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Influence of cenospheres of fly ash on the mechanical properties and wear of permanent moulded eutectic Al–Si alloys

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In recent years, aluminium matrix composites reinforced with ceramic particulates have attracted considerable interest due to their inherent good mechanical properties and low cost. In this investigation, composites have been produced with cenospheres of fly ash as a reinforcement material and eutectic Al–Si alloy as a matrix. Stir casting route has been adopted to disperse cenospheres of fly ash (from 1% to 10%) in the Al–Si alloy matrix. The results indicate that with increase the content of fly ash, hardness and ultimate tensile strength increase by 34.7% and 44.3% respectively, while the density decreases by 13.2%. The wear loss decreases by 33% at the highest sliding distance. However, percentage elongation showed only a marginal decrease for various percentages of fly ash studied in this investigation.

Keywords: *metal matrix composites; fly ash; cenospheres; mechanical properties; wear*

1. Introduction

Metal–matrix composites are materials in which tailored properties are achieved by systematic combinations of various constituents [1]. Conventional monolithic materials generally have limitations in terms of their strength, stiffness, coefficient of expansion, and density. Eutectic Al–Si alloy (LM6) is one of the commonly used alloys in the non-heat treated condition for automotive engines because of its good mechanical properties, high strength-to-weight ratio, wear resistance and low coefficient of expansion. Apart from stress relieving and improvement in ductility, heat treatment does not significantly change the properties of such alloys [2]. Several authors re-

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ported that particulate reinforced composites exhibit superior mechanical properties compared to unreinforced alloys.

Particulates such as SiC, TiC, TiB_2 and fly ash have been used to reinforce Al alloys to improve their mechanical properties and wear resistance [3–8, 16, 17]. In recent years, the use of fly ash as a reinforcement material in Al alloys has been reported to be desirable from both environmental and economic points of view due to its availability as a low cost waste material [9]. Mahendra et al. [10] reported a higher tensile strength and hardness for Al–4.5% Cu alloy–fly ash based composites. Ramachandra et al. [11] in a study on the mechanical properties of hypoeutectic Al–Si/Fly ash composites showed that an increase in the percentage content of fly ash particulates results in an increase in the hardness and tensile strength but the density decreases as the fly ash content increases.

Fly ash is a byproduct of coal combustion collected from electrostatic precipitators and bottom ash at the bottom of furnaces. It is a fine-grained, powder material that is carried off in flue gas and usually collected by means of electrostatic precipitators, bag housings, or mechanical collection devices such as cyclones. Fly ash obtained from electrostatic precipitators varies in size from 5 μm to 75 μm [17]. It consists of hollow microspheres known as cenospheres which generally float on water in the ash collection ponds. Since the particles solidify in suspension, cenospheres of fly ash are generally spherical in shape and more uniform in quality, shape and size compared to normal fly ash. The density of cenospheres is 0.6–0.9 $g\cdot cm^{-3}$.

A detailed study of available literature reveals that very few systematic investigations have been carried out to investigate the influence of fly ash particulates, especially cenospheres, on the mechanical properties and wear of eutectic Al–Si alloys.

In this investigation, an attempt has therefore been made to study the influence of cenospheres of fly ash on the hardness, density, ultimate tensile stress (UTS), elongation, surface roughness and wear of eutectic Al–Si alloys.

2. Experimental

Matrix used. Eutectic Al–Si alloy LM6 containing 12.2% Si was used as a matrix. The composition of the alloy is given in Table 1.

Table 1. Composition of LM6 alloy [wt. %] designated as a base alloy

Si	Fe	Cu	Mn	Mg	Zn	Al
12.2	0.32	0.002	0.62	0.065	0.021	Bal

A typical microphotograph of cenospheres of fly ash is shown in Fig. 1 and the composition of cenospheres of fly ash used in this study is shown in Table 2.

