Mechanical Properties of Al_2O_3 Particle-Reinforced A356 Composite Produced by a Multi-step Process Regime

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ABSTRACT

The aim of this study was to produce a composite material of A356 aluminum alloy reinforced with 250 μm alumina (Al_2O_3) powder. A multi-step process regime was developed. Strain was induced via milling in production of A356 chips. The chips were dry mixed with Al_2O_3 at 5, 10, and 15 wt% and cold pressed, followed by sintering at 600°C for 20 min. Then the molten composite was sand casted into a cylinder with a diameter of 20 mm and length of 50 mm. Afterward, all cast specimens were heat treated by solution treatment at 527°C for 12 h, quenched in water, and naturally aged at room temperature for 10 h; then artificially aged at 177°C for 12 h and furnace cooled. Specimens were subjected to hardness and wear tests. The results of hardness testing of the 'as received' A356 and casted A356-5, 10, and 15 wt% Al_2O_3 were 23.5 HRB, 41.3 HRC, 44.0 HRC, and 46.0 HRC, respectively, and the average hardness values after heat treatment were 46.0 HRB, 46.3 HRC, 48.0 HRC, and 51.1 HRC, respectively. The percentage of Al_2O_3 was a significant factor based on statistical analysis. The hardness values increased significantly after heat treatment. In addition, heat-treated A356-5, 10, and 15 wt% Al_2O_3 exhibited average wear rates of 0.00387, 0.00375, and 0.00350 mm^3/m, respectively. Increasing the amount of alumina reduced the wear rate, but the difference was not statistically significant. The cross-section micrographs revealed that the alumina powders were uniformly dispersed in A356 matrix.

Keywords: A356/Al_2O_3, Strain-induced, Sintering, Hardness, Sand casting

INTRODUCTION

Currently, aluminum metal matrix composites (AMMCs) have been widely studied and broadly accepted by industries as efficient alternative materials in many applications, especially as components in drum or disc brakes. Generally, the matrix metal exhibits good ductility and impact strength, and high thermal and electrical conductivity. Most reinforcing materials are ceramics with high elastic modulus, and contribute to good fatigue and wear resistance. As with any composite material, AMMCs rely upon the combined characteristics of each component to achieve properties that are otherwise difficult to attain in any single class of material. The combination of properties can only be fully realized when the matrix and reinforcing material have the correct bonding properties. For instance, the interface characteristics between the materials are critical to determining whether loads are properly distributed on a microscopic level in a way that the forces are forward of the reinforcing material (Hashim et al., 2001).

A356 aluminum, an aluminum-silicon-magnesium alloy, has good casting properties and high toughness, corrosion resistance, machinability and strength-to-weight ratio. It is one of many aluminium alloys commonly used in industrial components that require high strength, such as aircraft parts, pump housings, impellers, and structural castings. In automotive applications, disk brakes are normally made from cast iron and stainless steel, which have high wear and corrosion resistance and good heat conductivity. However, disk brakes can also be produced using aluminum alloys reinforced with Al_2O_3, which can exhibit similar properties, but also are lightweight by comparison (Varuzan et al., 2000; Zhang et al., 2007). Al/SiC and Al/Al_2O_3 composite products can be used to replace copper, steel, titanium, and cast iron components in several industries (Telang et al., 2010). AMMCs can reduce the weight of braking systems by 50-60 percent (Stephenson, 1996).

The properties of metal matrix composites that use particle reinforcement depend on several factors; for example, particle size, the amount and type of reinforcing phases, and the strength of the matrix-reinforced particle interface. Kok (2005) reinforced 2024 AMMCs with three different sizes and weight fractions of Al_2O_3 particles up to 30 wt% fabricated by a vortex method with subsequent application of pressure. The coarser particles were more uniformly dispersed, while the finer particles formed agglomerations of particles and contributed to porosity. The hardness and the tensile strength of the composites increased with decreasing size and increasing weight fraction of particles.

