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FABRICATION OF LOW COST OF ALUMINIUM MATRIX COMPOSITE REINFORCED WITH SILICA SAND

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Abstract: *The fabrication and testing of aluminium-silica particulate composites (Al-SiO_2) have been prepared by using powder metallurgy method. Two grades of silica particulates were used, i.e. silica sand and commercial silica. Silica content in the composite was 0, 10, 20, 30 and 40 vol. %. Mixing of Al-SiO_2 was performed using planetary mill for 2 hours with ball to powder weight ratio of 10:1. Powder compaction was conducted at 200 MPa pressure and sintering was performed under flowing argon gas for 5 hours at 600^oC. Results showed that Vickers hardness and modulus of rupture of Al-SiO_2 composite increased with the increasing of silica content phase up to 30 vol. % and finally drop when 40 vol. % of silica was incorporated. Aluminium matrix composites reinforced with silica sand showed that the mechanical properties were slightly better than composites reinforced with commercial silica, which is beneficial in reducing the material cost.*

Keywords: alumunium/silica composites, silica sand particulates, powder metallurgy

1.   INTRODUCTION

Aluminium is the most popular matrix for the metal matrix composites. Aluminium is quite attractive due to its low density, their capability to be strengthened by precipitation, good corrosion resistance, high thermal and high electrical conductivity and damping capacity. The addition of hard and stiff ceramic phase has been established to improve the modulus behaviour and strength properties in the metallic matrices.[1,2] For instances, reinforcing aluminium metal with silica particulate yields a material that displays combination of physical and mechanical properties of both the metal matrix and the silica.[3] These superior properties offered by particulate-reinforced Al-based MMCs make these materials attractive for applications in the automobile, aerospace, defense and leisure industries.[4,5]

However, in order to qualify for the applications where strength requirement is essential, the effect of reinforcing phases and other microstructural changes inflicted on the metallic matrix as a result of the presence of the

reinforcing phases requires careful monitoring. In related studies, investigators reported the effect of volume percentage of ceramic phase, size and type of particulate reinforcement on the properties of aluminium composite.[6,7]

The demand for structural materials to be cost effective and also to provide high performance has resulted in continuous attempts to develop composites as serious competitors to the traditional engineering alloys. Accordingly, the objective of the present study was to investigate the mechanical properties of aluminium matrix composites reinforced with low-cost silica sand, which is attained from mines. Particular emphasis was placed to study the effect of presence of silica reinforcing particulates on the microstructural variation in the metallic material and to correlate the particulate's associated microstructural variation in the metallic material with the hardness and modulus of fracture of the metallic matrix.

2.   EXPERIMENTAL WORK

The matrix material used in the present study was aluminium (99.8%) while two grades of silica powder were used as reinforcing phase, i.e. commercial grade silica powder with an average size of 45 μm and silica powder originated from silica sand. The latter was grounded by using planetary mill for particle refinement and followed by sieving process with 45 μm sieve. The particle size distribution of silica powder was carried out by Malvern particle analyser. Two types of Al-SiO$_2$ composites with different grade of silica, i.e. commercial silica and silica sand, were prepared using powder metallurgy technique. Mixture of Al-SiO$_2$ powder with composition of 0%, 10%, 20%, 30% and 40% (based on the volume percentage of SiO$_2$) were mixed in a planetary mill for 2 hours. Then, the powder was pressed at 200 MPa using a Universal Testing Machine (UTM). Sintering was carried out in a tube furnace at a constant temperature of 600°C for 5 hours under flowing argon gas. The final sintered compact had a bar shape with an average dimension of 100 × 10 mm, and thickness ranging between 3 to 4 mm.