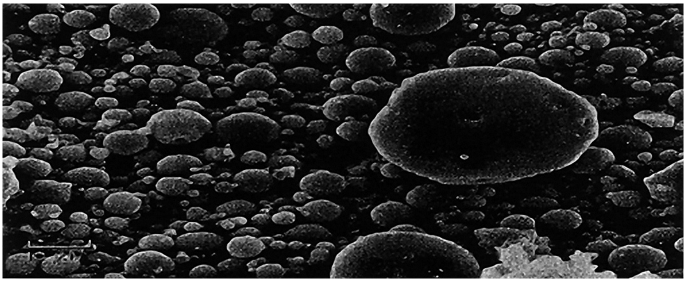

Fig. 1. Typical microphotograph of cenospheres of fly ash

Table 2. Composition of cenospheres of fly ash [wt. %]

Al_2O_3	SiO_2	Fe_2O_3	TiO_2	Carbon/LOI
29.9	56.92	8.44	2.75	1.99

Reinforcement used. Cenospheres of fly ash were used as a reinforcement material in this investigation. They are formed in the temperature range of 920–1200 °C [9]. The particle size distribution and cumulative distribution of the cenospheres used in this study was measured using ASTM standard sieves [18] and is shown in Table 3 and Fig. 2.

Table 3. Results of sieve analysis as per ASTM standards

ASTM sieve	Sieve opening [μm]	Cenospheres retained (R) [wt. %]	Cumulative cenospheres [wt. %]	Multiplier S	Product RS
12	1700	0.22	0.22	5	1.1
20	850	1.38	1.6	10	13.8
30	600	2.12	3.72	20	42.4
40	425	2.28	6	30	68.4
50	300	8.34	14.34	40	333.6
70	212	25.86	40.2	50	1293
100	150	50.68	90.88	70	3547.6
140	106	7	95.88	100	700
200	75	1.44	97.42	140	201.6
270	53	0.58	100	200	116
PAN	PAN	0	100	300	0
Total		$\sum R = 99.9$			$\sum RS = 6317.5$

The average grain fineness number was computed from the data given in Table 3:

$$\frac{\sum RS}{\sum R} = \frac{6317.5}{99.9} = 63.23$$

It was found experimentally that about 75% of the cenospheres particles have particle size in the range of 150 to 212 micrometers

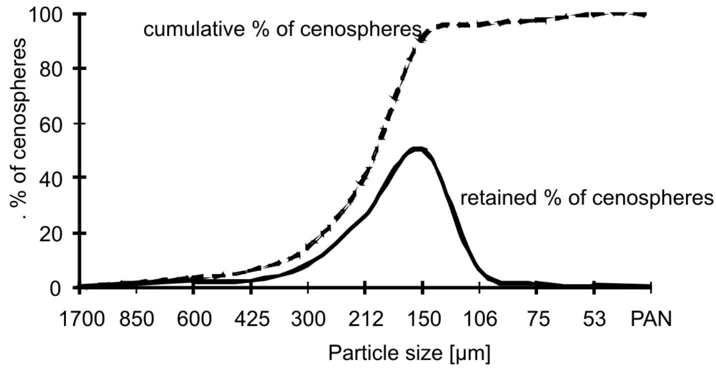

Fig. 2. Retained and cumulative % of cenospheres vs. particle size

Melting procedure. 2 kg of eutectic Al–Si alloy (LM6) ingots were melted in graphite crucibles using an electric resistance furnace. When the temperature of the molten alloy reached 850 °C, the crucible containing the melt was taken out for degassing. For degassing, hexachloroethane tablets, wrapped in a paper was plunged into the bottom of the crucible containing the molten metal and held at the bottom using a perforated plunger, until the bubbling action ceased. The metal was allowed to stand for a few minutes and the dross from the surface of the molten metal was skimmed using a perforated flat spoon. The temperature of the melt was checked using an alumel–chromel thermocouple. The molten metal was cast in a metallic die of $147\times125\times25$ mm^3, which was pre-heated to 200 °C and coated with a protective layer of china clay, water and sodium silicate to prevent contamination. The pouring was carried out at 650 °C. In order to check for reproducibility, three sets of castings were poured under identical conditions.

