Wear properties of 10 vol.% silicon carbide particulate-reinforced aluminum composite fabricated by powder injection molding

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Abstract. Wear properties of aluminum matrix composites reinforced with silicon carbide particulate of 10 vol.% addition was investigated in as-sintered and heat-treated conditions under varying loads at -5, -25, -45 and -65N using a ball on flat type of wear test. The composite was fabricated by powder injection molding and sintering at 650 °C for 3 hours. Solution treatment was carried out at 550 °C for 2 hours followed by age-hardening at 160 °C for 6 hours. SEM and XRD results indicated Al and SiCₚ are present as matrix and reinforcement, while AlN, Al₂Cu and Mg₂Si were also detected. Further precipitation of Al₂Cu and Mg₂Si in heat-treated samples promoted maximum macro and micro Vickers hardness values, which were achieved at 161 and 157 Hv respectively. Wear weight loss increased with increasing minus load level. The coefficient of friction was found in the range of 0.042-0.048. Wear mechanisms were determined as the combination of abrasive, adhesion and oxidation.

1. Introduction
Aluminum matrix composites have been increasingly used for engineering applications such as automotive, aerospace, biomedical and electrical applications [1]. Light weight, good hardness and strength as well as wear resistance are attractive properties, which are controlled by starting materials used and fabrication techniques. Silicon carbide particulate as the reinforcing material provides isotropic properties, if good distribution of the reinforcement and effective bonding between the reinforcement and the matrix are attained [2]. Strengthening mechanisms were applied to improve mechanical properties of aluminum composite such as solid solution and precipitation hardening. In recent years, it is known that small addition of silicon carbide reinforcement can improve hardness of the aluminum matrix. However, the efficiency of reinforcements are not good enough for hardness and tensile strength due to the different hardness between reinforcement and matrix [2]. Further, effective interfacial bonding between aluminum matrix and silicon carbide strongly determines the final properties, which depends on selected processing routes. Research on stir-mixing, liquid infiltration and powder technology of aluminum composites are under intense investigation to enhance properties and scope engineering applications [3]. However, there are certain limitations of liquid-state forming processes such as wettability of aluminum and silicon carbide, and brittle aluminum carbide (Al₄C₃) occurring along interfaces between aluminum matrix and silicon carbide. Powder metallurgy
however has advantages such as low-cost for mass production of small parts, uniform distribution of particle reinforcements, and solid state process to reduce the reactions between the matrix and particles [4]. Though, studies on conventional powder metallurgy of aluminum composites have been increasing published, powder injection molding (PIM) of aluminum composites on the other hand are quite limited. With versatility of the PIM in producing small complex shaped components at low cost, it is also a good candidate for the production of aluminum composite with uniform reinforcement distribution.

Microstructure and properties such as hardness and tensile have been documented elsewhere [5]. In this research, wear properties of 10 vol.% silicon carbide reinforced aluminum composite has been studied to extend the possibility of using aluminum composite subjected to engineering wear. The research aim is to study the influences of different loads on wear behaviour of powder injection molded silicon carbide reinforced aluminum composite after sintering and precipitation hardening under ball on flat type of wear test.

2. Experimental

Aluminum powder and silicon carbide particulate reinforcement were used as the feedstock. The compositions of aluminum alloy powder (by weight percent) is Cu 4.3-4.7, Mg 0.4-0.6, Si 0.5-0.8, Fe 0.07 and balanced Al. Silicon carbide particulate was added at 10 vol.% to the aluminum powder prepared by ball-mill mixing for 2 hours at 280 rpm. before mixing with a multi-component polymeric binder. The mixed powders of 55 % solid loading were injection molded at 170 °C and 45 MPa to produce green samples of 20x20x5 mm³ in dimensions. After debinding in hexane, the brown samples were sintered at 650 °C in a high purity nitrogen atmosphere. Solution heat treatment was carried out at 550 °C for 2 hours, followed by age-hardening at 160 °C for 6 hours. Microstructure (OM and SEM), bulk density and wear resistance were examined for the as sintered and heat-treated samples. Ball on flat type of wear test according to ASTM G 133-95 were employed, using load varying at -5, -25, -45, and -65N, for a sliding distance of 100 m. with no lubrication. The 440-C stainless steel balls of 6.3 mm. diameter, having 62 HRC hardness were used as the counterface material.

3. Results and discussion

3.1. Microstructure and phase analysis

Sintered microstructure of the aluminum composite exhibits uniform distribution of silicon carbide particulate in the aluminum matrix in the as-sintered condition, as shown in Figure 1 a). Some areas contain micro-porosity along silicon carbide clusters. SEM micrograph at 1000X magnification reveals precipitate phase of Al$_2$Cu after heat treatment, as shown in Figure 1 b), confirmed by EDS analysis.