The theoretical density of unreinforced and each set of composites were calculated according to the rule of mixtures. The green density of the compacted sample was determined by dividing the mass of sample by its volume and the sintered density of sintered samples was measured using pycnometer density machine. Both green and sintered densities results were then compared with theoretical density of composites as in equation (1):

$$\rho_{green} \text{ (or } \rho_{sintered}) \text{ (\%TD)} = \frac{\rho_{green} \text{ (or } \rho_{sintered}) \text{ (g/cm}^3)}{\text{Theoretical Density of Composite (g/cm}^3)} \times 100\% \quad (1)$$

where ρ_{green} and $\rho_{sintered}$ are green and sintered densities, respectively meanwhile %TD is percentage of theoretical density. The sintered composites were then subjected to mechanical tests. Hardness was measured using a Vickers hardness tester while modulus of rupture was obtained by the 3-point bending test. The fracture surfaces after the bending test were characterized by using scanning electron microscope. Microstructural observation was performed under optical and scanning electron microscopes in order to investigate the presence of porosity and distribution of silica particulates.

3.   RESULTS AND DISCUSSION

According to the XRF analysis in Table 1, commercial silica has SiO_2 content (99%), which is higher than silica sand (97%). Figure 1 shows the particle size distribution of silica sand and commercial grade silica. The median particle size for silica sand and commercial grade silica is 13 and 45 micron, respectively. The commercial grade silica was widely distributed whilst the silica sand has narrow particle size distribution. From Figure 2, it can be seen that commercial silica consists of many small particles and also large particles, which indicate that the size distribution of the commercial silica [Fig. 2(b)] is broader than silica sand [Fig. 2(a)]. The physical and mechanical properties of the prepared composites were measured as a function of the second phase content. The green and sintered densities were measured experimentally and compared to the theoretically calculated density. Tables 2 and 3 show that as the commercial silica and silica sand content was gradually increased, the green and sintered densities of the corresponding composite decreased. A slight decrease was observed in the theoretical density because the density of silica (2.65 g/cm³) is slightly lower than the density of aluminium (2.7 g/cm³). Obviously, the green density of the composite (in terms of %TD) decreased with increasing reinforcement content. Such result is expected since silica is a ceramic material and thus is harder than aluminium. Therefore, silica deforms less readily under the applied compaction load compared to aluminium. In addition, the morphological features of silica particles are significantly different from those of alumunium and as a result, the inter-particle friction effects are different. Eventually, composite with lower bulk density was produced after sintering process.
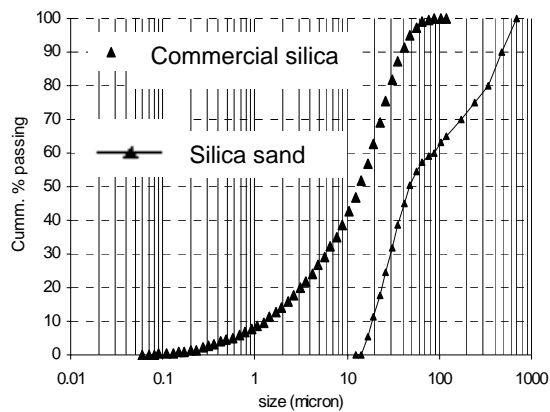
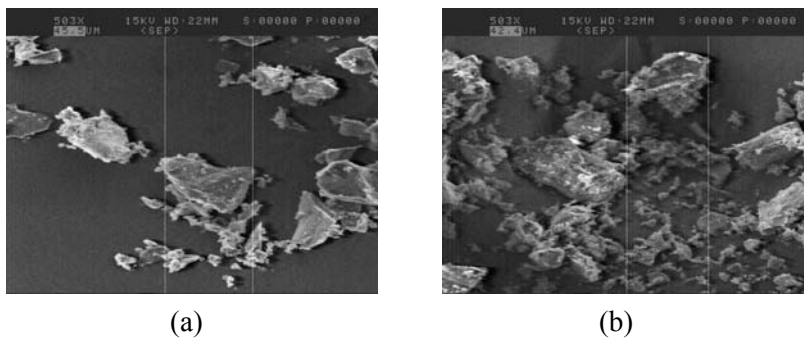Figure 1: Particle size distribution of silica sand and commercial silica

(a)   (b)

Figure 2: SEM micrograph of (a) silica sand and (b) commercial silica (503×)

