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Physio-mechanical Properties of Aluminium Metal Matrix Composites Reinforced with Al_2O_3 and SiC

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***Abstract*—**Particulate reinforced metal matrix composites (MMCs) are potential materials for various applications due to their advantageous of physical and mechanical properties. This paper presents a study on the performance of stir cast Al_2O_3 SiC reinforced metal matrix composite materials. The results indicate that the composite materials exhibit improved physical and mechanical properties, such as, low coefficient of thermal expansion, high ultimate tensile strength, high impact strength, and hardness. It has been found that with the increase of weight percentage of reinforcement particles in the aluminium metal matrix, the new material exhibits lower wear rate against abrasive wearing. Being extremely lighter than the conventional gray cast iron material, the Al-Al_2O_3 and Al-SiC composites could be potential green materials for applications in the automobile industry, for instance, in making car disc brake rotors.

***Keywords*—**Metal Matrix Composite, Strength to Weight Ratio, Wear Rate

I. Introduction

PARTICULATE reinforced light metals have shown great promise because of their outstanding mechanical and physical properties. A major goal in manufacturing and utilizing metal matrix composites (MMCs) is to achieve the highest possible strength to weight and weight to stiffness ratios in a low cost light material. Particulate reinforced aluminium matrix composites are widely used in its application in the automotive industries because of their low cost and isotropy in property values [1, 2]. Automotive vehicle braking system is subjected to high wearing. Therefore, brake failure could be minimized by using materials with low wearing rate and high hardness [1-3]. Car manufacturers focus their attention on the design and manufacturing of fuel efficient cars. By having low-density and light-weight brake rotors, fuel consumption of vehicles would be reduced. It has been found that the mechanical properties of aluminium matrix composites are affected by the volume fraction of the reinforcement particles [4].

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It is hypothesized that aluminium metal matrix composites with Al_2O_3 and SiC particle reinforcements could be reliable materials to replace the conventional gray cast iron in the automobile industry. Factors affecting the strengthening properties of the composites would be the amount and dispersion or distribution of the reinforcement particles in the metal matrix.

In this paper, aluminium metal matrix composites with silicon carbide (SiC) and Aluminium oxide (Al_2O_3) as reinforcement particles are studied to evaluate their physical and mechanical properties. The microstructure of composite material are also discussed in this paper.

II. Experimental Procedure

The composites used in the experiments are produced by the stir casting method [5]. For Al-Al_2O_3 composite material, Al356 alloy powders are mixed with Aluminium oxide (Al_2O_3) particles of uniform size (400 μm) in the weight fraction of 5%, 10%, and 15%. For Al-SiC composite material, Al356 alloy powders are mixed with SiC in the weight fraction of 5%, 10%, and 15%. Moisture in the particles is evaporated by adding the particle reinforcement into the matrix early in the process, before it disperses into the molten metal matrix. As a result, the wettability between the reinforcement particles and the metal matrix improves [5]. All the samples are melted in the furnace for 2 hours at 700°C. The molten metal is stirred using a stirrer with a simple paddle [6] as an agitator. The molten composite is then left to solidify on the ceramic plate inside the furnace. The solidified cast material is shown in Fig. 1(a). The composite block is then machined and cut into desired specimen test samples as seen in Fig. 1(b).

Fig. 1(a) Solidified cast Al-Al_2O_3 composite material (b) Specimen of Al-Al_2O_3 composite materials for testing

The mechanical properties of matrix and reinforcement particles are shown in Table I.

TABLE I
Mechanical properties of Al_2O_3, SiC, and Al356 [7]

Properties	Aluminium Oxide	Silicon Carbide	Aluminium Alloy 356

Density (g/cm^3)	3.98	3.30	2.70
Tensile Strength (MPa)	416.0	588.0	228.0
Coefficient of Thermal Expansion ($10^{-6}/°C^{-1}$)	7.4	4.6	21.5
Modulus of Elasticity (GPa)	380	345	72.4

III. Analytical Results

The analytical properties for different aluminium matrix composite with Al_2O_3 and SiC as reinforcement particles can be estimated through equations (1) to (3) [8].

$$\rho_c = \rho_m v_m + \rho_p v_p \quad (1)$$

Where ρ_c is the composite's density, ρ_m is the matrix's density, ρ_p is the reinforcement particle's density, v_m is the volume fraction of the matrix and *Vp* is the volume fraction of the particle.

$$\sigma_c = \sigma_m v_m + \sigma_p v_p \quad (2)$$

Where σ_c is the composite's tensile strength, σ_m s is the matrix's tensile strength, and σ_p is the reinforcement particle's tensile strength.

$$\alpha_c = (\alpha_m E_m v_m + \alpha_p E_p v_p)/(E_m v_m + E_p v_p) \quad (3)$$

Where α_c is the composite's coefficient of thermal expansion, α_m is the matrix's coefficient of thermal expansion, α_p is the reinforcement particle's coefficient of thermal expansion, and the *E's* are the respective Moduli of Elasticity.

