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Dry Sliding Wear Behavior of Aluminum 6063 Composites Reinforced with TiB_2 Particles

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Abstract

The influence of titanium diboride (TiB_2) loading on the dry sliding wear characteristics of aluminum 6063 matrix alloy-titanium diboride (Al/TiB_2) composite materials has been assessed using a pin-on disc wear tester at different loads. The composites with 5 and 10 wt% of fine TiB_2 particles were fabricated using stir casting technique. For comparison, as-cast of the base alloy were made under the same processing applied for Al/TiB_2 composites. The hardness of the composite materials was measured using Brinell hardness tester. Scanning electron microscopy (SEM) was used to analyze the wear surfaces of samples. The results indicate that fine TiB_2 particles markedly improved the wear performance of the aluminum 6063 matrix alloy. The coefficient of friction decreases with increase in the amount of TiB_2, but this effect was more pronounced in dry sliding. Hardness of composites increased with increasing TiB_2 loading. The wear rates increase with increase in load and dependent upon TiB_2 loading in the base alloy. Among the composites tested, Al/TiB_2 composites containing 10 wt% TiB_2 exhibited superior wear resistance over the base alloy and 5 wt% Al/TiB_2 composites. These observations were correlated in terms of the TiB_2 loading in base alloy which resulted in the variations of the hardness.

Keywords

TiB_2 Reinforced Aluminum 6063, Hardness, Sliding Wear, Wear Rate, Wear Resistance

1. Introduction

Owing to the high strength-to-weight ratio, aluminium has been found wide application in areas where light weight is of primary considerations. Aluminium based particulate-reinforced metal matrix composites are well known for their higher specific modulus and strength as well as for their excellent wear resistance when compared to their monolithic counterparts [1]. Metal matrix composites have emerged as an important class of high performance material for use in aerospace, automobile, chemical and transportation industries because of their improved strength, high elastic modulus and increased wear resistance over conventional base alloys. Aluminium based composites SiC, B_4C, Al_2 O_3, TiC [2] and graphite reinforce aluminium or its alloys have been the interest of research. Among these reinforcements, TiB_2 has emerged as a promising candidate for Al-base composites; this is due to fact that the TiB_2 is stiff, hard and does not react to form the reaction products at the reinforcement interfaces [3] [4] [5]. TiB_2 is a refractory compound that exhibits outstanding features such as high melting point (2790˚C), high hardness (86 HRA or 960 HV) and high modulus characteristics. Its resistance to plastic deformation even at high temperatures portrays it to be a good potential reinforcing candidate in an aluminum matrix. 5 and 10 wt. % TiB_2 particles reinforced aluminum (Al6063) metal matrix composites produced by using master alloys of Al-Ti & B by stir casting process to obtain the material for the experiment [6] [7] [8] [9]. Limited published work is only available on the sliding wear behavior of composites with TiB_2 as reinforcement material [10] [11] [12]. Mandal *et al.* [10] in their study of sliding wear of composites stated that TiB_2 particles markedly improved the wear performance of Al-4Cu alloy. Lee *et al.* [11] showed that increased volume fraction of TiB_2 in the composite has not led to a parallel increase in wear resistance. This behavior is attributed to the presence of the unavoidable Al_3Ti phase in the Al-Ti-B system. Zhao Min *et al.* [12] showed TiB_2/Al composites exhibit higher wear resistance than SiCp/Al composite. Severe plastic deformation and adhesive wear were found on the worn surfaces of SiCp/Al composite, but no such worn surfaces observed in the TiB_2/Al composites. Roy *et al.* [13] have compared wear resistance of aluminium reinforced with TiC, TiB_2, B4C, SiC. It was stated that TiB_2 showed better wear resistance than the other dispersiods.

Kumar *et al.* [14] [15] noted that abrasive wear resistance improved by the addition of TiB_2 particle in the Al-4Cu alloy and it increases as the TiB_2 content in the composites increases. Ramesh *et al.* [16] observed that a decrease in wear rate with increase in the TiB_2 content in the composites. Maximum reduction is in the wear rate for the composites containing 10 wt% TiB_2 when compared with matrix alloy. Sivaprasad *et al.* [17] noted that as wt% of TiB_2 particles increases, volume loss decreases, and with increase in distance traversed, volume loss increases.

Natarajan *et al.* [18] showed that the dry sliding at room temperature increases the wear resistance of Al-6063 alloy by the reinforcement of TiB_2 particles. Basavarajappa *et al.* [19] showed that wear rate decreases as the sliding speed increases when SiC particles reinforced into Al-2219 alloy, up to transition speed and load, due to work hardening of surface, formation of Iron oxide and crushing the SiC particles. The present study was attempted to study the dry sliding wear behavior of Al-6063 alloy reinforced with TiB_2 particles at different loads, sliding velocity and different wt% reinforcement. The worn surfaces are studied using SEM photographs.

2. Experimental Details

2.1. Materials

Aluminium 6063 alloy was selected as the base line material as it possesses good formability, weldability, machinability and corrosion resistance, with medium strength compared to other grades of aluminium alloys. Its nominal chemical composition is shown in **Table 1**. The commercially available Al-6063 matrix alloy and master alloy are melted in an electric resistance furnace. The percentage weight of Al-Ti & B % was varied from 0 - 10 wt% in steps of 5 wt%. The mixture of matrix alloy and master alloy were melted in an electric resistance furnace at a temperature of 800˚C and allowed to stand for duration of about 30 min to get melts. The melt was degassed using commercially available chlorine based tablets (Hexa-chloroethane) to remove the entrapped gases before stirring the melt using stirrer to get in-situ composites of TiB_2 in Al 6063 alloy. The melt is poured into the preheated metallic moulds. The different % composition (0, 5 and 10) of Al-6063-TiB_2 composites rods are prepared of size Ø 22 mm × 120 mm.