![Figure 1. Microstructures showing a) silicon carbide distributed in aluminum matrix (OM) and b) at higher magnification (SEM)](image)

EDS mapping analysis, as shown in Figure 2, indicates the aluminum matrix contains main elements such as Al and Cu. Si was found where silicon carbide particulate is located. XRD results of the aluminum composite after sintering and heat treatment are demonstrated in Figures 3 a) and b)
respectively. The main phases are aluminum matrix and silicon carbide. It is noted that AlN was detected in both of sintered and heat-treated conditions due to the effect of nitrogen gas in sintering atmosphere. Furthermore, there are higher peaks of precipitate phases such as Al$_2$Cu and Mg$_2$Si found in the heat-treated composites, which contribute to improved hardness.

Figure 2. EDS mapping analysis of Al, Si and Cu.

Figure 3. XRD result of silicon carbide particulate reinforced aluminum composite after sintering (top) and precipitation hardening (bottom).
3.2. Density and hardness

Density was measured to be 1.82 g/cm$^3$ after injection molding and then increased to 2.63 g/cm$^3$ after sintering. This accounts for 93.2% theoretical density in the sintered condition according to the rule of mixture by taking the densities of aluminum alloy = 2.78 g/cm$^3$ and silicon carbide = 3.20 g/cm$^3$ respectively. The sintered density, which is lower than the theoretical density is plausibly due to porosity left after sintering, as previously shown in Figure 1a).

Macro and micro Vickers hardness values of heat-treated samples significantly increase as compared to those of as-sintered samples, as shown in Table 1. The maximum values were measured at 160.1 and 156.9 Hv respectively. This is due to precipitation hardening of Al$_2$Cu and Mg$_2$Si in the matrix.

### Table 1. Macro and micro Vickers hardness values for as-sintered and heat-treated conditions.

|                | Macro Hardness (Hv) | Micro Hardness (Hv) |
|----------------|---------------------|---------------------|
| As sintered    | 130.1               | 136.0               |
| Heat treated   | 160.1               | 156.9               |

3.3. Wear properties and worn surfaces

Wear grooves at varying minus loads at a stroke length of 10 mm are depicted in Figure 4. Increasing wear groove width is observed with increasing minus load level. Furthermore, plastic deformation at the edges of the wear grooves along the wear track at higher minus load level is evident.

Wear test parameters such as frictional force (Fx) and normal force (Fz) were measured in real time as shown in Figures 5 a) and b) for loads at -25 and -65N respectively, presented at t = 0 – 400 second. The coefficient of friction (COF) was then obtained accordingly.

Wear weight loss as a function of load for as-sintered and heat-treated samples are illustrated in Figures 6 a) and b) respectively. It is noted that wear weight loss at -5N load for both conditions is undetectable. It can be seen that a slight increase trend of wear weight loss was observed with increasing minus load [6]. The COF are reported in Figures 7 a) and b), and was found in a range of 0.042 - 0.048 and 0.044 - 0.047 for as-sintered and heat-treated conditions respectively. These values are comparable to those observed in laser composite surfaced aluminum with silicon carbide by J. Dutta Majumdar et. al, [7]. Many researches [8] also supported that the COF values were found insensitive to load or pressure applied. However, COF at very low minus load of -5N was significantly higher. Further study is required for more explanation.

![Figure 4](image_url). Wear grooves at varying loads at a) -5N, b) -25N, c) -45N and d) -65N.
Figure 5. Test parameters at a) -25N and b) -65N, showing Fx, Fz and coefficient of friction (COF).

Figure 6. Wear weight loss as a function of load in a) as-sintered and b) heat-treated conditions.

Figure 7. Coefficient of friction as a function of load in a) as-sintered and b) heat-treated conditions.

Worn surface of aluminum composite were investigated by using SEM, as demonstrated in Figures 8 a) and c) at low magnification for -25N and -65N respectively. Abraded surfaces are evident in all samples at every load levels, indicating abrasive wear, but with a lower degree at -5N. As the counterface stainless steel ball is much harder in comparison to the aluminum composite, it is believed that silicon carbide might have been pulled out and abraded on the softer aluminum matrix. The increasing contact load between stainless steel ball and the aluminum composite had made the latter to deform progressively, as shown in Figure 4. Secondary electron micrographs at higher magnification are shown in Figures 8 b) and d). Rough surface area of wear grooves are possibly due to deformation of the soft aluminum matrix. Severely deformed matrix would then be delaminated, transferred and adhered onto other surface. Back-Scattered Electron mode analysis as depicted in Figure 9 a) indicates certain amount of silicon carbide distributed throughout the aluminum matrix. However, BSE micrograph of the worn surface at the same magnification reveals only small traces of silicon carbide left on the surface, as seen in Figure 9 b). It is then confirmed that some silicon carbide particulate previously embedded in the aluminum matrix fell out and might have abraded on to the softer
aluminum matrix during the ball on flat wear test, introducing three body abrasion. Similar results by F. Alshmri, et. al. [9] and I. Dinaharan, et. al. [10] indicated harder particles (silicon or fly ash) being pulled out and promoted three body abrasion wear, which then created fine spherical wear debris [9, 10]. Though, silicon carbide fracturing was also possible in this research at higher load, the evidence of fractured silicon carbide was however hardly observed. Therefore, it is worth to investigate effects of silicon carbide content on the degree of abrasive wear on this composite in future work.