The material selection criterion (MSC) or also known as the strength to density ratio is a vital indicator of a probable candidate replacement material [9]. The strength to density is given by,

$$\text{Strength to density ratio} = \frac{E^{\frac{1}{3}}}{\rho} \quad (4)$$

where E= Modulus of Elasticity (GPa) and ρ=Density ((g/cm^3))

The theoretical results obtained from the equations (1-4) are recorded in Table II.

TABLE II
ESTIMATED PROPERTIES OF DIFFERENT COMPOSITIONS

Sample	Density ρ (g/cm^3)	Tensile strength σ (MPa)	Coefficient of Thermal Expansion μ ($10^{-6}/°C$)	Strength to density ratio
100% Al	2.70	228.0	21.5	1.54
Al with 5% Al_2O_3	2.76	237.4	18.4	1.615
Al with 10% Al_2O_3	2.83	246.8	16.3	1.663
Al with 15% Al_2O_3	2.89	256.2	14.7	1.705
Al with 5% SiC	2.73	246.0	18.1	1.622
Al with 10% SiC	2.76	264.0	15.6	1.685
Al with 15% SiC	2.79	282.0	13.8	1.74

Table II indicates that the density of the material sample increases as the amount of particulate reinforcement increases [10]. This is expected as the density of the particulate is higher compared to that of the matrix material. It is observed that the tensile strength and strength-to-density ratio increase significantly with the increase of reinforcement particles.

It is also shown that the coefficient of thermal expansion (CTE) decreases with the increase of reinforcement particles. CTE measures the fractional change in volume per degree change in temperature. For automobile application, where variation of temperatures is present, a smaller CTE value of the material is preferred [7].

It should be noted that the properties obtained analytically are to be considered as ideal cases with the assumption that the distribution of the particles in the mixture is homogeneous and perfect bonding exists between the matrix metal and the reinforcement particles during the stir casting process. But in reality, there may likely to be flaws in terms of homogeneity of the distributed particles. Due to poor stirring, clustering and segregation of the reinforcement particles may occur, resulting in poor bonding between the particles and the metal matrix during the manufacturing process.

IV. Experimental Results and Discussion

A. Density

The results obtained are comparable to the theoretical results. From Table III, it is observed that aluminium metal matrix composites with aluminium oxide (Al_2O_3) as particle reinforcements have higher density values compared to Aluminium metal matrix composites with Silicon Carbide (SiC) as particle reinforcements, since the density value for aluminium oxide (Al_2O_3) is relatively higher than that of silicon carbide (SiC). However, the proposed composite materials are significantly lighter than gray cast iron of density $7.2g/cm^3$.

TABLE III
DENSITY OF DIFFERENT COMPOSITIONS

Composition with Al_2O_3 wt%	Density, ρ (g/cm^3)
100% Al 356 alloy	2.70
Al with 5%Al_2O_3	2.73
Al with 10%Al_2O_3	2.86
Al with 15%Al_2O_3	3.02
Composition with SiC wt%	**Density, ρ (g/cm^3)**
100% Al 356 alloy	2.70
Al with 5%SiC	2.75
Al with 10%SiC	2.78
Al with 15%SiC	2.81

B. Hardness and Tensile Strength

The Rockwell hardness test is conducted using a steel sphere of 1/16" diameter as an indentor. The conversion from Rockwell hardness to Brinell hardness number is obtained by using the standard conversion scale [7].

Tensile strength obtained from Brinell hardness values using the equation 5 are shown in Table IV.