Preparation of composites. The melting procedure, indicated above, was adopted until degassing of the molten metal. After degassing, 5 g (0.0025 wt. %) of magnesium ribbons were added to the melt to improve the wettability of the particles with the matrix. A vortex was created by rotation of stirrer blades at an optimum speed for a predetermined time period. A vortex forming in the molten metal helps to distribute the reinforcement particles uniformly throughout the matrix. Cenospheres were slowly added to the molten metal while continuously stirring with a mechanical stirrer. Once again, three sets of castings were poured under identical conditions to check for reproducibility.

Test procedure. The castings, produced as mentioned above, were taken out of the die, cooled and then cut into 5 equal sections along the length from one end to the other as shown in Fig. 3. The samples were then machined to get standard test specimens for determining hardness, UTS and percentage elongation, surface roughness and slide wear. The densities of the samples were determined by the well known Archimedes principle.

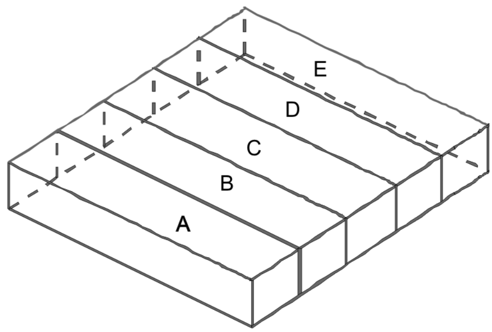

Fig. 3. Casting cut into sections along its length

Hardness. A Brinnel hardness test was conducted on the specimen using a standard Brinnel hardness tester. A load of 500 kg was applied on the specimen for 30 s using a 10 mm ball indenter and the indentation diameter was measured using a micrometer microscope. The Brinnel hardness number (BHN) was computed using the formula:

$$BHN = \frac{2P}{\pi D\left(D - \sqrt{D^2 - d^2}\right)}$$

where P is the load applied, D the diameter of the ball indenter and d the diameter of indentation.

Ultimate tensile strength (UTS) and elongation. An electronic tensometer of the Monsanto type W was used for tensile testing. The tensometer specimen was loaded between two grips that were adjusted manually. A constantly increasing force was applied to the specimen by electronic means. The load and elongation were continuously recorded. The UTS and percentage elongation were calculated.

Surface roughness. The surface imperfections consist of a succession of hills and valleys which vary both in height and spacing. These are measured using a Tally surf instrument. The surface roughness parameters R_a (*average roughness value*) and R_q (root mean square roughness) were selected. The stylus was moved over the surface and the readings were noted.

Dry sliding wear. A dry sliding wear test was conducted at ambient temperature using a pin-on-disc wear testing machine with a data acquisition system. Wear was determined by the weight loss method. Specimens of 6 mm diameter and 20 mm long were used for the dry sliding wear tests. The wear tests were carried out at a constant sliding velocity of 125.6 m·min^{-1} (500 rpm) for a track radius of 40 mm, load of 1 kg and sliding distances of 3768 m, 5652 m and 7536 m corresponding to 30, 45 and 60 min, respectively. A hardened steel disc of 60 HRC was used as the counterface.

3. Results and discussion

3.1. Hardness

Figure 4 shows an increase in hardness with the increase in the percentage of cenospheres of fly ash, when compared with the unreinforced eutectic Al–Si alloy. For instance, the hardness was found to be 50 BHN for 1% fly ash (an increase of 8.6% over the base alloy) and 62 BHN for10% fly ash (an increase of 34.7% over the base alloy).

