CHAPTER 5

TRIBOLOGICAL CHARACTERISTICS OF STIR CAST A356-Mg_2Si-TiB_2 HYBRID COMPOSITE

5.1 INTRODUCTION

A good combination of wear resistance and coefficient of friction is crucial requirements for present day components of automotive and aerospace industry. If we consider composite materials then their composition, dispersion of reinforcements in the composite and their morphology are key factors affecting the tribological properties.

The present chapter deals with the investigation of tribological properties of stir cast A356/10Mg_2Si-xTiB_2 composites in dry sliding condition. Tribological behaviour has been studied at various input variables like sliding distance, applied load, sliding velocity and wt.% of TiB_2. Worn surfaces have been examined under SEM with EDS and AFM. Debris analysis has also been done by SEM and EDS. Obtained results have been correlated with the worn surface topography.

5.2 WEAR & FRICTION BEHAVIOR UNDER DRY SLIDING

5.2.1 Influence of Sliding Distance

Figure 5.1 (a-d), 5.2 and 5.3 (a-d) present influence of sliding distance on wear volume, wear rate and COF respectively for A356 alloy and A356-10Mg_2Si composites and A356-10Mg_2Si-xTiB_2 hybrid composite with varying TiB_2 content at various loads of 10 N to 40 N. Fig. 5.1 indicates that wear volume increases linearly up to the 3000m of sliding distance after that it increases slightly with higher rate at lower loads.

Which may be due to the domination of adhesive component of wear leading to sticking of surface with time /sliding distance. Whereas, at higher applied loads with sliding distance, interfacial temperature of pin surface increases due to frictional heating during sliding. In this scenario, asperities of soft matrix phase may deform and contact points are only hard particles which may restrict the wear to a lower level as observed in case of higher load in Fig. 5.1 (d). Therefore, it can be clearly understood that on addition of second reinforcement particles, steady state wear is attained much earlier, which may be due to decrease in adhesive forces on reinforcement of hard particles.

Figure 5.2 depicts the influence of sliding distance on wear rate of composites at 30 N load. It reveals that wear rate initially decreases as the sliding distance increases, but beyond 3000 m the wear rate of alloy and single reinforced composites begins to increase, whereas hybrid composites gradually stabilize and steady-state wear is achieved. Fig. 5.3 shows the influence of sliding distance on COF of matrix alloy and composites. The figure clearly indicates that COF varies with sliding distance, which can be associated with adhesion between the mating surfaces. The surface temperature of pin contact increases as the sliding distance increases, resulting in surface oxidation. Therefore, formation and rupture of oxide layer fluctuate the COF. However, COF of composites get more or less stabilized at higher applied loads after moving certain distance as shown in Fig. 5.2 (d). Liu S et al. and Chourasiya et al. have also reported similar results [119, 126].

