

Investigating the effect of reinforcing particulates on the weight loss and worn surface of compocast AMCs

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Abstract

This paper aims to investigate the abrasive wear behavior of the sol-gel coated B₄C particulate reinforced aluminum metal matrix composite. Sliding wear is related to asperity-to-asperity contact of two counter surfaces, which are in relative motion against each other. The effective wear from the specimen surface is due to the combined effect of a number of factors. An increase in the applied load leads to increase in penetration of hard asperities of the counter surface to the softer pin surface, increase in micro cracking tendency of the subsurface and also increase in the deformation and fracture of asperities of the softer surface. In general, composites offer superior wear resistance as compared to the alloy irrespective of applied load and B₄C particles volume fraction. This is primarily due to the presence of the hard dispersoid which protects the matrix from severe contact with the counter surfaces, and thus results in less wear, lower coefficient friction and temperature rise in composite as compared to that in the alloy. The worn surfaces of all specimens were covered with grooves parallel to the sliding direction and some plastic deformations. These grooves are typical features associated with abrasive wear, in which hard asperities on the steel counter face or hard particles between the pin and disc, plough or cut into the pin cause wear by the removal of the material. Plastic deformation, material smearing, cavities and craters imply adhesive wear.

Key words: dry sliding, adhesive, mechanically mixed layer

1. Introduction

Wear is the process occurring at the interfaces between interacting bodies and is usually hidden from investigators by the wearing components. It is usual to classify wear in terms of four different categories: adhesive wear, abrasive wear, fatigue wear and tribochemical wear. Adhesive wear is characterized by the appearance of junctions between the surfaces that are subject to friction. Abrasive wear occurs when a hard material is put into contact with a soft material. This type of wear can cause scratches, wear grooves, and leads to material removal. Surface fatigue wear occurs when a material is subject to cyclical stresses. Tribochemical wear is a phenomenon which involves the growth of a film of reaction products due to chemical interactions between the surfaces in contact with each other and the surrounding environment.

The enhancement in tribological properties of Alu-

minum Matrix Composites (AMCs) has been effectively attainable by introducing the ceramic particles [1]. There are excellent reviews on the tribology of AMCs. Chung et al. [2] reported that increasing the ceramic particle content enhanced the wear resistance of the base alloy [2]. During sliding wear of AMCs, a layer is formed over the specimen surface, which strongly dictates the wear behavior of the materials. Shabani et al. [3] showed that subsurface micro cracks are generated during the wear of AMCs which finally leads to removal of wear debris, especially from asperity contacts. The formation of these micro cracks is due to combined action of load, sliding speed and sliding distance. In addition, higher temperature rise also leads to greater flowability of surface materials and thus increases greatly the possibility of compaction of wear debris on the specimen surface. In this case, valleys between the asperities of the counter surface get partially occupied with the material of the speci-

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men, which results in the reduction of surface abrasive action effectiveness of the counter surface asperities. With increase in sliding distance, the temperature increases to a critical value at which specimen surface gets oxidized. This oxidized surface either gets fragmented or becomes stable to some extent. The fragmented oxide particles sometimes act as lubricating agent and thus these oxide layers reduce the effective wear rate. Furthermore, the fragmentation and compaction of wear debris, counter surface material and thin oxide layers lead to formation of mechanically mixed layer (MML) which protects the specimen surface from wear [3]. However, further increasing sliding distance leads to increasing temperature which leads to subsurface softening, and because of plastic incompatibility and thermal mismatch, the MML gets fractured and subsequently removed from the specimen surface. Thus at higher sliding distances it is expected that the formation and removal of MML are taking place simultaneously and the rate of removal and the rate of growth of MML might be the same, and thus the wear rate remains unchanged with sliding distance [4]. It is reported that as the sliding distance reaches the point of seizure, the MML becomes unstable because of greater degree of temperature rise in the subsurface resulting in higher degree of thermal as well as plastic incompatibilities between MML and subsurface [5].