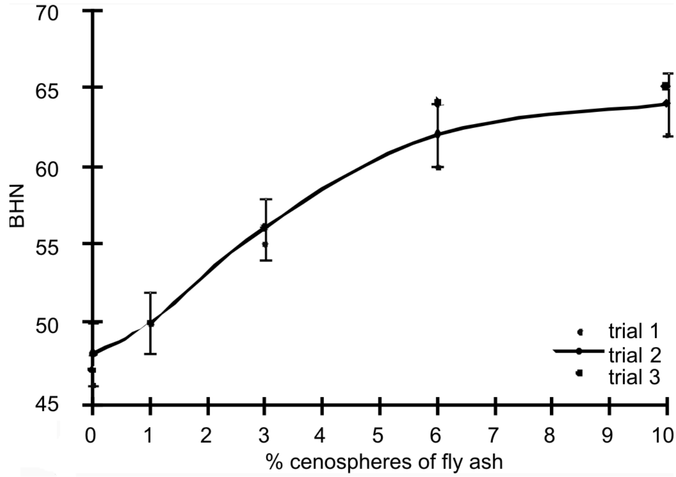

Fig. 4. BHN vs. % cenospheres of fly ash

It has been reported that addition of ceramic particles increases the hardness of composites [3, 5–8, 10, 11]. The increase in hardness is expected because of the presence of ceramic reinforcements which are very hard, and act as barriers to the movement of dislocations within the matrix and exhibit greater resistance to indentation [8]. This trend is also observed in our study.

3.2. Density

The density of the eutectic alloy was found to be 2.65 $g\cdot cm^{-3}$. This is in agreement with reported literature [2]. The densities of the cast composites, at various percentages of fly ash are shown in Fig. 5. The scatter of three readings was within 2%. It is observed that the density decreases as the percentage of fly ash increases, when compared with the unreinforced eutectic Al–Si alloy. For example, the density of the composite was found to be 2.62 $g\cdot cm^{-3}$ for 1% fly ash (decrease of 1.13% compared with LM6. Similarly, the density for 10% fly ash was 2.31 $g\cdot cm^{-3}$ (decrease of 13.2%). Several investigators have reported a similar trend with the addition of particulates like fly ash [10, 11]. This can be attributed to the difference in densities of aluminium and fly ash.

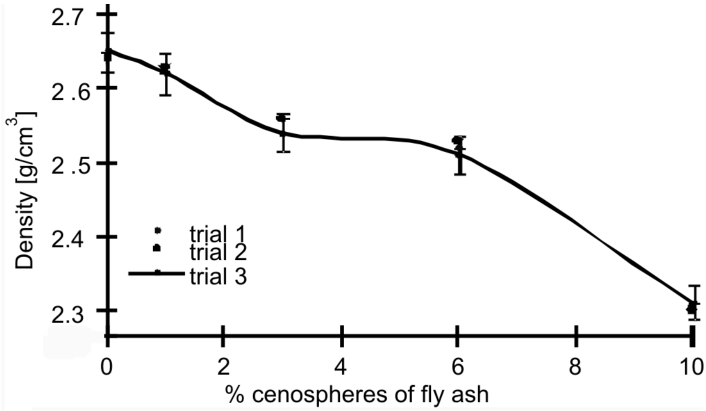

Fig. 5. Density for varying percentages of fly ash

3.3. Recovery of cenospheres

The recovery of cenospheres in the laboratory made Al–Si alloy–cenosphere composite system was calculated using the linear interpolation method, taking into account the density, volume of the alloy as well as of cenospheres. Linear interpolation is the simplest method of reliably estimating values at positions in between the data points [19]. It is observed that the recovery is 98.5% at 1% addition and decreases gradually as the percentage addition of cenospheres increases, as shown in Table 4.

Table 4. Recovery of cenospheres

Content of cenospheres [%]	1	3	6	10
Recovery [%]	98.5	95.6	93.6	83.4

3.4. Ultimate tensile strength and percentage elongation

Figure 6 shows the variation in UTS with the increase in the percentage content of fly ash. It was noted that the UTS for 1% fly ash is 158.8 MPa (16.2 kg·mm^{-2}) (an 8.5% increase over the untreated alloy). Similarly the UTS for 10% fly ash is 211 MPa (21.54 kg·mm^{-2}) and shows an increase of 44.3% when compared with the unreinforced eutectic Al–Si alloy (LM6).This could be due to the fact that the lighter microspheres of fly ash act as barriers to the movement of dislocation, thereby increasing the ultimate tensile strength of the composite [7].