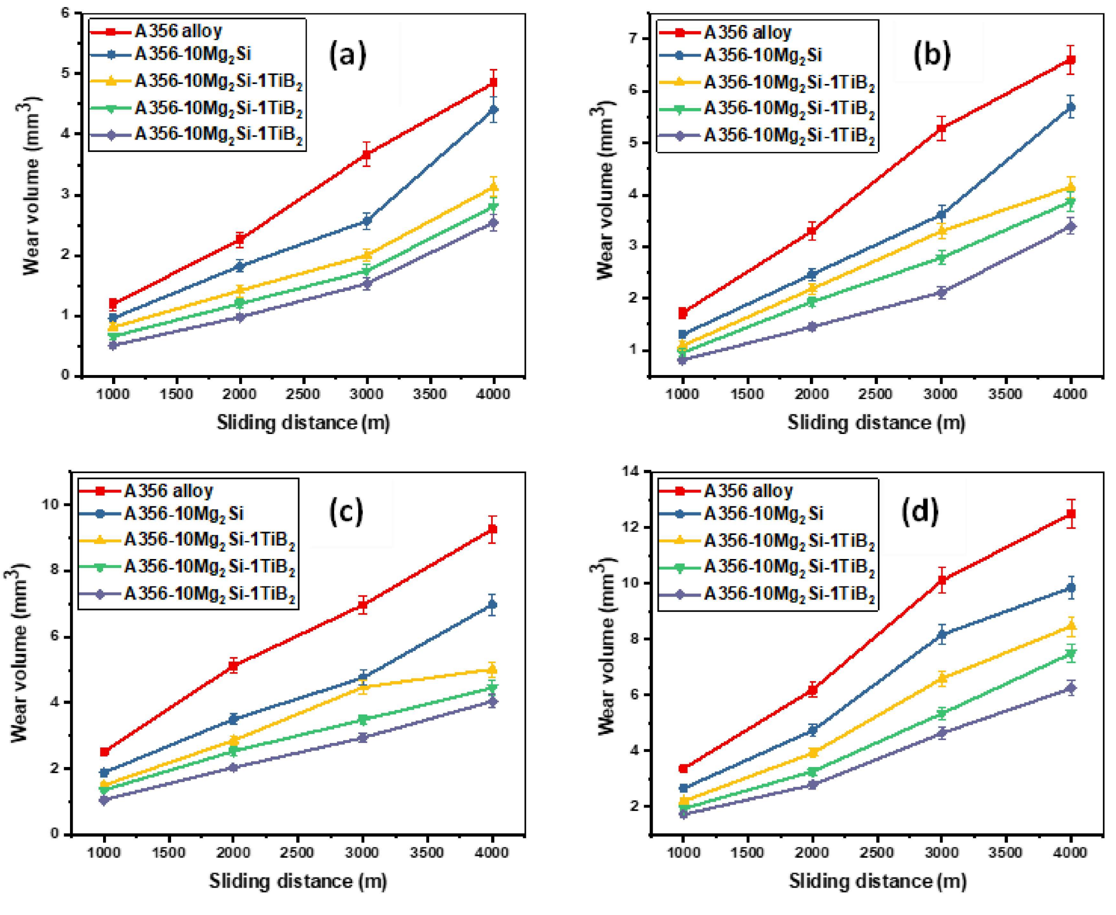


Fig. 5.1 Influence of sliding distance on wear volume at various applied loads (a) 10 N (b) 20 N (c) 30 N (d) 40 N

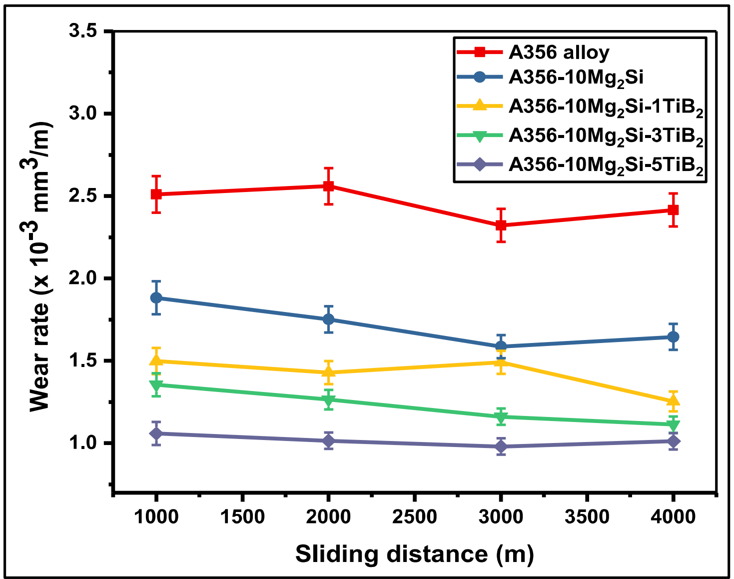


Fig. 5.2 Influence of sliding distance on wear rate at a fixed applied load of 30 N