The wear rate of the unreinforced alloy is found to be higher than that of the composites. This is primarily due to the fact that the hard dispersoids, present on the surface of the composite, act as protrusions, protect the matrix from severe contact with the counter surfaces [6], and thus resulting in less wear in composite as compared to that in the alloy. The hard particles resist against destruction action of abrasive and protect the surface, so with increasing its content, the wear resistance enhances [7]. Additionally, the hard dispersoid makes the matrix alloy plastically constrained and improves the high temperature strength of the virgin alloy [8]. During dry sliding wear of aluminum based composite, wear of the counter face is usually evident. The extent of iron deposition is reported to be more significant for AMC/steel sliding couples in comparison to Al/steel sliding couples due to micro cutting and ploughing of reinforcing hard ceramic particles on the counter face. Razavizadeh reported that an extensive mechanical mixing took place between the aluminum matrix composite and the steel counterpart during sliding wear, and MML containing elements from the two sliding counterparts was formed on the worn surface [9].

In this study, B_4C powders were incorporated into the semisolid matrix alloy and sliding wear behavior of composites had been examined under varying applied loads and sliding distances. The benefits of semisolid agitation processes include reduced solidi-

fication shrinkage, lower tendency for hot tearing, and suppression of segregation, settling or agglomeration and faster process cycles [10, 11]. These advantages are accompanied with lack of superheat (lower operating temperatures) as well as a lower latent heat which results in a longer die life together with a reduced chemical attack of the reinforcement by alloy, also a globular, non-dendritic structure of the solid phase which then explains the thixotropic behavior of the material [12].

2. Experimental procedure

Al composites reinforced with the B_4C particles have been used for the present study. The Al alloy has the chemical composition of 4 % Cu, 4 % Mg, 0.5 % Fe, 0.25 % Cr, 0.25 % Mn, 0.25 % Ti, 0.25 % Zn and the rest Al.

The process of stir casting was used which generally involves the admixture of ceramic particulate reinforcement with a molten metal matrix. The B_4C powders (particle size of 40 μm) were first coated with TiB_2 via a sol-gel process. Mg was added to the melt in the final stage prior to pouring task to enhance the wettability between metal matrix and reinforcement particles. The process involved melting the alloy in the graphite crucible using an electrical resistance furnace. The furnace was controlled using a J-type thermocouple located inside the gas chamber. The temperature of the alloy was raised to about 850 °C and stirred at 800 rpm using an impeller fabricated from graphite and driven by a variable ac motor. The stirrer was positioned just below the surface of the slurry and the coated particles were added uniformly at a rate of 50 g min^{-1} over a time period of approximately 3 min. The temperature of the furnace was gradually lowered until the melt reached a temperature in the liquid solid range (i.e. 590 °C) while stirring was continued. The squeeze casting was obtained by pouring composite slurry into preheated permanent die and punch which was allowed to solidify under squeeze pressure of 80 MPa for duration of 5 min. High temperature graphite powder was used in the die to facilitate removal of cast blanks from the die after cooling. The pressure applied during solidification in the squeeze casting technique resulted in excellent feeding during solidification shrinkage. For the purpose of comparison, unreinforced Al alloy was also cast following the procedures which were identical to those for the composite samples. A continuous purge of nitrogen gas was used inside and outside of the crucible to minimize the oxidation of molten aluminum and graphite parts. The obtained cast bars were turned to small pins (diameter of each pin was 6 mm and its length was 25 mm). These pins were subsequently used in the wear test. The disk with a diameter of 50 mm and

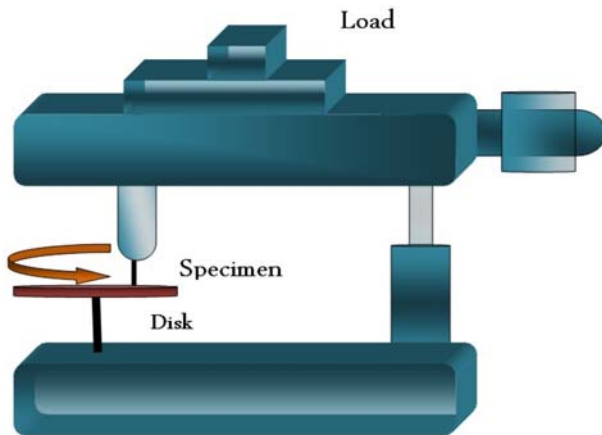


Fig. 1. Schematic diagram of the abrasion wear test.