2.2. Microscopy, Density and Hardness Measurements

In order to know the dispersion of TiB_2 in Al6063, the samples for microscopic examinations were prepared based on the standard metallographic procedures, etched with Keller's agent and were analyzed by scanning electron microscope (SEM).The density of the composites was obtained by the Archimedes's principle of weighing small pieces cut from the composite disc first in air and then in water. Then, theoretical density of composite and its alloy was calculated from the chemical analysis data. The porosity of the composites was also determined. The hardness of the composites and matrix alloy were measured after polishing to a 3 mm finish. The magnification of the images was 500×. Hardness of all samples was measured by Brinell hardness tester and mean of at least five readings was taken to represent the sample.

2.3. Dry Sliding Wear Test

A pin-on-disc machine shown in **Figure 1** was used to investigate the dry sliding wear behavior of the aluminium alloy and TiB_2/Al-6063 composites as per ASTM G99. Specimen of Ø 8 mm × 28 mm in length were cut out of rods of size Ø 22 mm × 120 mm, by the specimen cutter, machined, and then polished me-

Table 1. Chemical composition of Al-6063 alloy.

Element	Mg	Si	Fe	Cu	Mn	Zn	Ti	Cr	Al
wt.%	0.45 - 0.9	0.2 - 0.6	0.35	0.1	0.1	0.1	0.1	0.1	Balance

Figure 1. Pin on disc wear testing machine.

tallographically in order to ensure very smooth surface.. Wear tests were conducted with loads ranging from 10 - 30 N, sliding speed of 500 - 1500 m and sliding velocity of 0.5 - 1.5 m/s at room temperature. All tests are conducted at 80 mm track diameter on the EN24 steel hardened disc with HRC60 by applying normal load. The surface finish of the counterface is 2 μm. All tests were conducted at room temperature. The duration of time for the test is calculated from the given sliding speed and sliding velocity. The weight loss is calculated considering the weight before and after the wear and the volume loss is determined.

3. Results and Discussion

3.1. Microstructure of TiB_2-Al Composites

The properties of the metal matrix composites (MMCs) depend not only on the matrix, particle, and the volume fraction, but also on distribution of reinforcing particles and interface bonding between the particle and matrix. In practical way, to achieve a homogenous distribution is difficult. The photomicrographs of the aluminum composite reinforced with 5 and10 wt% of TiB_2 are shown in Figure 2(a) and Figure 2(b) respectively. The particles, with the average particle size of 25 μm, mainly formed in the surface showed a character of homogenous distribution within the matrix alloy.

3.2. Density and Hardness of TiB_2-Al Composites

The variations of density and hardness of the composites are shown in Figure 3. The density and hardness of the MMCs increased more or less linearly with the weight fraction of particles in the alloy matrix due to the increasing ceramic phase of the matrix alloy. A significant increase in both density and hardness

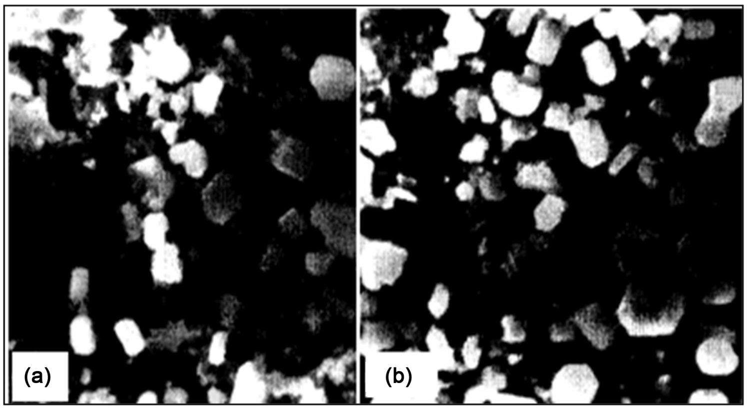


Figure 2. Photomicrographs of Al 6063 composites: (a) 5 and (b) 10 wt. % TiB_2.