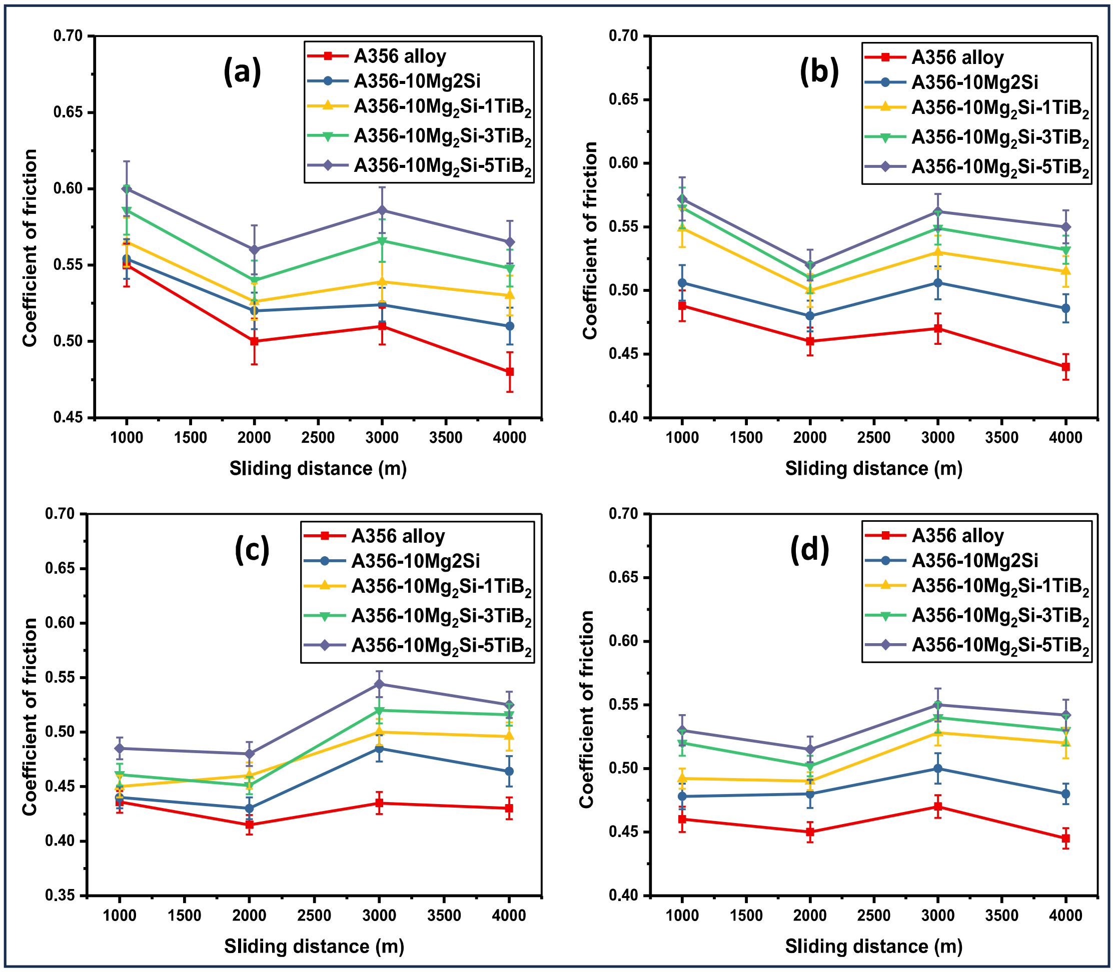


Fig. 5.3 Influence of sliding distance on COF at various applied loads (a) 10 N (b) 20 N (c) 30 N (d) 40 N

SEM with EDS and AFM were used to examine the worn surface of composites in order to better understand the wear mechanism. The influence of sliding distance at 30 N load is presented in Figs. 5.4 to 5.5 for A356-10Mg_2Si-3TiB_2 hybrid composites. Figures 5.4 (a-d) depicts the SEM image of worn surfaces of hybrid composite A356-10Mg_2Si-3TiB_2 with varying sliding distance of 1000 m-4000 m. It is evident that at lower sliding distance, the worn surface exhibit shallow ploughing and less amount of delamination, however, at higher sliding distance, the worn surface shows the large amount of delaminating, deep ploughing, wear debris and cracks. During sliding wear, there is rise in temperature at the interface of material pair (composite pin sample and counter face) and that softens the composite pin sample surface. So, at the less sliding distance, due to lesser rise in temperature surface is comparatively less soft and the deformation by the hard asperities of the counter steel disc is less, that is why the worn surface shows the less amount of delamination and the shallow ploughing. However, at the high sliding distance, the condition is different. The interfacial temperature is high and the composite pin sample is softer and the deformation by the hard asperities of the counter steel disc is more which results the surface features are extensively affected at high sliding distance. These features of worn surfaces are also in agreement with the wear results.