a thickness of 10 mm was made of the steel hardened up to 63 HRC and polished to a very fine grade with surface roughness about 0.22 μm . Before the abrasion tests, each specimen was polished to 0.5 μm . Figure 1 shows schematic diagram of the abrasion wear test. The pin-on-disk wear machine consists of the stationary pin pressed at the required load against the disk rotating at the defined speed. An AC motor ensures the stable running speeds of the disk. The testing machine is equipped with a set of measuring transducers. The experiment was carried out at room temperature (21 $^{\circ}\text{C}$, relative humidity 55 %) with water as the lubricant. The samples were cleaned with acetone and weighed (up to an accuracy of 0.01 mg using microbalance) prior to and after each test. The temperature rise and friction force were recorded from the digital display interfaced with the wear test machine. The wear tests were conducted up to the total sliding distance of 2000 m. The mass loss of the pin was used to study the effect of B_4C addition on the wear resistance of the composite materials under consideration. The worn surfaces of the samples were examined using scanning electron microscope (SEM) equipped with energy dispersive X-ray spectroscopy (EDS) (EDAX).

3. Results

The volume fraction of B_4C particles was measured by means of an image analyzer system attached to the optical microscope. A sedimentation experiment was conducted on the composites containing 15 vol.% particles. Figure 2 shows the B_4C concentration as a function of the distance from the bottom of the mould (D). This clearly indicates that when the composite slurry was held at the molten state, the lower parts of the ingot contained a lower volume percent of particles than the upper parts, representing an uneven macroscopic particle distribution. The microstructures of

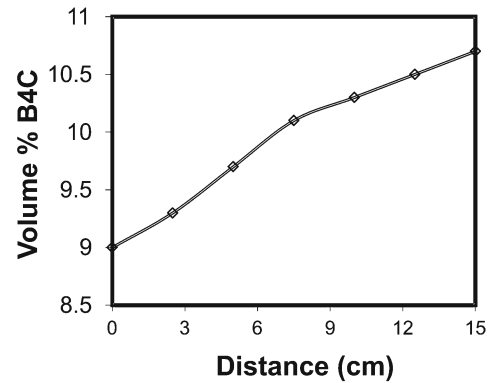


Fig. 2. The B_4C concentration versus the distance from the bottom of the mould (D).

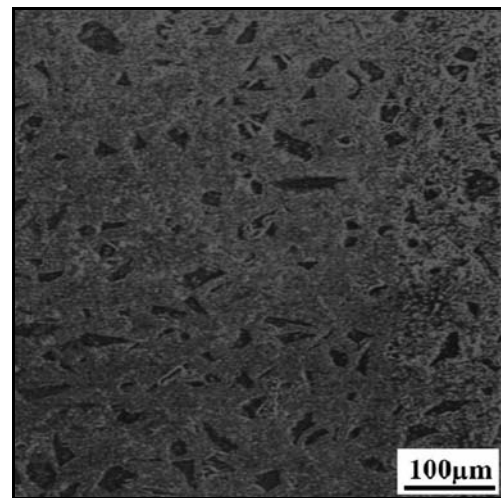


Fig. 3. Microstructure of the composite showing uniform distribution of B_4C particles.

the coated composites were examined by SEM in order to determine the distribution of the B_4C particles and presence of porosity. Typical SEM micrograph of the compocast B_4C reinforced Al alloy composites is shown in Fig. 3.

The distribution of the B_4C particles within the matrix alloy was characterized by a distribution factor (DF) defined as $\text{DF} = \text{S.D.}/\text{Af}$, in which Af is the mean value of the area fraction of the B_4C particles measured on 100 fields of a sample, and S.D. is its standard deviation. Figure 4 shows the gradual decrease in DF for the composites when the particle content increased, indicating the improvement in the uniformity of the B_4C particle distribution. A non-uniform microscopic distribution of the reinforcing phase within a sample is reflected as a relatively high value of DF.