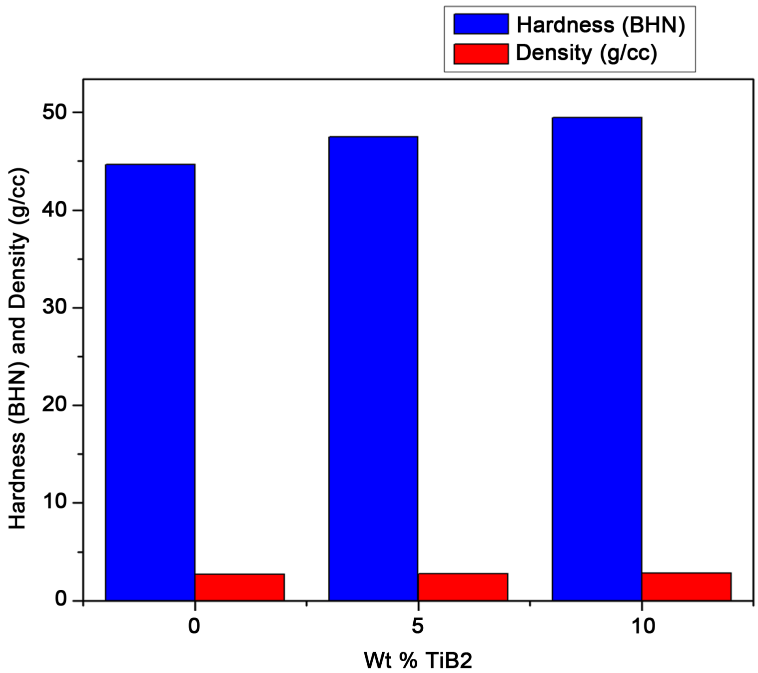


Figure 3. Density and hardness of TiB_2/Al 6063 composites.

was found in 10 wt% TiB_2 into aluminum composite. The increase in density indicates that particle breakage may not have any significant influence on the composites. It is believed to achieve an improvement of the bonding between the particle and matrix. The porosities of composites were evaluated from the difference between the expected and the observed density of each sample. The variations of porosity level in these composites are 1.3% and 1.5% for 5 and 10 wt% TiB_2 in aluminum composites respectively. The porosity level increased, since the contact surface area was increased.

3.3. Wear Rate

Dry sliding wear tests were conducted to assess the wear behavior of the TiB_2 reinforced with Al-6063 composite materials. The experiments were conducted using pin on disc wear testing machine by adopting 81 regular experiments for the 3 types of material containing 0, 5 and 10 wt% TiB_2 reinforced with Al-6063 composite materials.

The wear rate of the matrix alloy and the composites are shown as a function of load and wt% of TiB_2 in **Figure 4(a)** and **Figure 4(b)** respectively, it shows that for a constant sliding speed and constant load, the wear rate decreases as a function of TiB_2 reinforcement in the composites. The **Figure 4(a)** also shows that, the wear rate increases as the load increases for a particular composite. From the **Figure 4(b)**, the addition of 10 wt% TiB_2 to the matrix alloy decreases the wear rate for all type of loads. High hardness and the good bonding, lower the wear rates in the composites with high TiB_2 content [11].

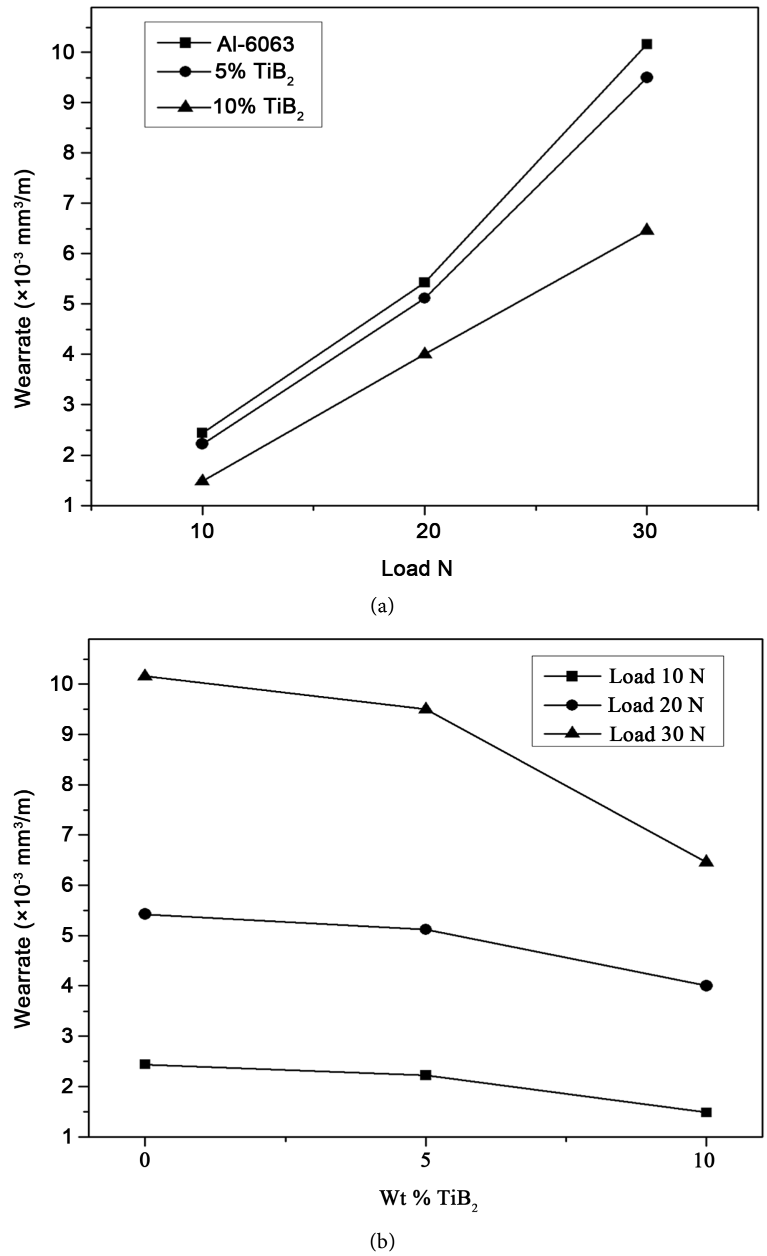
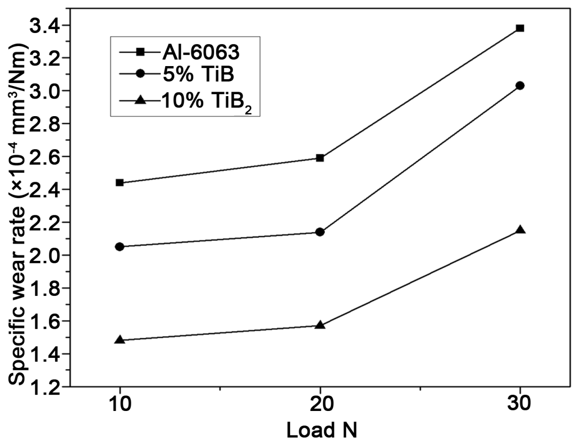