Table 1: XRF analysis of silica sand and commercial sand

	Commercial sand (wt %)	Silica sand (wt %)
Al_2O_3	0.25	1.9
SiO_2	99.0	97.0
K_2O	-	0.21
TiO_2	-	0.1
Fe_2O_3	-	0.19
ZrO_2	-	0.15

Table 2: The variation in density with increasing commercial silica content

Commercial silica (vol. %)	Theoretical density (g/cm^3)	Green density		Sintered density	
		(g/cm^3)	(%TD)	(g/cm^3)	(%TD)
0	2.7000	2.3295	86.3	2.5735	95.3
10	2.6968	2.1280	78.9	2.5154	93.3
20	2.6898	2.0970	77.9	2.4586	91.4
30	2.6848	2.0500	76.4	2.4490	91.2
40	2.6797	1.9823	74.0	2.4350	90.8

Table 3: The variation in density with increasing silica sand content

Silica sand (vol. %)	Theoretical density (g/cm^3)	Green density		Sintered density	
		(g/cm^3)	(%TD)	(g/cm^3)	(%TD)
0	2.700	2.3295	86.3	2.5735	95.3
10	2.6968	2.2020	81.6	2.5508	94.6
20	2.6898	2.1600	80.3	2.4719	91.9
30	2.6848	2.0810	77.5	2.4665	91.8
40	2.6797	2.0102	75.0	2.4407	91.1

Referring to Tables 2 and 3, it was found that sintered density of aluminium matrix composite reinforced with silica sand is higher than those reinforced with commercial silica. SEM micrograph in Figure 3 reveals the difference in microstructures developed in the sintered Al-commercial silica and Al-silica sand composites. Investigation conducted on copper-silicon carbide particulate composites by Moustafa et al.[8] proposed that poor adhesion between SiC reinforcement particles and Cu-matrix is due to the presence of gaps and porosity between SiC and Cu-matrix. Figure 3(a) shows the presence of coarse gaps and porosity in Al-40 vol. % commercial silica while very small size of porosity is observed in Al-silica sand composites [Fig. 3(b)], which suggest a better adhesion between Al matrix-silica particulate in Al-silica sand composite. The presence of porosity in the case of Al-40 vol. % commercial silica composites could be attributed to the finer size of some of the commercial silica particles, which has been observed in Figure 2(b). During sintering, in the case of Al-commercial silica, fine silica particles decrease the Al-Al contact but increase the SiO_2-SiO_2 contacts, which resulted in a weak interfacial bonding between SiO_2 particle-Al matrix and therefore leaving much more residual pores. This finding provides explanation for the higher sintered density accomplished in aluminium matrix composite reinforced with silica sand.
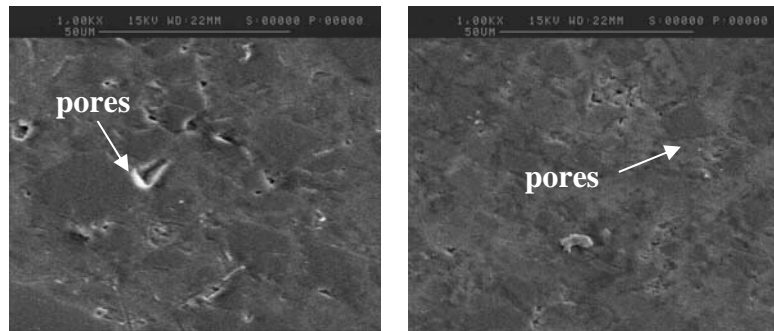
Figure 3: SEM micrograph of (a) Al-40 vol. % commercial silica and (b) Al-40 vol. % silica sand ($10^5\times$)

Result of composite hardness shows that when the amount of silica phase was increased until 30 vol. %, the hardness increased as well for both type of composites (Fig. 4). Such behaviour is partly due to the contribution of the constrained metallic matrix as well as that of replacing some of the soft aluminium by the harder SiO_2 particles. However, when the amount of the second phase was increased up to 40 vol. %, the hardness decreased. It is well accepted that silica inhibits solid phase sintering of aluminium because of its high melting temperature.[8] Optical micrograph in Figure 5 shows that addition of 40 vol. % silica has led to very close interparticle distance between silica particles. Since too much silica particles present in the aluminium matrix, the aluminium powders are not well bonded when the reinforcement content reaches 40 vol. % and therefore the hardness of aluminium composites decreases. Also, it is noted that the hardness of aluminium matrix composites reinforced with silica sand is higher than those reinforced with commercial silica. Again, this trend is closely related to the composites density. Since the latter has lower sintered density, its hardness decreased as well.