The wear tests were performed at various normal loads of 5, 10, 15, 20, 25 and 30 N, and a sliding speed

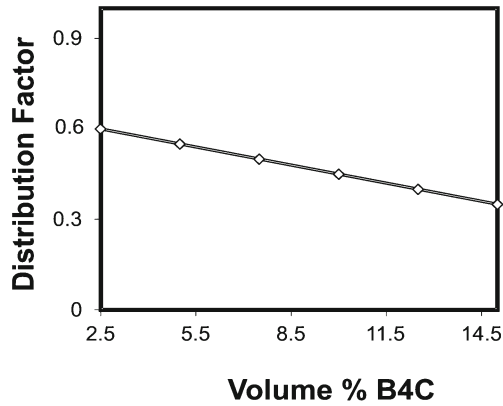


Fig. 4. The distribution factor versus the B₄C particles content.

of 0.3 m s^{-1} using a pin-on-disk type test machine. Figure 5 shows the weight losses for different volume percentages Al-B₄C composites during wear test at an applied load of 20 N. The wear rate of the unreinforced alloy is found to be higher than that of the composites. The lowest value of mass loss in wear test was distinct for Al-15vol.%B₄C and the highest mass loss in wear test was for bare Al alloy. Although the rate of change for the composites is much smaller than that of the matrix, the weight loss of the matrix and the composites increases linearly with the sliding distance. It is clear that the unreinforced matrix alloy wore much more rapidly than the reinforced composite materials.

4. Discussion

The uniformity in distribution of particles within the sample is a microstructural feature which determines the in-service properties of particulate AMCs. A non-homogeneous particle distribution in cast composites arises as a consequence of sedimentation (or flotation), agglomeration and segregation. The subject of particle distribution in particulate MMCs has been studied by several investigators either qualitatively or

quantitatively. The macroscopic particle segregation due to gravity (settling) has also been studied both experimentally and theoretically, the latter of which generally involves the correlation of particle settling rate within the composite slurry with the Stocks' law [13–18].

Boron carbide (B₄C) powder was chosen as reinforcement because of its higher hardness (very close to diamond) than the conventional and routinely used reinforcement such as SiC, Al₂O₃, etc. Further, its density (2.52 g cm^{-3}) is very close to Al alloy matrix [13]. The wettability of B₄C particles represents a very important issue which is poor at temperatures near the melting point of aluminum (660°C) [19]. It is reported that B₄C powders coated with some of Ti-compounds might have reasonable wettability with aluminum [20–23]. Figure 3 shows that fabrication of these composites via compocasting technique leads to reasonably uniform distribution of particles in the matrix and minimum clustering or agglomeration of the reinforcing phase. During the solidification process of the composite slurries, the reinforcing particles are pushed to the interdendritic or intercellular regions and tend to segregate along the grain boundaries of matrix alloy. The quantitative assessment of the B₄C particle distribution within composite samples shows the gradual decrease in DF for the composites when the particle content increased, indicating the improvement in the uniformity of the B₄C particle distribution (Fig. 4). These results can be attributed to the restricted movement of particles within the melt during solidification as a consequence of the increased effective viscosity of the slurry and the less pronounced coarsening effects resulting in a finer matrix microstructure which in turn causes a more uniform ceramic particle distribution.

The wear resistance of the composites is considerably improved due to the addition of the B₄C particles and increases with increasing B₄C volume fraction up to 15 vol.%. Generally, the most important feature in improved wear resistance of all composites is the presence of B₄C particles whose hardness is much greater than the matrix alloy [5]. It is well known that hard

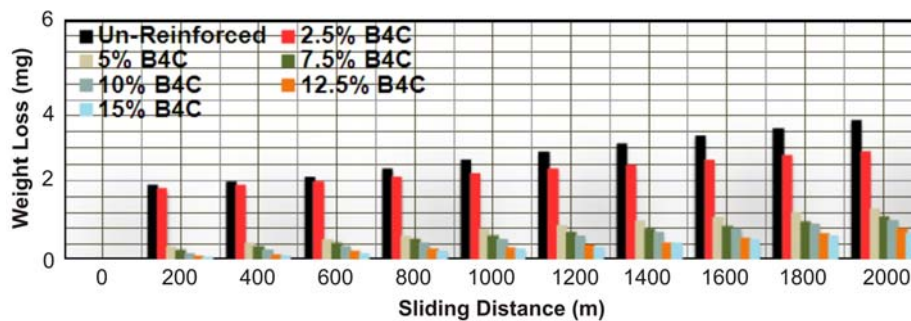


Fig. 5. Weight loss as a function of sliding distance.