Figure 4. (a) Variation of wear rate with load for TiB_2/Al-6063 composites; (b) Variation of wear rate with content of TiB_2 reinforcement in Al-6063 matrix alloy.

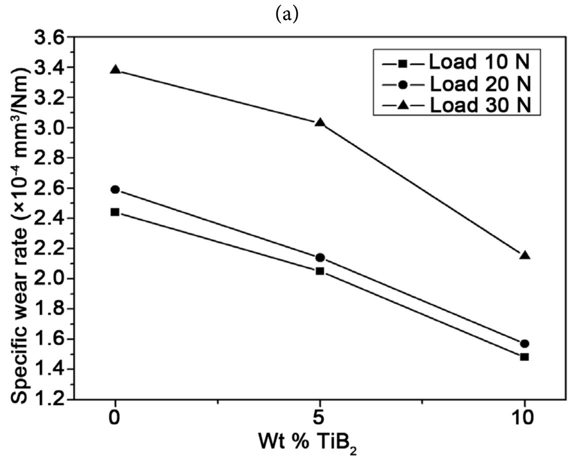
3.4. Specific Wear Rate

The specific wear rate of the matrix alloy and the composites are shown as a function of load and wt. % of TiB_2 in Figure 5(a) and Figure 5(b) respectively, defined as the volume of material worn per unit load. Figure 5(a) shows that the specific wear rate increases drastically at higher loads. Figure 5(b) shows specific wear rate decreases as the increase in wt. % TiB_2 particles in the composites and it decreases as the load increases due to work hardening. This significant improvement in the wear resistance of the TiB_2/Al-6063 composites can be attributed to the following factor:

1) The increase in the hardness of the Al 6063 with increase in the loading of TiB_2 reinforcement. The wear rate decreases with increase in hardness. Various researchers reported that the severity of adhesive wear greatly depends on the material hardness. Further, there is an experimental support and practical evidence to suggest that the onset of adhesive process, such as scuffing and seizure are reduced by increasing the hardness of the parts in contact.
2) Also, the excellent bonding between reinforcement and matrix as evidenced by SEM picture shown in Figure 2.



(a)



(b)

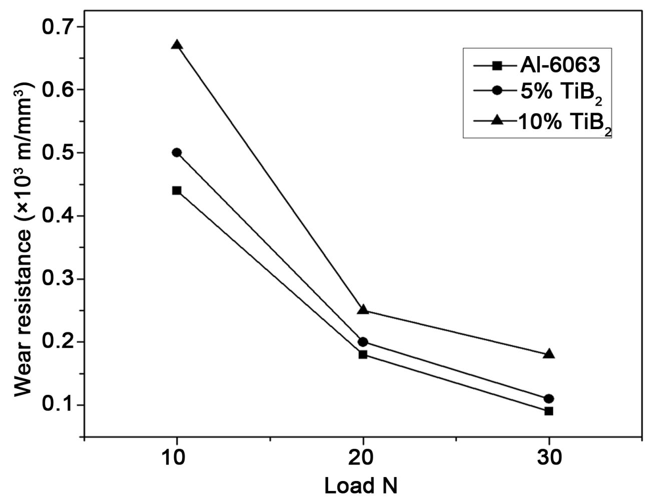
Figure 5. (a) Variation of specific wear rate with load TiB_2/Al-6063 composites; (b) Variation of specific wear rate with content of TiB_2 reinforcement in Al-6063 matrix alloy.

3.5. Wear Resistance

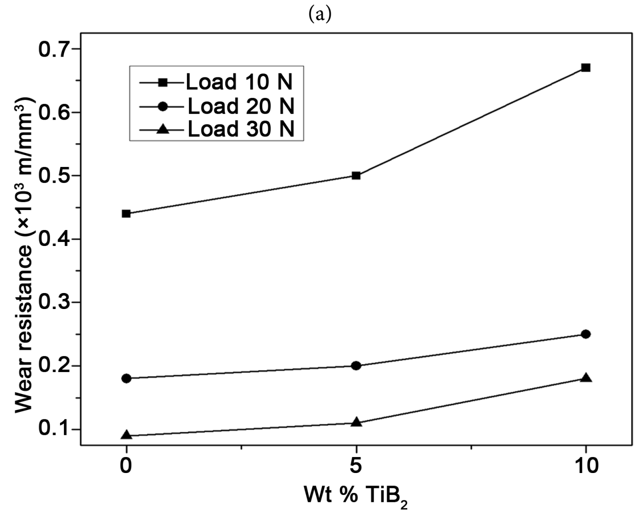
Figure 6(a) and Figure 6(b) shows the wear resistance, defined as the reciprocal of the wear rate, of the composites as a function of normal load and TiB_2 reinforcement, respectively. Figure 6(a) shows that the wear resistance decreases as the normal load increases and Figure 6(b) shows it increases as the wt% TiB_2 reinforcement in the composite increases.

