ABSTRACT

In this study, two different types of lignite fly ash (FA), a highly calcareous (CaO>40 wt. %) and a siliceous one, were utilized for the fabrication of A356 Al-based composites by liquid metal stir casting technique. FAs were sampled from Kardia and Megalopolis Power Stations of Greece (1250 MW and 850 MW respectively). As it was previously reported and currently experimentally shown after several alloy-FA stir-mixing attempts, molten Al alloys normally present no wettability with as received high-Ca FA particles, a fact leading to ash particles being almost totally rejected by the metallic matrix. However, through the current research study, it was verified that conducting stir mixing of fine, gradually pre-heated calcareous FA particles at a higher molten alloy-temperature (T_{melt} >900ºC, while previous attempts referred to ~700ºC) can eventually result in the incorporation of high-Ca FA particles into the melt and in the subsequent successful synthesis of lightweight Al alloy composites

containing at least 10 wt. % FA, with enhanced tribo-properties. FA particles with a mean diameter of less than 10 microns were utilized for the fabrication of composites, the microstructure of which was tested by means of Scanning Electron Microscopy (SEM) and their wear performance by using a pin-on-disc machine, by applying ASTM G99-90.

INTRODUCTION

Metal matrix composites (MMCs) find applications in automobile and aerospace because of their excellent combination of physical, mechanical and tribological properties[1]. Primarily thanks to their high specific strength and stiffness, those composites could also be successfully used in weight critical applications[2]. On the other hand, however advanced they may be, the usage of MMCs is still relatively limited due to their high production cost.

Among the various discontinuous reinforcement used, coal-fed power plants fly ash (FA) is one of the most inexpensive available. The current study focuses upon implementing liquid metal stir casting technique for the incorporation of high-Ca lignite fly ash particles into molten aluminum alloy. It is mentioned that most of the relative previous efforts referred to Class F ashes[3-8] and very limited research is reported regarding calcareous (Class C) ash. Calcareous ash particles normally present restricted wettability with molten Al and therefore premium scope of this study is to modify regular casting conditions (stir casting temperature, ash pre-treatment, rate of ash addition), in order for a desirable ash particle-molten alloy contact angle to be achieved.

MATERIALS AND METHODS

Raw materials

356 Cast aluminum alloy (Al-7Si-0.35Mg) is chosen as the matrix alloy with fly ash particles as the reinforcement. Fly ash used for the purpose of this study was sampled from the lignite-fired power stations of Kardia, Northern Greece (1250MW) and Megalopolis, Southern Greece (850MW). Ash samples were manually sieved and the grain fraction of (0-25) μm was obtained and used as reinforcement to matrix alloy. The average particle size was 11μm in the case of Kardia fly ash (KFA) and 9.5μm in the case of Megalopolis fly ash (MFA). Table 1 shows the chemical composition of KFA and MFA, as determined by means of X-Ray Florescence.

Table 1. Chemical composition (wt. %) of KFA and MFA fine particles.

Oxides	**SiO_2 (%)**	**Al_2O_3 (%)**	**Fe_2O_3 (%)**	**TiO_2 (%)**	**P_2O_5 (%)**	**CaO (%)**	**MgO (%)**	**Na_2O (%)**	**K_2O (%)**	**SO_3 (%)**
KFA (<25μm)	22.89	10.74	5.22	0.70	0.23	49.59	5.11	0.03	0.60	4.15
MFA (<25μm)	49.45	12.21	12.51	0.66	0.17	16.31	4.11	0.41	0.82	2.61