ceramic particles in the matrix alloy provide protection to the softer matrix during sliding and strengthen the aluminum matrix. This protection will limit the deformation, and also resists the penetration and cutting of the asperities of the sliding disk into the surface of the composite. The B_4C particles also improve load-bearing capacity and thermal stability of the composites [24].

It is noted that the weight loss of the composites is less than that of unreinforced alloy, increases with increase in sliding distance, and has a declining trend with increasing the particles volume fraction. It is known that the wear loss is inversely proportional to the hardness of alloys. In case of unreinforced Al alloy, the depth of penetration is governed by the hardness of the specimen surface and applied load. But, in case of Al matrix composite, the depth of penetration of the harder asperities of hardened steel disk is primarily governed by the protruded hard ceramic reinforcement. Thus, the major portion of the applied load is carried by B_4C particles. The role of the reinforcement particles is to support the contact stresses preventing high plastic deformations and abrasion between contact surfaces, and hence reduce the amount of worn material. However, if the load exceeds a critical value, the particles will be fractured and comminuted, losing their role as load supporters [25]. Figure 6 shows the hardness values for the unreinforced alloy and composites investigated in this study. It is observed that the addition of hard ceramic B_4C particles increases the hardness of an Al alloy.

During sliding, frictional force acts between the counter surfaces which causes frictional heating of them. While the counter surfaces are in relative motion, the frictional heating is continuous because of insufficient time for heat dissipation. The variation of temperature with sliding distance at an applied load of 25 N is presented in Fig. 7. It is noted that temperature rise is greater in the case of unreinforced alloy as compared to that in the composite irrespective of the applied load and surface conditions. During the sliding, in fact, a considerable fraction of energy is

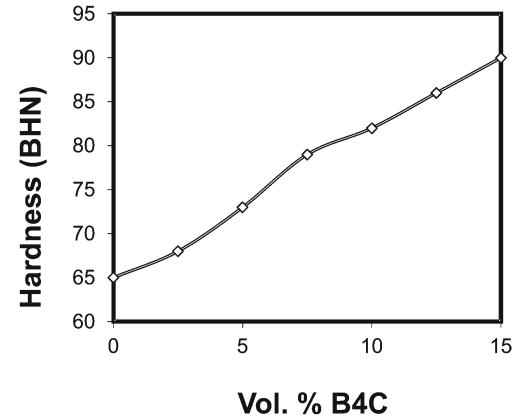


Fig. 6. Hardness as a function of B_4C particles volume fraction.

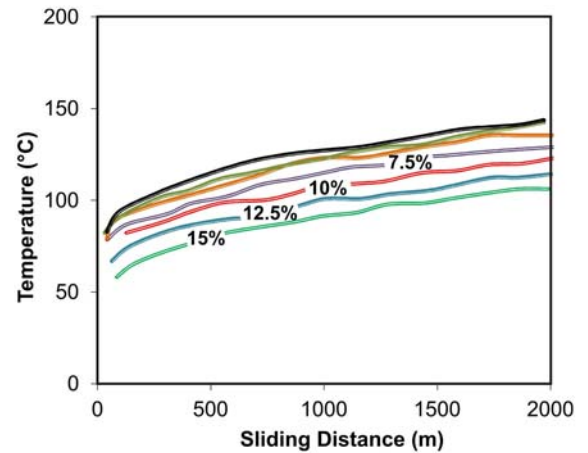


Fig. 7. Temperature as a function of sliding distance.

spent on overcoming the frictional force, which leads to heating of the contact surfaces. Initially, the asperities are stronger and sharper, and that is why frictional force and as a result frictional heating takes place at higher rate. After a certain period, because of the in-