3.6. Worn Surface Morphology

Dry sliding wear involves the transfer of material from one surface to another during relative motion due to a process of solid state welding, or wear due to localized bonding between contacting solid surfaces. Such type of wear leads to material transfer between two surfaces or loss from either surface. Thus, the SEM analysis of worn surfaces formed during the dry sliding wear in the steady state regime provides an important tool disseminate the wear behavior of the composites more accurately.



(a)



(b)

Figure 6. (a) Variation of wear resistance with load TiB_2/Al-6063 composites; (b) Variation of wear resistance with content of TiB_2 reinforcement in Al-6063 matrix alloy.

Figures 7(a)-(c) shows the microstructure of the TiB_2 reinforced Al-6063 alloy. From the figures, it is evident that TiB_2 particles are more or less disparesed uniformly in the Al-6063 matrix. The size of the TiB_2 particles ranges from 15 to 35 μm. It also seen from the figures that the TiB_2 reinforced Al-6063 composites are free from porosity and shrinkage cavity.

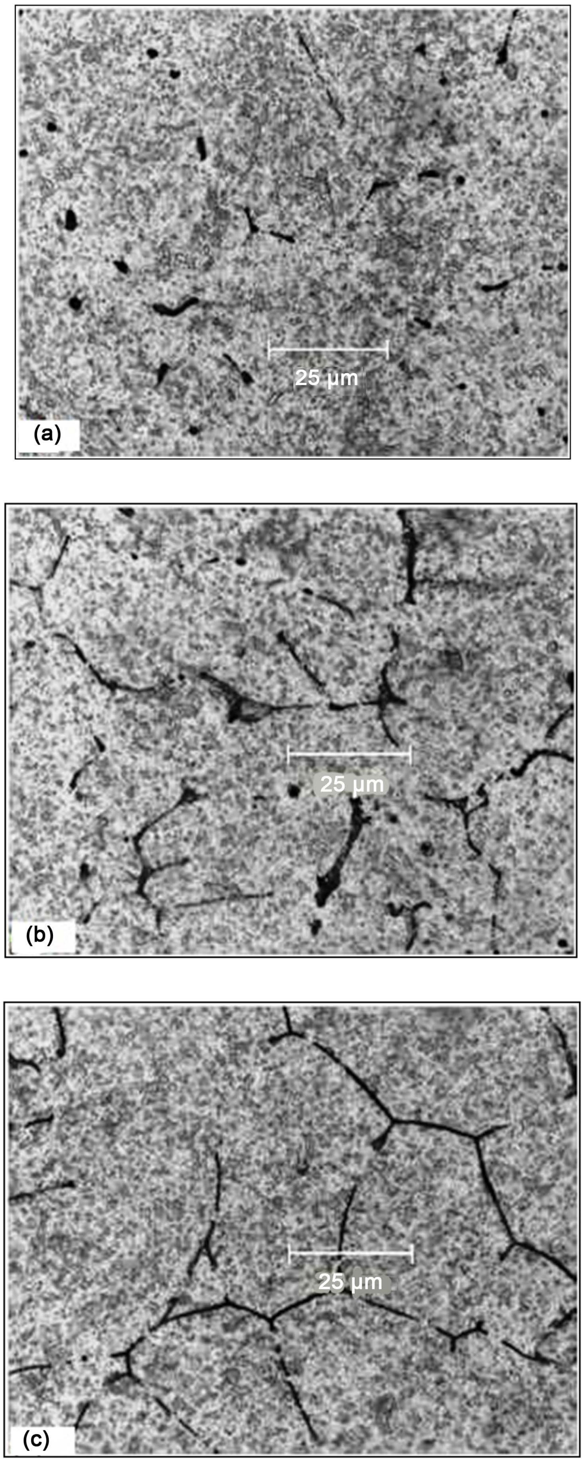
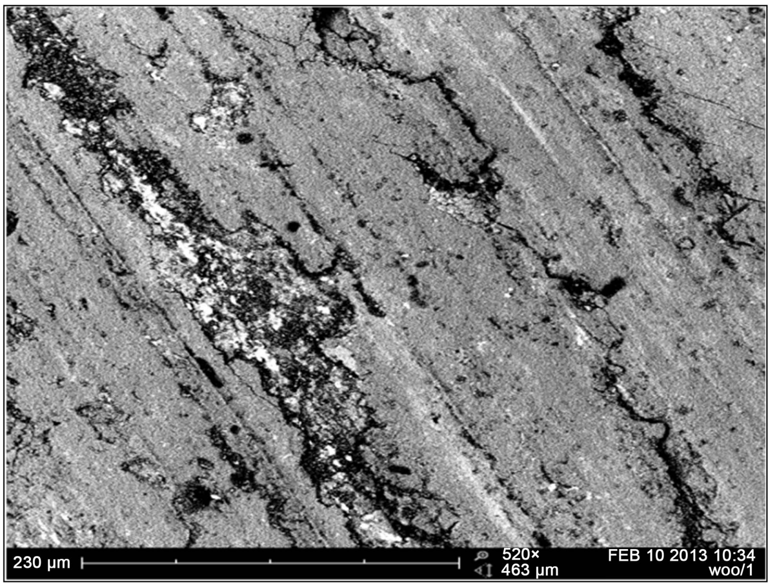