Al/Al_2O_3 composites have also been produced by conventional powder metallurgy, with pure aluminum powder with 10 wt% fine alumina sintered and compressed; the alumina showed better thermal stability at high temperatures (Rahimian et al., 2009). Composites containing Al_2O_3 were superior to those containing SiC in abrasive wear resistance using a dry sand/rubber wheel abrasion tester, because of the formation of a brittle bonding layer at the interfaces between the aluminum matrix and SiC. Wear resistance of a composite containing large 142 µm Al_2O_3 was better than that of composites containing smaller Al_2O_3 particles, and was comparable to AISI 1345 steel, heat treated to a hardness of 57 HRC (Bhansali and Mehrabian, 1982).

This study investigated the castability of A356/Al_2O_3 composite produced via a multi-step regime – milling, sintering, rapid melting, and sand casting, as well analyzed the mechanical properties and microstructures of the various weight fractions.

MATERIAL AND METHODS

Materials

This experiment used commercial A356 aluminum alloy ingots. Chemical compositions were analyzed using Spark Emission Spectrometer (Model CI-4 P/N 081646, Baird, USA). The A356 consisted of Al, Si-7.23, Mg-0.31, Cu-0.036, Fe-0.107, Zn-0.005, Ti-0.153, and Ni-0.005 (wt%). The A356 aluminum alloy ingot was machined into small chips sizing approximately 4x7x0.1 mm before casting. The alumina (Al2O3) angular particles were commercial grade alumina (Great Rich Mineral Limited, China) with a uniform size of 250 µm. The theoretical mechanical properties of both materials are listed in Table 1.

Table 1. Typical physical and mechanical properties of A356 and Al_2O_3 (Calister, 2007).

Materials	Density (g/cm^3)	Tensile strength (MPa)	Modulus of elasticity (GPa)
A356	2.70	228.0	72.4
Aluminium Oxide (Al_2O_3)	3.98	416.0	380

Composite compositions

The composites of A356 mixed with Al_2O_3 were produced at weight fractions of 5, 10, and 15%. The density of each composite was computed by the following equation (Donald and Pradeep, 2009) and expressed as g/cm^3:

$$\rho_c = \rho_m v_m + \rho_p v_p \tag{1}$$

where ρ_c is the composite's density, ρ_m is the matrix's density, v_m is the matrix's volume fraction, ρ_p is the reinforcing phase's density, and v_p is the reinforcing phase's volume fraction.

Volume fraction of composites was calculated by the followed equation and expressed as percentage.

$$v_c = \frac{1}{1+\frac{\rho_p}{\rho_m}\left[\frac{1}{w_p}-1\right]} \tag{2}$$

where, v_c is the composite's volume fraction and w_p is the reinforcing phase's weight fraction. Values of estimated density calculated from equation 1 and volume fraction calculated from equation 2 are listed in Table 2.

Table 2. Calculated volume fraction and density of composites.

Materials	Volume fraction (%)	Density (g/cm^3)
A356-5wt% Al_2O_3	3.46	2.75
A356-10wt% Al_2O_3	6.92	2.79
A356-15wt% Al_2O_3	10.38	2.82

The composite casting

A356 chips were dry mixed with alumina particles of 250 μm and compressed into a small cylinder by hydraulic pressure as shown in Figure 1(A). To remove moisture and improve wettability between the alumina particles and aluminum, the compressed composite was sintered at 600°C for approximately 20 min in an electric furnace, and then transferred into an induction furnace and melted at 1,350°C. After 5 min holding time in the furnace without stirring, the molten composite was poured into a green sand mold and sand casted into a solid rod with a diameter of 20 mm and length of 50 mm as shown in Figure 1(B). Subsequently, all casted specimens were subjected to solution treatment at 527°C for 12 h, quenched into water, and then naturally aged at room temperature for 10 h; then artificially aged at 177°C for 12 h and slowly cooled in the furnace (Figure 2).

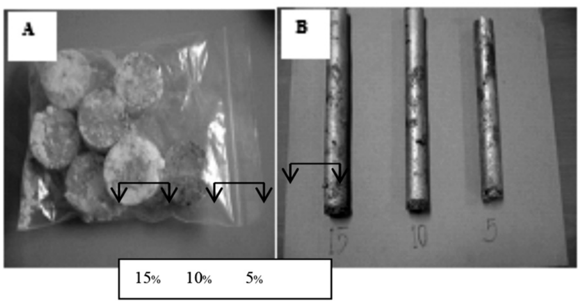

Figure 1. Photographs of the pressed composite mixture before sintering (A) and the casted sand composites with alumina of 5, 10, and 15 wt% (B). Arrows show positions for microscopy.