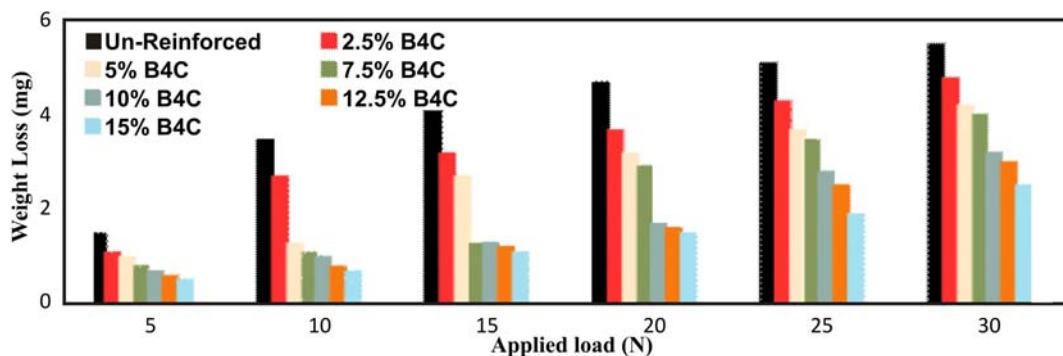


Fig. 8. Effect of applied load on wear resistance.

crease in flowability of the material on the specimen surface, slipping action is higher which results in reduction of frictional heating. The more possibility of adhesion between the counter surfaces leads to higher degree of friction.

It is noted in Fig. 8 that the wear rate in all the samples increases marginally with applied load prior to reaching the critical load. The increase in the applied load leads to increase in the penetration of hard asperities of the counter surface to the softer pin surface, increase in micro cracking tendency of the sub-surface, and also increase in the deformation and fracture of asperities of the softer surface. On the other hand, a higher amount of material from the pin surface gets accumulated at the valleys between the asperities of counter surfaces resulting in reduction in height and cutting efficiency of counter surface asperities.

Beyond the critical load for each composite, the wear rate starts increasing abruptly with the applied load. The load at which the wear rate increases suddenly to a very high value is termed as the transition load. When the applied load is greater than the transition load, the wear rate of the composite shoots up to significantly higher value.

This is attributed to the significantly higher frictional heating and thus the localized adhesion of the pin surface with the counter surface, and also to an increase in softening of the surface material and thus more penetration of the asperities. Under such conditions the material removal due to the delamination of adhered areas, micro cutting and micro fracturing increases significantly. This leads to destruction of MML, which was formed at lower applied load at the initial period of sliding. As a result, after a critical load there is a transition from smooth linear increase wear rate to sudden increase in wear rate. It was reported in the previous research that when the applied load induced stresses that exceeded the fracture strength of carbide particles, the particles fractured and largely lose their effectiveness as load bearing components. The shear strains are transmitted to the matrix alloy and wear proceeds by a subsurface delamination process. Furthermore, liberated reinforcing particles as wear debris roll over the contacting surfaces which create three body abrasion type situations and cause more wear on both the contacting surfaces. However, an extent of this situation depends on sliding speed, applied load and frictional heating. In this case, the lower ductility of Al-B₄C composites appears to control the wear rates rather than the hardness of particles, resulting in wear rates almost similar to those observed in Al alloys without B₄C reinforcement. On the other hand, when the nominal load induces stresses lower than the strength of particles, the particles act as load bearing components. In this case, the B₄C particles remain intact during wear in order to support the applied load and act as effective

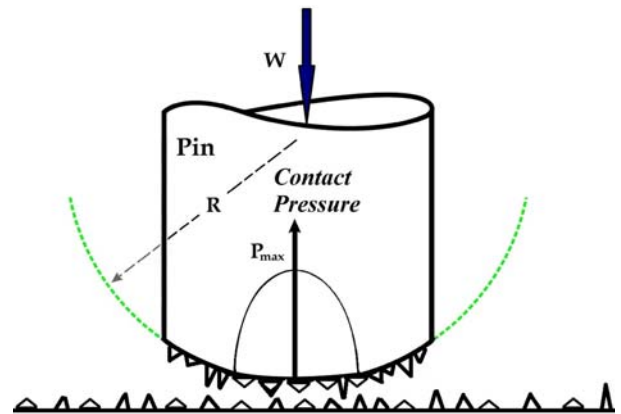


Fig. 9. Schematic illustration of three-body abrasive wear.

abrasive elements. The particles protruding from the surface of the composite bear most of the wear load, and the surface hardness of the composite is mainly a result of the hardness of the particles [26–28].