![Figure 8. Secondary electron micrographs of worn surfaces at a) -25N and b) higher magnification, c) -65N and d) higher magnification.](image)

![Figure 9. Back-scattered electron micrograph a) before wear test and b) after wear test.](image)

Wear debris obtained from all tests at varying minus loads have shown two different forms of agglomerate and flake like-shape. EDS point analyses of wear debris at load levels of -25N and -65N, are illustrated in Figures 10 a) and b) respectively. Peaks of Al, Mg, Cu and O elements were detected in spectrum 1 of agglomerate wear debris. Flake like-shaped wear debris was EDS analysed (spectrum 2), showing Al, Mg, Cu and O elements having different composition in comparison to that of agglomerate one (spectrum 1). EDS analysis on wear debris obtained from lower minus load test indicates higher content of Al on the flake-like form of wear debris, which signifies that this product might be from the deformed aluminum matrix. Moreover, higher level of oxygen observed in the agglomerate form suggests more of oxidation product. At higher level of minus load (~65N), the level of Al and O content detected in both agglomerate and flake-like forms are comparable, as shown in Figures 10 a) and b). It is therefore believed that oxidation wear might have occurred in a mild level during the wear test and is more significant at higher minus load level [11]. Moreover, there was however no peaks of Fe, Ni or Cr detected. This implies the mutual transfer of material between the
wearing aluminum composite and the stainless steel counterface appears to be insignificant. Only aluminum matrix was deformed, oxidized, detached and transferred to be adhered on other areas. In addition, it is noticed that the size of flake-like form of wear debris also became significantly larger with increasing minus load level. Dry sliding wear test on aluminum-high silicon hypereutectic alloys by F. Alshmri, et.al [9] indicated comparable result, where the transition from powder-type to flake like-shape as the load increased was reported. This flake-like wear debris found in this research also confirmed the operating wear mechanism is related to adhesive [10]. Together with the appearance of plastic deformation at the wear groove edges along the wear track previously mentioned, analogous to those observed from works by B. Hekner, et. al. [12] and S. Sawla and S. Das [13], these evidences substantiates the influence of plastic deformation on wear mechanisms at higher minus load level in this ball on flat type of wear test.

**Figure 10.** EDS point analysis of wear debris at applied loads of a) -25N and b) -65N.
Therefore, wear mechanisms of aluminum matrix reinforced with 10 vol.% silicon carbide particulate fabricated by powder injection molding tested under ball on flat type of wear test with load varying at -5 to -65N can be determined as follows. Wear damage of the aluminum composites shows several wear mechanisms such as abrasive, adhesive and oxidation wear. Firstly, abrasive wear of aluminum reinforced with silicon carbide is caused by different hardness between the aluminum matrix and silicon carbide. Much harder silicon carbide particulate first fell out from the matrix and abraded onto the softer matrix surface. Secondly, aluminum matrix was deformed and delaminated to give wear debris and some was then transferred from one surface to another. Adhering of these transferred materials at the wear groove edge is also evident. Increasing minus load level introduced much more severity of the wear damage. Finally, it is known that aluminum passively produces oxide film layer on its fresh surface. During ball on flat of wear test in ambient atmosphere, the oxide film layer was removed and the fresh surface will react with oxygen immediately to form new oxide layers in repeated cycles of reciprocating wear test.

4. Conclusions
Wear mechanisms of powder injection molded aluminum composite reinforced with 10 vol.% silicon carbide is due to abrasive, adhesive and oxidation. Abrading of silicon carbide on the softer aluminum matrix is due to hardness difference between the two materials. Mutual transfer between the two mating materials is not apparent. Only softer aluminum matrix was plastically deformed, oxidized, detached and transferred to be adhered on other areas. Severe wear damage at high applied minus load of -65N involved plastic deformation of the soft matrix at the wear groove edges. Degree of damage such as wear weight loss, wear groove width and oxidation increased with increasing minus load level. The coefficient of friction has not significantly changed with the load applied and was found in the range of 0.042-0.048. However, wear damage of the composite after sintering and precipitation hardening are not significantly different.

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