Synthesis of composites

A356 Al/FA composites are prepared through the stir casting technique, which involves melting of aluminum alloy, mixing of preheated ash particles in the melt through mechanical stirring and casting of the FA-melt mixture. Ash particles are preheated at 1073 K for 8 h, by applying a 373 K increase of temperature/hour. The alloy melt is mechanically stirred at 600 rpm using a graphite-made impeller driven by an electric motor. The impeller, as well as the graphite crucible (which contains the 0.5kg-charge of the alloy to be melt) is coated with boron nitride. The preheated ash particles are added to the melt at a feed-rate of 3g/min. Such a low feed rate is chosen in order for the maximum-possible dispersion to be achieved. In the case of KFA addition, particles are added at 1148 ±5 K and the casting is carried out at 1223 ±5 K. It is mentioned that initial alloy-KFA stir-mixing attempts were conducted at much lower temperatures (starting from 1023 K). However, severe rejection of ash by the melt was observed at low temperatures, mainly due to the non-wettability of high-Ca FA particles with molten alloy. By increasing the temperature of molten alloy to the aforementioned point (1223 K), much less FA rejection occurred and since 95% of the added particles have sufficiently been incorporated into the melt, under mixing. In the case of MFA addition, particles are added at 973 K ± 5 K (siliceous ash particles are wettable and thus a regular Al alloy castings temperature is selected). Mg 1.5 wt. % is added along with MFA particles as wetting agent. Finally, the composites are shaped into rectangular plates in mild steel moulds.

Fig. 1. *Left:* Molten alloy stirring (pre-heated FA particles are added to the melt in the rate of 3g/min). *Right:* A356 Al/KFA 10% wt. composites.

Characterization of composites

The microstructure of composites was examined by means of Energy-Dispersive X-ray Spectrometry (EDS-SEM, JSM-6300 JEOL). Dry sliding wear tests were conducted in air at ambient atmosphere using a Pin-on-Disc machine (CSEM High Temperature Tribometer, operated by the authorized personnel of CERECO S.A.) according to ASTM G 99-90. Pins of specimens were tested against spheres of alumina (Al_2O_3, diameter: 6mm); a new sphere was used for each test. Prior to actual wear tests, sliding surfaces of test specimens were rubbed on 400/600 grid SiC emery paper. The surface of the disc was polished to a surface roughness of 0.1 ± 0.02 R_a, using a series of abrasive papers. Experiments were conducted under dry conditions, at room temperature (25ºC, relative humidity: 65 ± 5%). The linear speed and sliding distance were 0.05 m/s and 94.20 m respectively. The load was 2 N. The rotational frequency of tested samples was set at 95 rpm; a total of 3,000 rounds were made by each sample. The wear rate was derived by the ratio WV / (FN×SD) (where WV the worn volume, FN the normal applied load and SD the total sliding distance). The friction coefficient was evaluated by measuring the track cross sectional area and height, at ten different points on the wear track, using CSEM REVETEST Scratch-Tester. The worn volume was calculated by multiplying the average track area with the circumference of the slide circle.

RESULTS AND DISCUSSION

Synthesis and microstructural observation of composites

Poor wetting of KFA particles by molten alloy was successfully addressed through the increase of casting temperature by approximately 20% to the initially planned. Indeed, casting at 1223 K resulted in the successful incorporation of high-Ca FA particles into the alloy; over 95 wt. % of the added particles were dispersed into the matrix and remained in the main body of composites after their solidification. What’s more, possible floatation of both MFA and KFA particles in the melt was confronted by particularly selecting the FA size fractions with density equal to this of A356 Al. It is also mentioned that the applied low addition rate of ash particles into the molten alloy finally led to an acceptable level of dispersion of particulates into the matrix. Another problem which usually occurs when ceramic particles are stir-mixed within metallic matrices is the segregation of the particles in the last freezing interdendrite regions due to the rejection of the particles by the solidifying interface[3]. Such a phenomenon did not observed in the current study after increasing the casting temperature and thus sufficiently addressing the FA rejection problem.

Figure 2 shows the micrographs of A356 Al alloy as cast and the A356 Al/KFA 10 wt. % composite. Microstructure of as-cast composites indeed reveals a relatively uniform distribution of fly ash particles in the matrix. However, at some locations clusters of smaller fly ash particles as well as pores were observed (Fig. 3). Actually, after successfully incorporating high-Ca FA particles into alloy melt, deagglomeration of FA particles is the major target of future research in the field of “ashalloy” composites, in order of materials with enhanced mechanical properties to get manufactured.