Further, dispersion of hard ceramic particles in a soft ductile matrix results in improvement in strength. This may be attributed to large residual stress developed during solidification and to the generation of density of dislocations due to mismatch of thermal expansion between hard ceramic particles and soft Al matrix [16]. The reason for the improved strength may perhaps be due to a good bonding between the cenosphere particles and also with the matrix [18]. Thus it can be seen that our results are in agreement with those reported in the literature.

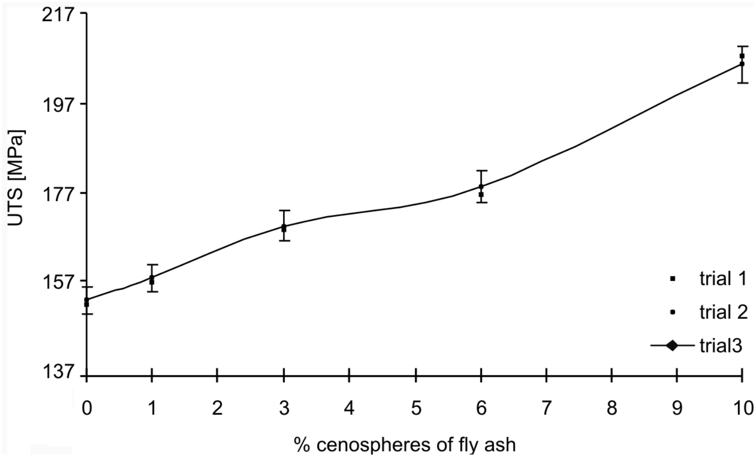

Fig. 6. Variation in UTS vs. % cenospheres of fly ash

Figure 7 shows that there is a marginal decrease in percentage elongation with the percentage increase in the fly ash. For instance, it can be seen that the elongation for 1% fly ash is 2.01%, while the elongation for 10% fly ash is 1.96%. This is in agreement with literature data [1, 6].

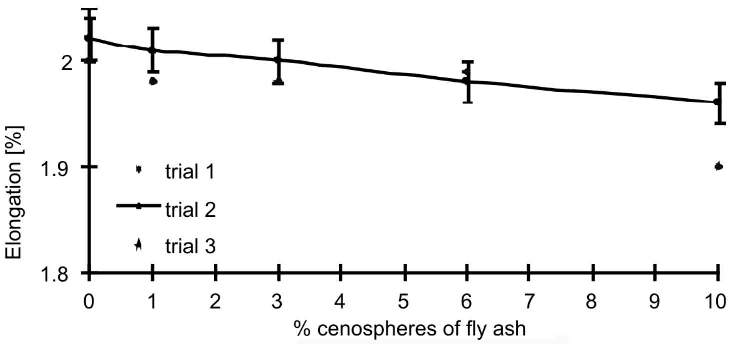

Fig. 7. Elongation vs. % cenospheres of fly ash

3.5. Surface roughness

A review of the literature reveals that no investigation seems to have been carried out to measure the surface roughness. From Figure 8 it is observed that the surface roughness increases as the percentage content of fly ash cenospheres increases, when compared with the unreinforced eutectic Al–Si alloy (LM6).

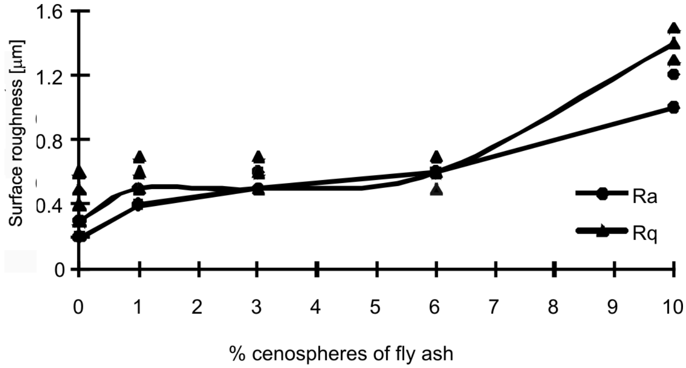

Fig. 8. Average surface roughness vs. % cenospheres of fly ash

For instance, R_a increases from 0.4 μm for 1% fly ash to 1 μm for 10% fly ash and R_q increases from 0.3 μm for 1% fly ash to 1.4 μm for 10% fly ash. Cenospheres of fly ash are extremely hard and contain much unburnt carbon [17]. This tends to have an adverse effect on the surface roughness.