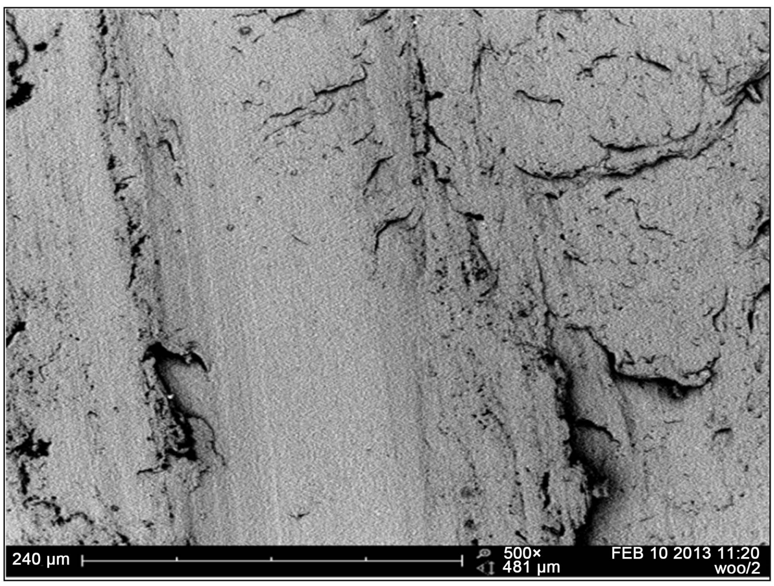
Figure 7. Microstructures of (a) Al-6063 alloy; (b) Al-6063/5% TiB_2 and (c) Al-6063/10% TiB_2.

For systematic analysis of the worn surfaces of neat alloy and its composites, selected photomicrographs at two different (low and high) loads and sliding velocities were examined using scanning electron microscopy. However, the same explanation holds good even for the other composites and its alloy with different sliding velocity and load.

The examination of the wear surfaces of the matrix alloy and composites reveal distinct pattern of grooves and ridges running parallel to the sliding direction as shown in Figures 8-13. The large amount of plastic deformation was observed on the surface of the neat alloy as shown in Figure 8. The degree of deformation is more pronounced as the load increases from 10 to 30 N at 0.5 m/s

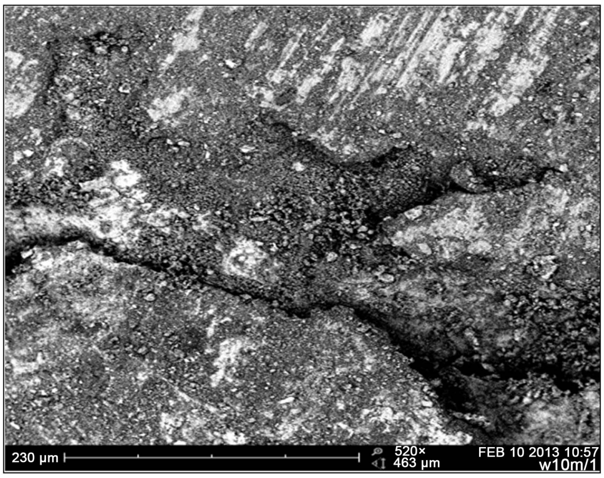


(a)

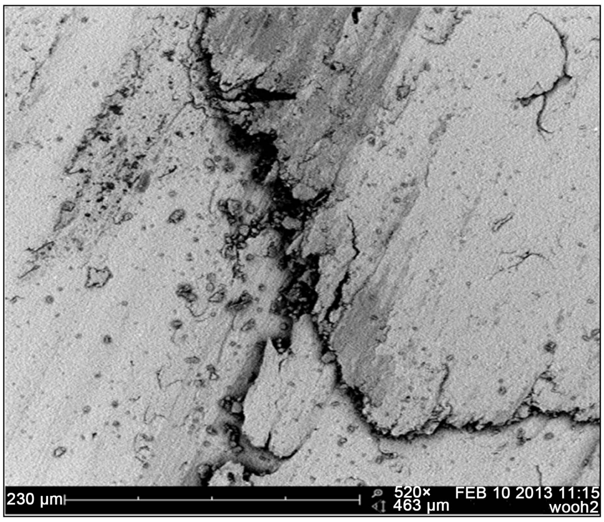


(b)

Figure 8. SEM photomicrographs of worn surfaces of Al-6063 alloy at 0.5 m/s (a) 10 and (b) 30 N.