Tensile strength (σ) =3.45×Brinell Hardness (HB) (5)

TABLE IV
HARDNESS AND TENSILE STRENGTH OF METAL MATRIX COMPOSITES OF DIFFERENT COMPOSITIONS

Composition with Al_2O_3 wt%	Rockwell Hardness (HR)	Brinell Hardness (HB)	Tensile Strength (MPa)
100% Al	25	70	241.5
Al with 5%Al_2O_3	31	76	262.2
Al with 10%Al_2O_3	40	80	276.0
Al with 15%Al_2O_3	42	82	282.9
Composition with SiC wt%	(HR)	(HB)	(MPa)
Al with 5%SiC	30.0	75.0	258.8
Al with 10%SiC	45.0	85.0	293.3
Al with 15%SiC	50.0	90.0	310.5

Table IV shows that Al-SiC composites exhibit relatively higher hardness and tensile strength compared to Al-Al_2O_3 composite materials for 10% and 15% particle reinforcements. A comparison of theoretical and experimental tensile strength for Al- Al_2O_3 composite material is presented in Fig. 2. The highest percentage difference of tensile strength between theoretical and experimental values is observed to be 11.83% for MMC with 10%wt of Al_2O_3. The lowest percentage difference is 5.92% for 100% Aluminium without any reinforcement particles. Al. In fact, in the composites, the reinforcement particles act as a strengthening agent that helps to fill in pores in the metal matrix, thus creating a stronger bond between the matrix's particles.

With the stronger bond between particles, the mechanical properties of the material will also improve [10].

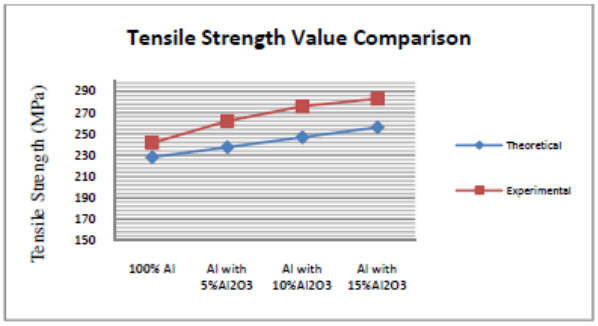

Fig. 2 Tensile strength comparison for MMC with Al_2O_3 reinforcements

C. Wear Rate

Wear behaviour for the particle reinforced aluminium matrix composites are obtained by using the wear test. The test is conducted by applying a constant load of 10N onto the specimen while the specimen is in contact with a 600 grit SiC adhesive paper at 300 rpm and 400 rpm grinding speeds for a fixed time period of 5 minutes. The specimen mass is obtained before and after the wear test to measure the mass loss (M) to find the wear rate using the equation below:

$$W = \frac{M}{\rho D} \quad (6)$$

where

W = Wear rate (mm^3/m)
M = Mass loss (g)
ρ = Density (g/mm^3)
D = Sliding distance (m)

TABLE V
WEAR RATE OF AL-AL2O3 COMPOSITES AT 300RPM GRINDING SPEED

Sample Composition	Mass Loss (g)	Density (g/mm^3)	Wear Rate (mm^3/m)
100% Al	0.50	0.00270	0.196
Al with 5%Al_2O_3	0.42	0.00273	0.163
Al with 10%Al_2O_3	0.38	0.00286	0.141
Al with 15%Al_2O_3	0.30	0.00302	0.105

TABLE VI
WEAR RATE OF Al-SiC COMPOSITES AT 300RPM GRINDING SPEED

Sample Composition	Mass Loss (g)	Density (g/mm^3)	Wear Rate (mm^3/m)
100% Al	0.50	0.00270	0.196
Al with 5%SiC	0.33	0.00275	0.127
Al with 10%SiC	0.28	0.00278	0.107
Al with 15%SiC	0.25	0.00281	0.094

TABLE VII
WEAR RATE OF Al-Al_2O_3 COMPOSITES AT 400 RPM GRINDING SPEED

Sample Composition	Mass Loss (g)	Density (g/mm^3)	Wear Rate (mm^3/m)
100% Al	0.65	0.00270	0.255
Al with 5%Al_2O_3	0.63	0.00273	0.245
Al with 10%Al_2O_3	0.58	0.00286	0.215
Al with 15%Al_2O_3	0.45	0.00302	0.158

TABLE VIII
WEAR RATE OF Al-SiC COMPOSITES AT 400RPM GRINDING SPEED

Sample Composition	Mass Loss (g)	Density (g/mm^3)	Wear Rate (mm^3/m)
100% Al	0.65	0.00270	0.255
Al with 5%SiC	0.50	0.00273	0.194
Al with 10%SiC	0.42	0.00286	0.156
Al with 15%SiC	0.36	0.00302	0.126