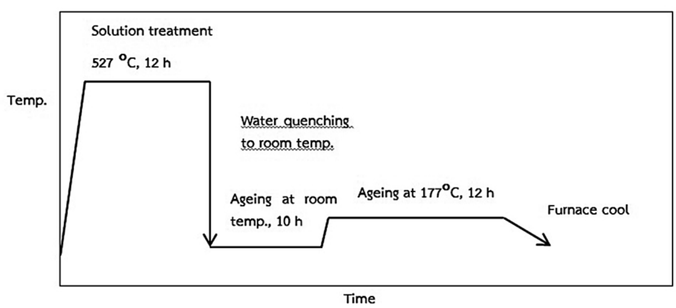

Figure 2. Heat treatment cycle.

Microstructural characterization

Microstructural characterization was carried out on the 'as-received', casted and heat-treated materials. All composite samples were machined at the bottom edge of the rods (arrows denoted in Figure 1). The cross-section microstructures were investigated using an Optical Microscope (BX60M, Olympus, Japan). Wear tracks were observed using a Scanning Electron Microscope, SEM (LEO 1450, Leo, UK). Percentage of the reinforced phase was determined using an area fraction method in multiphase function of the AxioVision microscope software (ZEISS, Germany). Results presented were the average values of five different cross-sections.

Hardness and wear tests

The cross-sections of machined specimens in all conditions were mechanically grinded and polished; hardness was measured using a Rockwell hardness tester (AR-1, Mitutoyo, Japan). The results – expressed in Scale B for 'as-received' A356 and in Scale C for composites – were the average of five measurements, presented together with the standard deviation . Wear was tested using a tribometer (Te79, Multi-Axis Tribometer, Phoenix Tribology, UK) following the pin-on-disc method according to ASTM G99 standard testing, with an applied load of 10 N, disk speed of 100 rpm, alumina ball (with hardness of approximately 1,500 HV) size of ¼ in, and pressing time of 1 h. Sliding distance was given at 112.85 m. The mass loss of each sample was measured five times and averaged. Wear rate was calculated by the following equation:

$$W = \frac{M}{\rho D} \tag{3}$$

where W is wear rate (mm^3/m), M is mass loss (g), ρ is density (g/mm^3), and D is sliding distance (m).

Both hardness values and wear rates were subjected to One-way ANOVA analysis using 95% confidence limit.

RESULTS

Microstructures of Al-Al_2O_3 reinforced composites

The microstructure of the 'as-received' A356 aluminum alloy is shown in Figure 3. The microstructure consists of α-Al dendritic and plate-like eutectic Si phases characteristic of casting alloy. Microstructures of the heat-treated composites are shown in Figure 4. All microstructures showed the uniform distribution of alumina particles in aluminum alloy phase. The average area percent of reinforced phase in Al-5wt% Al_2O_3, Al-10wt% Al_2O_3, and Al- 15wt% Al_2O_3 were approximately 11.08±0.37, 12.58±0.27, and 15.05±0.83 percent, respectively; the phase fraction increased with increasing alumina weight percent.

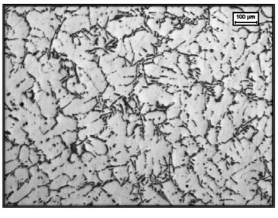

Figure 3. 'As-received' microstructure of the A356 ingot.

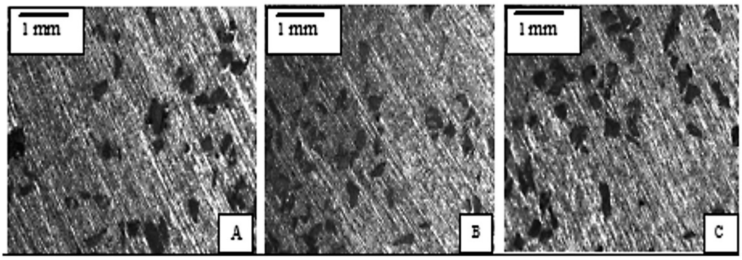

Figure 4. Optical micrographs after heat treatment show distribution of alumina particles in the A356 matrix with various alumina weight fractions, together with the average percentage of alumina phase. (A) A356-5wt% Al_2O_3 (alumina phase = 11.08±0.37%), (B) A356-10wt% Al_2O_3 (alumina phase = 12.58±0.27%), and (C) A356-15wt% Al_2O_3 (alumina phase = 15.05±0.83%).