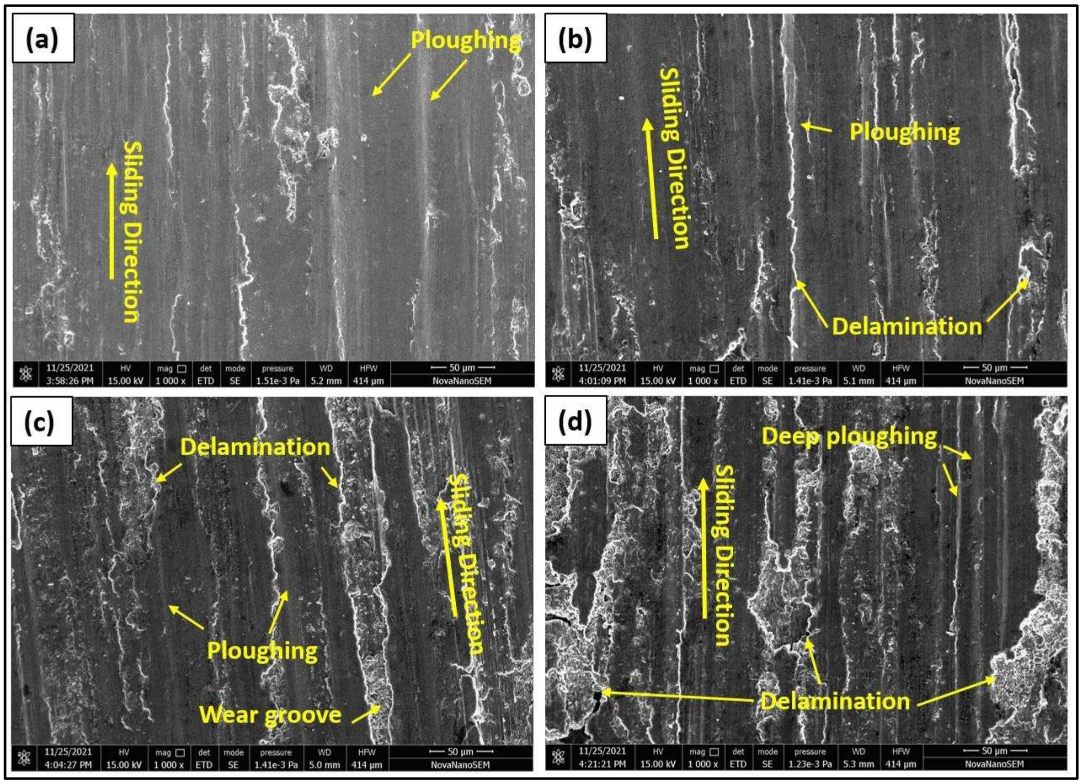


Fig. 5.4 SEM images of worn surface of A356-10Mg_2Si-3TiB_2 hybrid composite at load of 30 N and sliding distance of (a) 1000 m (b) 2000 m (c) 3000 m (d) 4000 m

Figure 5.5 displays the AFM image of worn surface of A356-10Mg_2Si-3TiB_2 with changing sliding distances at 30 N load. The micrograph clearly indicates that increasing the sliding distance from 1000 m to 4000 m increases the peaks and valleys height from 2 µm to 4 µm. These findings are consistent with those made in SEM micrographs of worn surfaces at various sliding distances, indicating that wear of composite increases with increasing sliding distance.