In both types of Al composites, it was found that the modulus fracture increased as the amount of the second phase was increased until 30 vol. % as shown in Figure 4. However, when the silica content reached 40 vol. %, the modulus fracture decreased. It was suspected that when reinforcement content reached 40 vol. %, the number of contacts between silica particles would increase, and the ductile aluminium matrix no longer isolates silica particles. Cracks would propagate easily between silica particles because the ductile matrix does not arrest cracks and thus, the composites became brittle. This explanation is well supported by Figure 5(d) where the agglomeration of silica prevented the coating of aluminium matrix on silica particles. Other investigator also observed that in Al-Al_2O_3 composite system, crack initiated at the metal-ceramic interface and then propagated inside the brittle ceramic.[9] The coefficient thermal expansion (CTE) of aluminium and silica are 2.3×10^{-6} and $12.3 \times 10^{-6}\,K^{-1}$, respectively.

Therefore, thermal mismatch is resulted due to the difference in CTE of aluminium and silica. The thermal mismatch may result in elastic stress which may cause the SiO_2 particles in compression and the Al matrix in tension states.[10] Consequently, this residual stress affects the material properties around crack tips. This residual stress would probably contribute to the brittle nature of the Al-40 vol. % silica. Therefore, the drop in modulus of fracture at 40 vol. % silica content in the present study could be explained by the less difficulty of crack propagation due to the overloading of silica particles in the aluminium matrix.
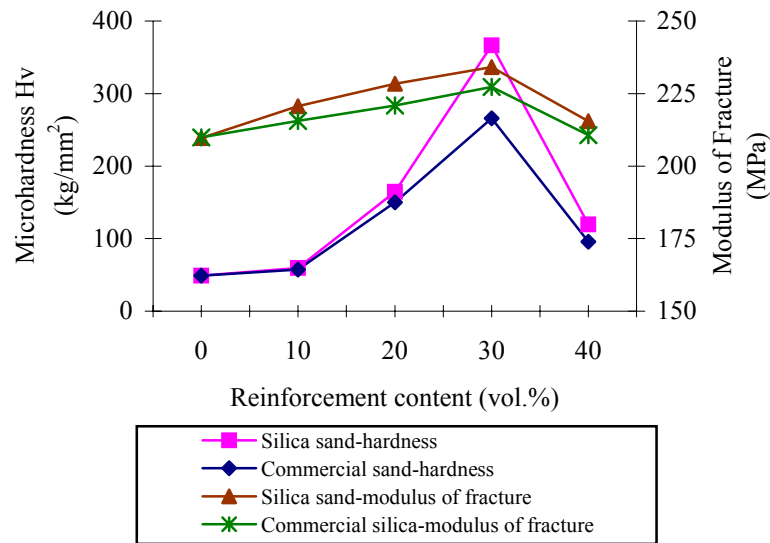

Figure 4: The relationship between Vicker's hardness, modulus of fracture and the reinforcement content