Hardness testing

The average Rockwell hardness value of A356 aluminum alloy in the 'as-received' and heat-treated conditions are shown in Table 3. The average hardness of A356 in 'as-received' condition was 23.5 HRB, and increased to 46.0 HRB after heat treatment. Hardness values of composite samples are listed in Table 4; the hardness of the casted composite materials increased with increasing weight percent of alumina phase. The standard deviations of the average hardness values were small, implying that reinforced particles were uniformly distributed in the matrix. From ANOVA test, p-value in the as-casted and T6 conditions were equal to 0.003 and 0.018, respectively, indicating that increasing the percentage of alumina and T6 significantly affected hardness.

Table 3. Results of average hardness with standard deviation of A356 in 'as-received' and heat-treated conditions.

Specimen	'As-received'		Heat-treated	
	HRB	**SD**	**HRB**	**SD**
Ingot A356	23.5	1.62	46.0	3.76

Table 4. Results of average hardness with standard deviation of composites in casted and heat-treated conditions.

Specimen	Casted		Heat-treated	
	HRC	**SD**	**HRC**	**SD**
A356-5wt% Al_2O_3	41.3	1.72	46.3	2.14
A356-10wt% Al_2O_3	44.0	1.26	48.0	1.84
A356-15wt% Al_2O_3	46.0	1.41	51.1	2.77

The wear rate after heat treatment of composites

Results of the wear tests are shown in Table 5. The A356-5wt%, 10wt%, and 15wt% Al_2O_3 exhibited wear rates of 0.00387, 0.00375, and 0.00350 mm^3/m, respectively; the differences were not significant. All samples showed very small weight losses and wear rates, indicating all composites had excellent wear resistance. Figure 5A to 5F shows SEM images in SEI mode of no-wear and worn surfaces of the various composites. The micrographs show wear marks clearly as white scratches. The particles were distributed on the surfaces without fracture. The 250 μm alumina particles were uniformly distributed and well bonded with the aluminum matrix.

Table 5. Results of the wear tests of the composites after heat treatment.

Specimen	Average mass loss (g/h)	Volume loss (mm^3)	Wear rate (m^3/m)
A356-5wt% Al_2O_3	0.00120	0.43700	0.00387
A356-10wt% Al_2O_3	0.00118	0.42300	0.00375
A356-15wt% Al_2O_3	0.00112	0.39500	0.00350

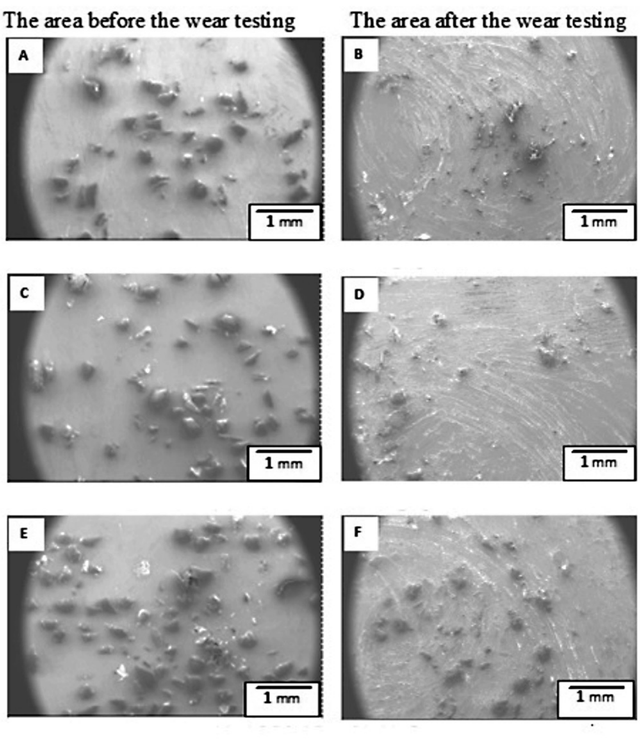

Figure 5. SEM images showing surfaces of Al-Al_2O_3 composites before and after wear tests. (A) A356-5wt% Al_2O_3 (before the wear testing), (B) A356-5wt% Al_2O_3 (after the wear testing), (C) A356-10wt% Al_2O_3 (before the wear testing), (D) A356-10wt% Al_2O_3 (after the wear testing), (E) A356-15wt% Al_2O_3 (before the wear testing), (F) A356-15wt% Al_2O_3 (after the wear testing).