From Tables V to VIII, it is observed that (a) the wear rate increases with the increase of grinding speed (rpm), (b) aluminium metal matrix composites with SiC as reinforcement particles have lower wear rates compared to aluminium metal matrix composites with Al_2O_3 reinforcement particles, and (c) the wear rate decreases significantly with the increase of particle reinforcements for both type of composite materials. For instance, the wear rate for Al with 15% SiC composite is

only 0.126 mm^3/m which is about 50% of the wear rate of 1005 Al (0.255 mm^3/m).

D.Microstructure of Al-Al_2O_3 Composites

Microscopy of different composites materials such as Al+5wt%Al_2O_3, Al+10wt% Al_2O_3, Al+15%Al_2O_3 and Al 356 alloy are shown in Fig. 3 (a-d). One of the most important considerations in the fabrication of metal matrix composites (MMCs) materials is the uniform dispersion or distribution of the reinforcement particles as highlighted earlier. In Figure 3a, the microstructure of aluminium Al356 alloy is shown, with no reinforcement particles. In Fig. 3b, 3c, and 3d, the reinforcing particles of Al_2O_3 are clearly visible as white specks. In Fig. 3d, uniform distribution of Al_2O_3 particles is achieved. On the other hand, distribution of reinforcement particles is not uniformly achieved in Fig. 6b and 6c. Some minor clustering and segregation of particles is seen in Fig. 6d. Non uniform distribution of the particles can be a result of poor stirring of the particles into the metal matrix during the fabrication process. Segregation of particles may also occur during the solidification of the composite, when the Al dendrites solidify first, thus rejecting the particles by the solid-liquid interface, causing segregation of inter-dendritic region.

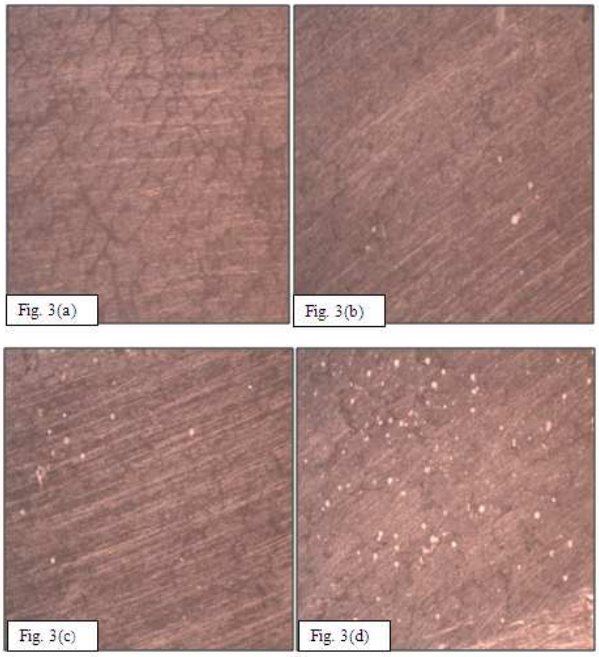

Fig. 3 Optical micrograph of alloys and composites (x35)
(a) Aluminium at pure state (b) 5wt% Al_2O_3 reinforcement (c) 10wt% Al_2O_3 reinforcements (d) 15wt% Al_2O_3 reinforcement

V. Conclusion

The following conclusions can be drawn from the present study:

1. The proposed composite materials exhibit coefficients of thermal expansion as low as 4.6 **x**10^{-6}/°C.

2. The composite materials achieve significant improvement in hardness and tensile strength compared to Al 356 alloy. For instance, the tensile strength of Al with 15% SiC is 23.68% more than that of 100% pure

3. The composite materials show significantly higher strength to weight ratios compared to 100% Al. For instance, Al with 15% SiC exhibits strength to weight ratio of 1.74. The corresponding values of strength to weight ratios for 100% Al and cast iron are 1.54 and 0.765 respectively. Therefore, the proposed composite materials can be applied as potential light-weight materials in automobile components.

4. It is found experimentally that the wear rate decreases significantly with the addition of reinforcement particles. Al-SiC composites exhibit lower wear rate compared to Al-Al_2O_3 composites.

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