Figure 6 illustrates the fracture surface of the unreinforced Al and Al-30 vol. % silica sand composites under SEM. The Al-30 vol. % silica sand was chosen for fracture analysis due to its excellent modulus of fracture result. The fracture surface of the unreinforced Al shows transgranular fracture behaviour [Fig. 6(a)]. Cracks can be observed propagates along the grain boundaries. While in Al-30 vol %. silica sand composite samples, surface topography shows that silica particles clearly can be seen embedded in the aluminium matrix and large voids are formed in the aluminium matrix as shown in Figures 6(b) and 6(c), which indicates the interface failure mechanism. No evidence of particle cracking is observed. It can be concluded from this observation that the crack propagation occurs along the interface of aluminium matrix and silica reinforcement.
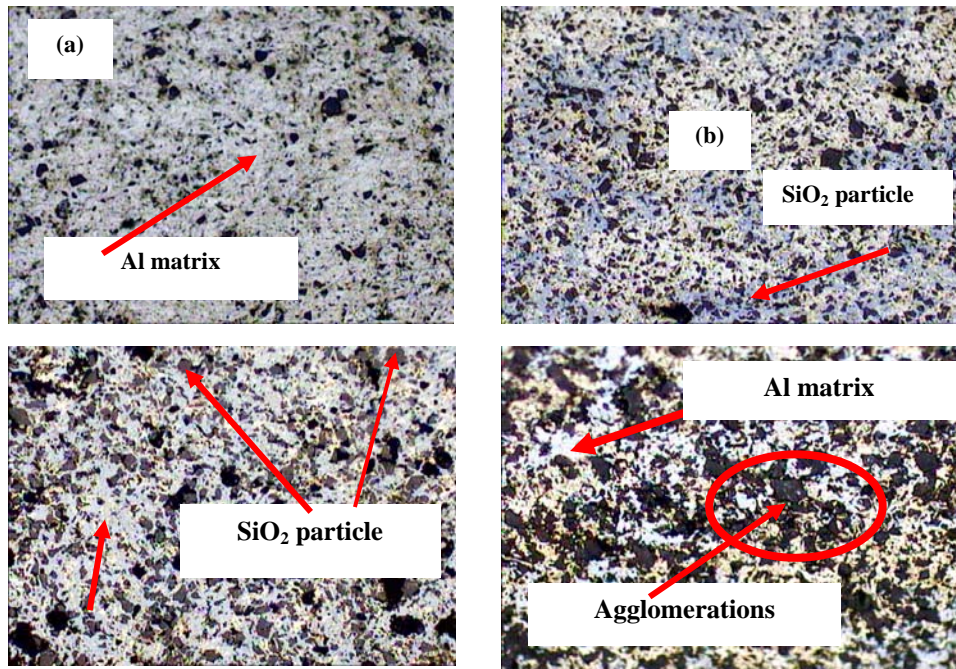
Figure 5: Optical microstructures of sintered Al-commercial silica (a) 10 vol. %, (b) 20 vol. %, (c) 30 vol. %, and (d) 40 vol. % (100×)
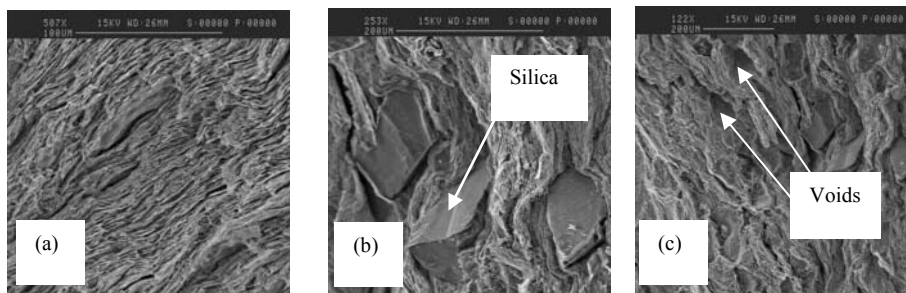

Figure 6: Fractography of (a) Al and (b and c) Al-30 vol. % silica sand

4. CONCLUSION

The density of Al-SiO$_2$ composites decreased slightly with the increased of silica content for both commercial grade and silica sand. In both types of Al-SiO$_2$ composites, both hardness and modulus of fracture were found to increase as the content of silica particulates was increased up to 30 vol. %. Further

addition of SiO_2 particulates only served to reduce these two mechanical properties. Therefore, there is no advantage in further increasing the silica content in aluminium composite. Aluminium matrix composite reinforced with silica sand showed a slightly higher hardness and modulus of fracture compared to the aluminium matrix composite reinforced with commercial silica. Thus, less expensive composite material is expected.

5.   ACKNOWLEDGEMENT

6.   REFERENCES

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