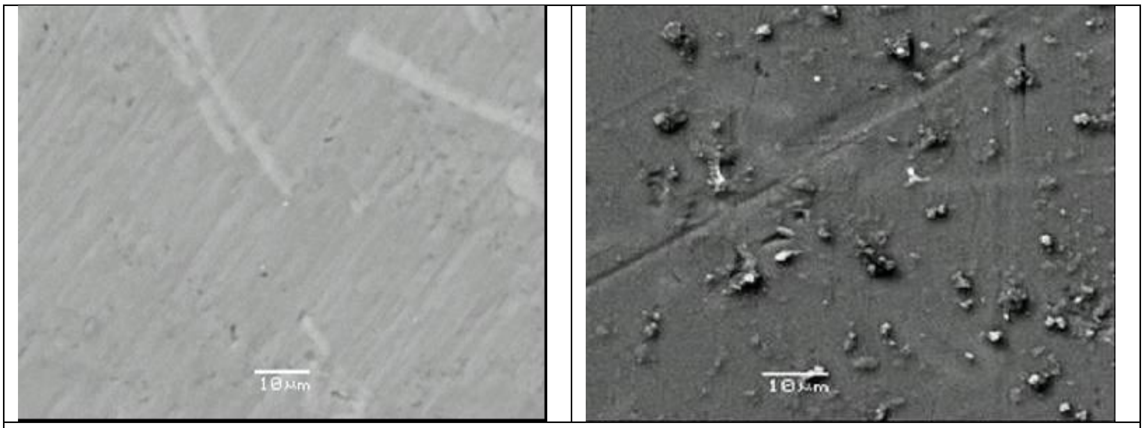

Fig. 2. *Left:* A356 Al alloy *Right:* A356 Al/KFA 10% wt. composite.

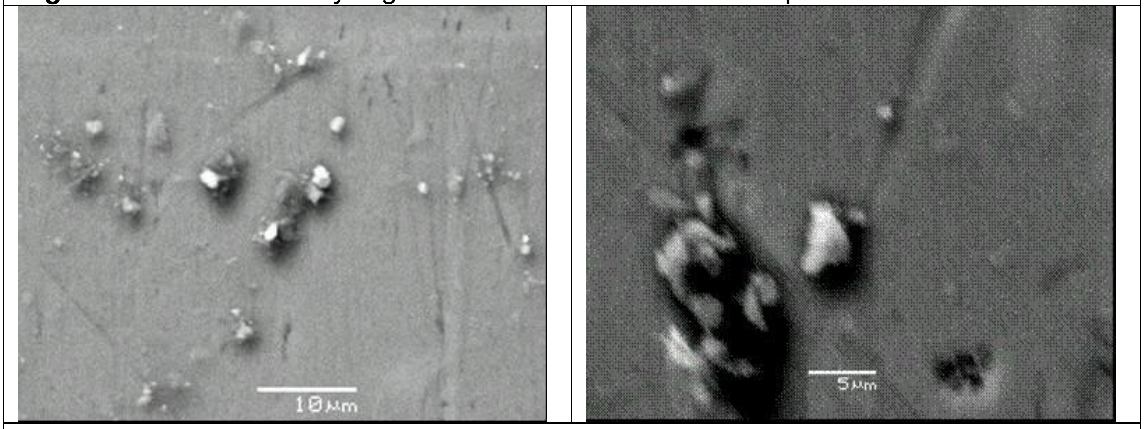

Fig. 3. *Left:* Fine FA particles clusters within A356 Al/KFA 10% wt. composite. *Right:* Hole along particle cluster on the surface of the A356 Al/MFA 10% wt. composite.

Tribological performance of composites

Table 2 shows the wear tests results of the fabricated composites. It seems that a 10 wt. % addition of both siliceous and calcareous FA particles can have a marginal positive effect on the tribo-properties of composites, as it can be inferred by the slightly lower friction coefficient obtained by the composites comparing to that of the unreinforced alloy.