DISCUSSION

This study fabricated Al-Al_2O_3 composites using a multi-process regime – sintering, rapid melting, and sand casting. During milling, the chips were mechanically sheared, generating strain within the chips. During sintering at 600°C, the aluminum chips partially welded together. This mechanism allowed the A356 aluminum matrix to better hold the alumina particles together before melting. Another benefit of sintering was the improvement in wettability. To prevent agglomeration and sedimentation of the reinforced phase from the molten matrix, the mix was rapidly melted and poured. The alumina was uniformly distributed in the cross-section area of the composites, as illustrated in Figures 4 and 5. The average reinforced phase fraction analyzed by image analysis of A356-5wt% Al_2O_3 was higher than the weight percent of alumina particles added, while the hardness values at 10 and 15% were close to the weight percent of alumina particles added, with small uncertainty. This also indicated that the particles were uniformly distributed. As we used simple cylinders only as samples, the effect of shape and size of mold on flowability of the molten composite should be studied further. In addition, chips and sintering technique provide an opportunity to shape composites in solid or semi-solid states.

When casted, the average hardness values of the composites increased with increasing fractions of alumina particles, which indicated that the amount of alumina particles affected hardness. The angular alumina particles obstructed the slip of the slip planes of the matrix, thus increasing the fraction of alumina increased resistance to plastic deformation of the matrix. Alumina particles also promoted dislocation density, due to the thermal expansion coefficient mismatch between the matrix and the reinforced phase. As a result, lattice strains and dislocations developed on cooling.

Hardness of the initial A356 after heat treatment significantly increased, due to formation of an Mg_2Si precipitated phase, while the hardness values of the composites slightly increased. We attributed the lower aging response of the composites to the reaction between Al_2O_3 and Mg during melting and casting that resulted in Mg depletion in the matrix. As suggested by Daoud and Reif (2002), Mg in the alloy reacts with imbedded alumina phase via reaction; $Mg(l) + \frac{4}{3}Al_2O_3(s) \rightarrow MgAl_2O_4(s) + \frac{2}{3}Al(l)$. $MgAl_2O_4$ spinel was found at the interface, resulting in a decreasing amount of magnesium available to form an age hardening phase, such as Mg_2Si in the matrix. Therefore, hardness of composites with increasing alumina fraction after aging increased slightly; in other words, the smaller amount of alumina fraction more effectively enhanced hardness and resistance to wear. Daoud and Reif (2002) also suggested that to compensate for the $MgAl_2O_4$ spinel reaction, more Mg should be added. The effect of $MgAl_2O_4$ spinel on matrix/reinforced interface bonding should be studied further. The wear rate of A356-5wt% Al_2O_3 reduced significantly. Wear resistance of the composites increased with increasing weight fraction of the reinforcing phase. Good wettability of alumina particles led to strong bonds at the interface. Wear rate at higher loads should also be studied further.

CONCLUSION

In this study, A356 MMCs containing 5, 10, and 15% weight fractions of Al_2O_3 particles (250μm) as the reinforcement material were produced through sintering, rapid melting, and sand casting. The sintering process improved wettability of alumina and partially bonded the alumina particles before melting. Rapid melting of MMCs without mechanical stirring of the melt prevented aggregation and sedimentation of the reinforcement phase. After casting, alumina particles were uniformly distributed in cross-sections of the composites. The hardness of the casted composites significantly increased as the alumina reinforcement fraction increased. After heat treatment, the hardness of all composite samples increased slightly. The composite materials exhibited a low wear rate, enhancing wear resistance. The wear rate decreased with the increasing fraction of the reinforcement phase.

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