3.6. Wear

In general, it is observed that the wear increases with the increase in time and distance. Figure 9 depicts the wear weight loss of the composites under different sliding distances. For instance, the weight loss is 0.06g at a sliding distance of 3768m, while the weight loss is 0.13g. at 7536m for 1% fly ash. A similar trend is observed for 3, 6 and 10% fly ash. This is due to the fact that cenospheres are hard, abrasive particles and resist wear better than the matrix. It is observed that, for a given sliding distance, the weight loss is lower for a higher percentage of fly ash. For example, the weight loss is 0.13g for 1% fly ash and 0.1g for 10% fly ash for a sliding distance of 7536 m. Similar trends were observed by other researchers [12–16].

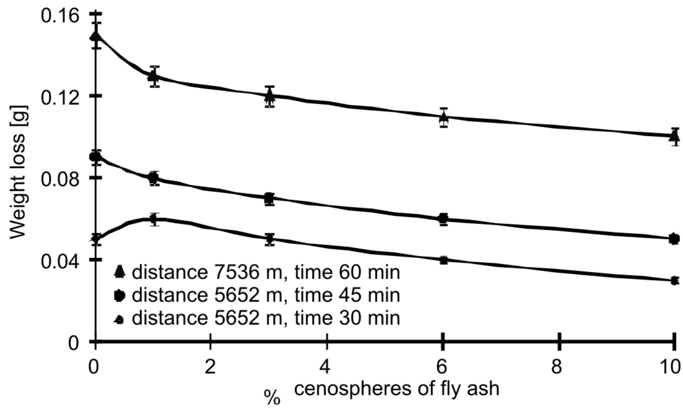

Fig. 9. Wear at 30, 45 and 60 min

The results shown in Figs. 4–9 indicate that fly ash cenospheres can increase hardness and UTS, while reducing density and wear. However, the surface roughness is found to increase, resulting in a poor surface finish, while the percentage elongation showed only a marginal variation for the various percentages of fly ash investigated.

4. Conclusion

An attempt has been made to evaluate the effect of various percentages of cenospheres of fly ash on the hardness, density, UTS, ductility, surface finish and wear, when compared with the unreinforced eutectic Al–Si alloy (LM6). The results of this investigation reveal the following:

It is observed that the hardness increases by 8.6% for 1% fly ash and by 34.7% for 10% fly ash based composite, compared with the base alloy.

Density decreases upon increasing percentage of fly ash addition. For instance, it decreases from 1.13% for 1% fly ash to 13.2% for 10% fly ash.

The ultimate tensile strength of the composite showed an increase ranging from 8.5% for 1% cenospheres of fly ash to 44.3% for 10% with the addition of cenospheres of fly ash.

The percentage elongation of the composite showed only a marginal decrease for the various percentages of fly ash studied in this investigation. It is found to decrease from 2.01% for 1% fly ash to 1.96% for 10% fly ash.

Sample analysis revealed there was a direct correspondence between the fly ash percentage and the wear loss: the higher the fly ash percentage, the lower the wear loss, and vice versa. For instance, the wear loss was found to be 0.1g for 10% fly ash compared with 0.13g for 1% fly ash for a sliding distance run of 7536m.

The surface roughness increases with the addition of cenospheres of fly ash. R_a increases from 0.4μm for 1% fly ash to 1μm for 10% fly ash and R_q increases from 0.3μm at 1% fly ash to 1.4μm at 10% fly ash.

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