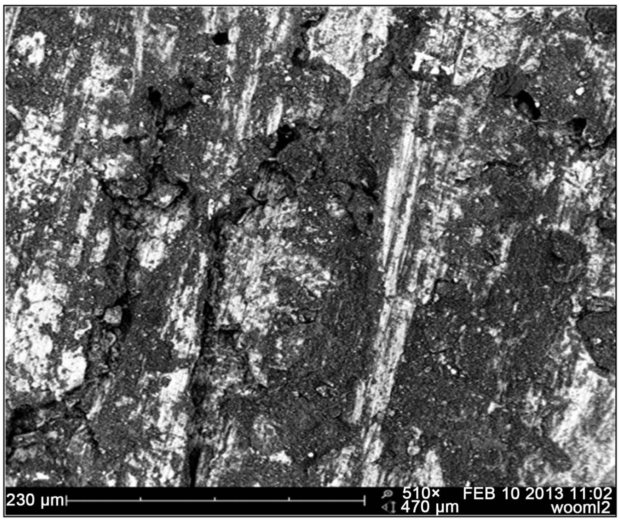


(a)



(b)

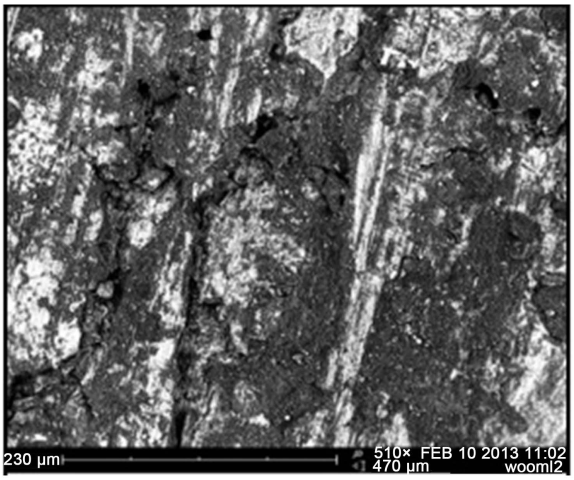
Figure 9. SEM photomicrographs of worn surfaces of Al-6063 alloy at 1.5 m/s (a) 10 and (b) 30 N.



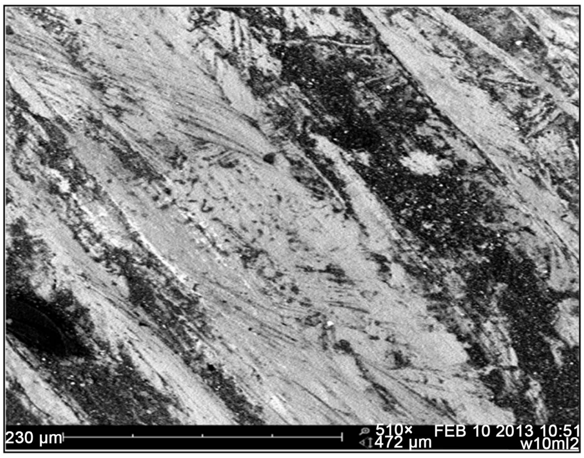
(a)

(b)

Figure 10. SEM photomicrographs of worn surfaces of Al-6063 with 5% TiB_2 at 0.5 m/s (a) 10 and (b) 30 N.

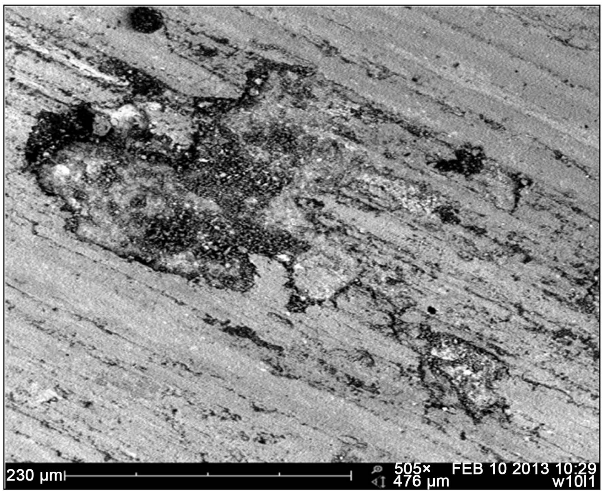


(a)

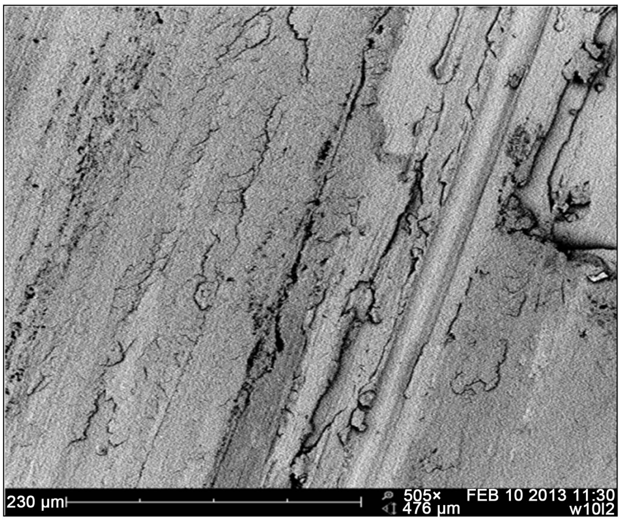


(b)

Figure 11. SEM photomicrographs of worn surfaces of Al-6063 with 5% TiB_2 at1.5 m/s (a) 10 and (b) 30 N.