It is reported that the friction coefficients for composites containing B₄C are higher than the aluminum-based alloys while sliding under identical conditions [3–5]. The higher coefficients of friction in the case of composites containing hard B₄C particles are due to the formation of tribofilm at the interface between pin and disk. If the effective load on the individual particle increased above its flexural strength, the particles get fractured. Parts of the removed B₄C particles are entrapped between two partners, i.e. asperities of softer material of pin and asperities of harder material (hardened steel disk), possibly leading to three-body abrasion; then it will result in surface roughness between contacting surfaces, and coefficient of friction increases. Figure 9 shows schematic illustration of a three-body abrasion model. The tribofilm contains debris from specimen and counter face steel disk. EDS analysis was used to detect the trace of Fe on the worn surfaces (Fig. 10a,b). The variation of Fe content on the worn surface with B₄C content is shown in Fig. 10c. It is observed that the formation of iron-rich layers on the contact surfaces increases with increasing the B₄C content [29].

The wear surface of the unreinforced alloy under the applied load of 15 N is depicted in Fig. 11. The flow of materials along the sliding direction, generation of cavities due to delamination of surface materials and tearing of surface material is also noted in this figure. It is noted that the slider could penetrate and cut deeply into the surface and cause an extensive plastic deformation on the surface, resulting in a great amount of material loss. Worn surface of the 10 vol.% composite at an applied load of 15 N is shown in Fig. 12. It indicates formation of continuous wear grooves, relatively smooth MML, and some damaged regions. However, the degree of cracks formation