Table 2. Tribological tests results of A356 Al-10 wt. % KFA and A356 Al-10 wt. % MFA composites (SC1 and SC2 respectively).

Sample	**Displacement (μm)**	**Worn Area (μm2)**	**Wear Volume (108μm3)**	**Friction Coefficient**	**Wear Rate (10-14 m3/Nm)**
A356 Al	30.75	11949	3.75	0.455	199.16
SC1	22.62	10283	3.23	0.451	171.38
SC2	36.12	13177	4.14	0.450	219.62

Figure 4 shows the micrographs of wear track of A356 Al/10 wt. % KFA. Surface of composite does not appear smooth because of the presence of distinct grooves. These grooves are caused by the ceramic FA particles ploughing the pin surface. Thus, it is inferred that the contribution of ash particles to friction coefficient of composites is mainly caused by ploughing grooves in the surface of softer matrix via plastic deformation resulting in fracture, tearing or fragmentation, as it was also reported in previous works dealing with Al alloys reinforced by ceramic particulates[8]. Worn surfaces of composites showed curling-up along the specimen edges, as well as craters and ploughing. Plastic ploughing and cutting were clearly less in the KFA-containing composite than the MFA-containing one, mainly thanks to the harder calcareous ingredients being present in the former.

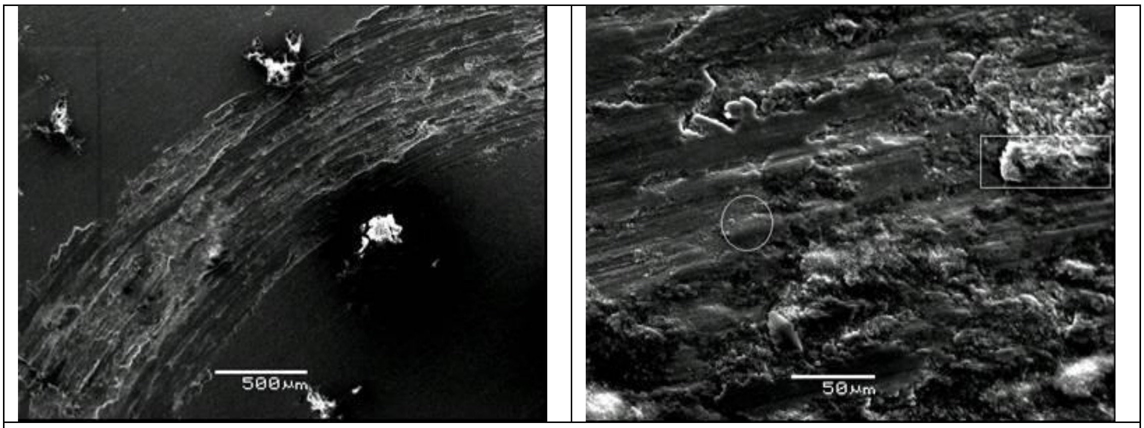

Fig. 4. Micrograph of worn surface of A356 Al/KFA 10% wt. composite.
Left: Scale legend is 500µm. *Right:* Scale legend is 50µm

CONCLUSIONS

1. High-Ca fly ash particles have successfully been incorporated into molten alloy for the synthesis of A356 Al/10 wt. % FA composites.
2. Poor wettability of high-Ca ash particles has efficiently been addressed by increasing the casting temperature to the point of 1223 K from 1000 K that was initially planned. Rejection of FA was by those means effectively tackled, without introducing external forces into the melt.
3. Replacement of aluminum alloy by both calcareous and siliceous fine fly ash particles can lead to the manufacturing of composites with slightly better tribological performance than the unreinforced alloy.
4. Basic goal of future research on the issue is the accomplishment of maximum, possible deagglomeration of fine fly ash particles in order for maximum dispersion to be achieved and subsequently mechanically upgraded composites to get manufactured.

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