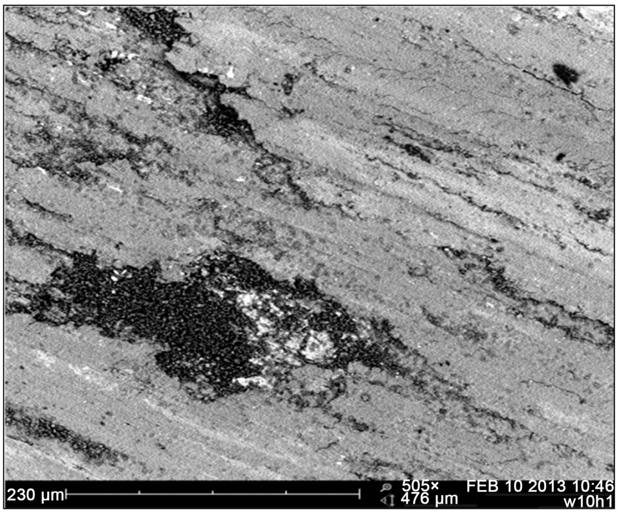


(a)

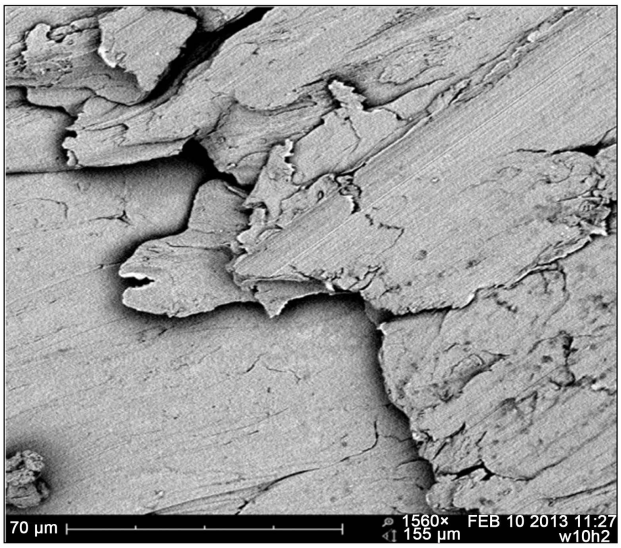


(b)

Figure 12. SEM photomicrographs of worn surfaces of Al-6063 with 10% TiB_2 at 0.5 m/s (a) 10 and (b) 30 N.



(a)



(b)

Figure 13. SEM photomicrographs of worn surfaces of Al-6063 with10% TiB_2 at 1.5 m/s (a) 10 and (b) 30 N.

(**Figure 8(b)**). At higher sliding velocity *i.e.*, 1.5 m/s leads to fisher cracks within the matrix (**Figure 9(a)**). They are consequential effect of high hardness because of alloying elements such as high silicon, Cr and Ti in pure aluminum and are originated from the sliding deformation. Under such conditions, tearing of the larger debris takes place and in the process, the TiB_2 particles adhered to the debris are being carried along, leaving behind large craters (**Figure 8(b)**). The grooves are deeper in the base alloy as compared to the composites tested under similar conditions(10 and 30 N loads and 0.5 m/s and 1.5 m/s), due to the absence of hard TiB_2 particle in the base alloy. The wear surface is rough in the base alloy as compared to composites.

The worn surfaces of TiB_2/Al-6063 composites exhibit a feather like structure. This worn surface is associated with plastic flow and adhesion effect, leading to a higher wear loss of composites slid at lower sliding velocity (0.5 m/s). However, the worn surface of these composites slid at higher velocity exhibits appearance of both smoother matrix region and rougher white patches. Some surface cracks are also evident from the photomicrographs as shown in **Figures 10-13** for 5 and 10 wt% TiB_2 reinforced Al matrix alloy respectively. According to the well known Archard's law of sliding wear, the volumetric wear loss of the specimen is inversely proportional to its hardness. In present investigation, addition of 10 wt. % of TiB_2 particles reinforced alloy leads to an increase in the hardness value thereby improving its wear resistance significantly. This is also well reflected from the wear data obtained from **Figures 4-6** and corroborates the worn surface features of composites.

4. Conclusions

Dry sliding wear tests using a pin-on-disc were conducted on TiB_2/Al-6063 composites. The contribution of the reinforcement content and the applied load as well as the sliding velocity on the wear process and the wear rate has been investigated. The following conclusions can be drawn from this study: Micro-structural examination showed that the dispersion of TiB_2 particles is more or less uniform and lower interface porosity.

1) Hardness of the aluminum alloy improved significantly by adding up of TiB_2 particles into Al-6063 alloy, while density of the composite also increased almost linearly with the weight fraction of particles.
2) The effect of the wt% of reinforcement found to be different for initial wear and the steady-state wear.
3) Sliding wear test results showed that wear rate increases as the increase in the applied load and increase in the sliding velocity. But as the TiB_2 reinforcement with the Al-6063 composite increased, the wear rate is decreased with increasing applied load and sliding velocity.
4) The specific wear rate of the composite decreases with the increase in both applied load and the TiB_2 particle reinforcement with the Al-6063 composite materials.
5) The wear resistance of Al-6063 alloy is improved by the addition of TiB_2 particle and it further increases as the addition TiB_2 particle in the composite material increases and it will be maximum for 10 wt% TiB_2.
6) The grooves are deeper in the base matrix alloy due to the absence of TiB_2 particle and provide smooth surface compared to composites.
7) Less damage of surface cracks observed in the higher reinforced composite compared to matrix alloy.
8) 10 wt% TiB_2 reinforced Al-6063 composite material posses higher wear resistance and less wear rate, hence it is hard and strong materials compared with matrix and 5 wt% TiB_2 reinforced Al-6063 composite material.

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