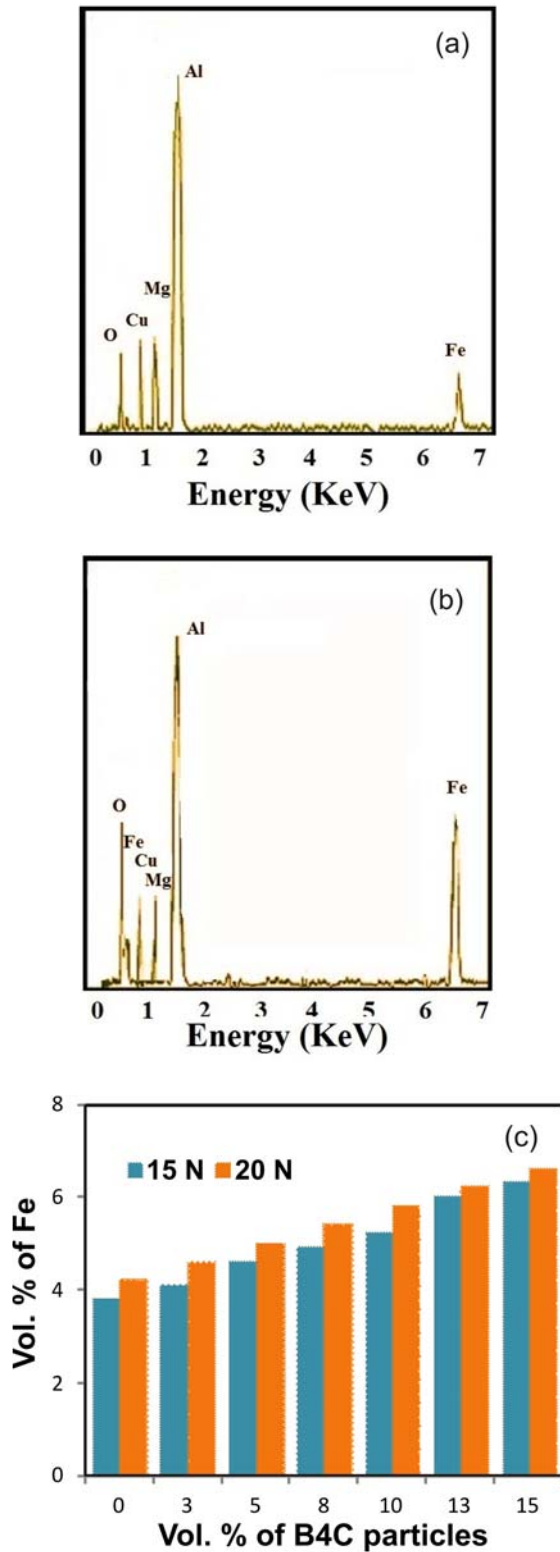


Fig. 10. Microchemical analysis of the worn surfaces: (a) unreinforced Al alloy, (b) composite, (c) variations of the Fe content on the worn surface with B₄C content.

on the wear surface is not much. The wear surface is characterized by the formation of parallel lips along

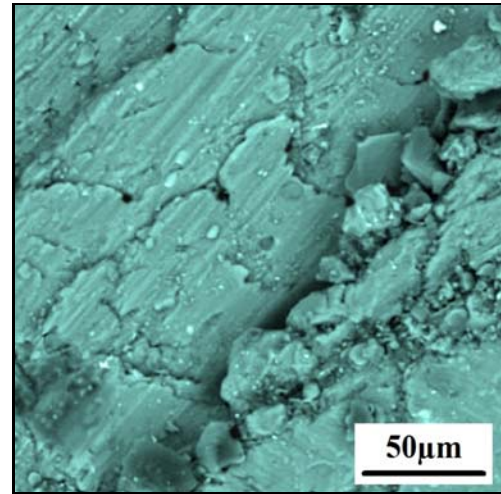


Fig. 11. SEM micrograph of worn surface of unreinforced Al alloy.

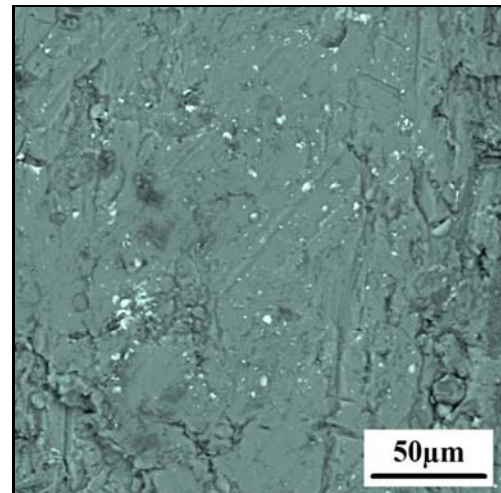


Fig. 12. SEM micrograph of worn surface of the Al matrix composite.

the continuous groove marking. Unlike the worn surface of the unreinforced alloy, the number of scratches by abrasives or hard asperities was small. Worn surfaces of the composites were smoother with shallower grooves along the sliding direction [30]. Therefore, it was reasonable that wear resistance of composites was higher than that of the unreinforced alloy.

5. Conclusion

The wear sliding test disclosed that the weight loss of the coated B₄C reinforced composites decreases with increasing volume fraction of B₄C particulates. The improvement of the tribological properties of Al

alloy matrix via addition of the ceramic particles including the SiC and Al₂O₃ reinforcements was reported by previous investigators, which is due to the resistance of hard particles against destruction action of abrasive, so with increasing its content, the wear resistance enhances. The wear rate in all the samples increases marginally with applied load prior to reaching the critical load. This result is also consistent with previous works and is ascribed to the increase in fracture of reinforcement, the penetration of hard asperities of the counter surface into the softer pin surface and micro cracking tendency of the subsurface. The critical load of the unreinforced alloy is measured between 5 and 10 N, while for the composite reinforced with 7.5 % B₄C, it is obtained between 15 and 20 N. After the critical load there is a transition from smooth linear increase wear rate to sudden increase in wear rate. This is attributed to the significantly higher frictional heating, and thus the localized adhesion and softening of the surface with the counter surface. During sliding, the temperature of the contact surface is initially less, and hence the asperities are expected to be stronger and more rigid. As time progresses, the frictional heating increases, which leads to higher temperature and softening of the surface materials.

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