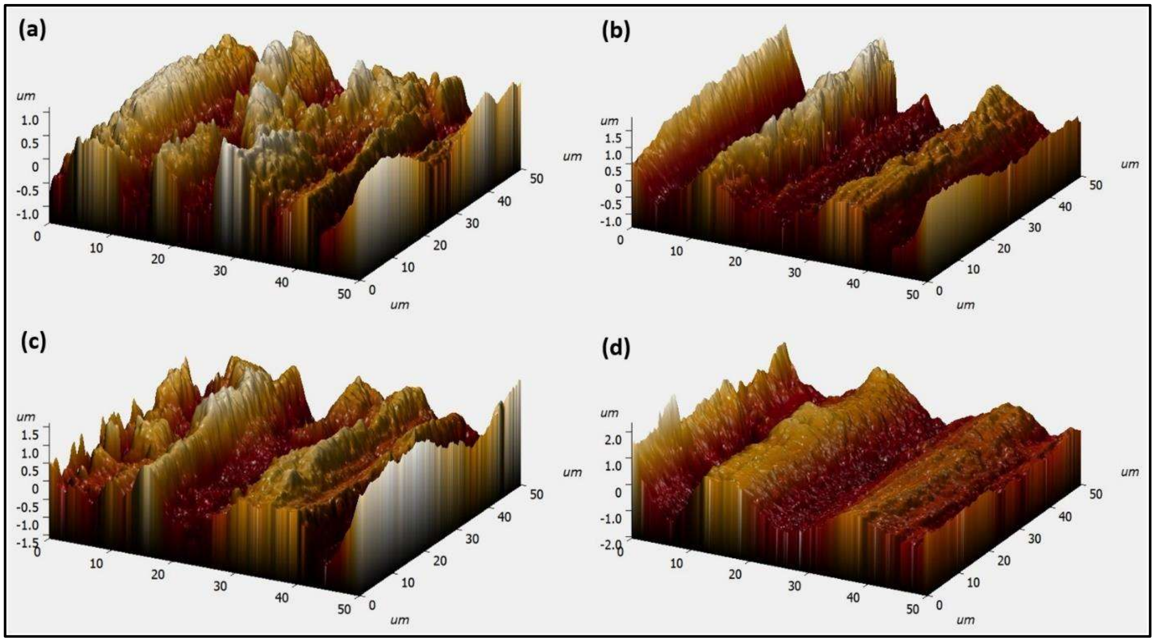


Fig. 5.5 AFM image of A356-10Mg_2Si-3TiB_2 hybrid composite at 30 N load and sliding distance of (a) 1000 m (b) 2000 m (c) 3000 m (d) 4000 m

5.2.2 Influence of Load

Figures 5.6 (a-d) and 5.7 (a-d) present the effect of applied loads on wear rate and COF of A356-10Mg_2Si-xTiB_2 composites at different sliding distance 1000 m - 4000 m. It indicates that with the increase of applied loads wear rate rises for A356 alloy and composites. Wear rate increases steadily up to 30 N load and beyond that it increases slightly. However, the value of COF decreases continuously up to 30 N load and get minima followed by increase with further increase in load. This trend is exhibited by all compositions. On applied load variation, there is interaction between hard asperities of EN31 disc surface and a soft asperity of fabricated composite surfaces occurs. At lower loads, the contact between the asperities of both surfaces is less and results in lower wear rate. However, at the high load, this interaction is high and ploughing and fragmentation of materials occurs and results in increased wear rate [115]. Temperature of composite pin samples also rises with increase of applied loads resulting in development of an oxide layer on pin surface that restricts metal to metal contact. This oxide layer decreases the COF up to 30 N load as shown in Fig. 5.7. With further increase in applied load, oxide film deforms, breaks and metal contact is exposed, increasing the COF and wear rate especially at high loads. However, in hybrid composite, interaction between hard particles and asperities of counter face may also form a MML between the surfaces which decreases COF and wear rate[127]. This MML layer remains maintained up to 30 N load, and beyond that it breaks and wear and COF increase. Thus, wear properties of hybrid composites are better than A356 alloy and single reinforced composite.

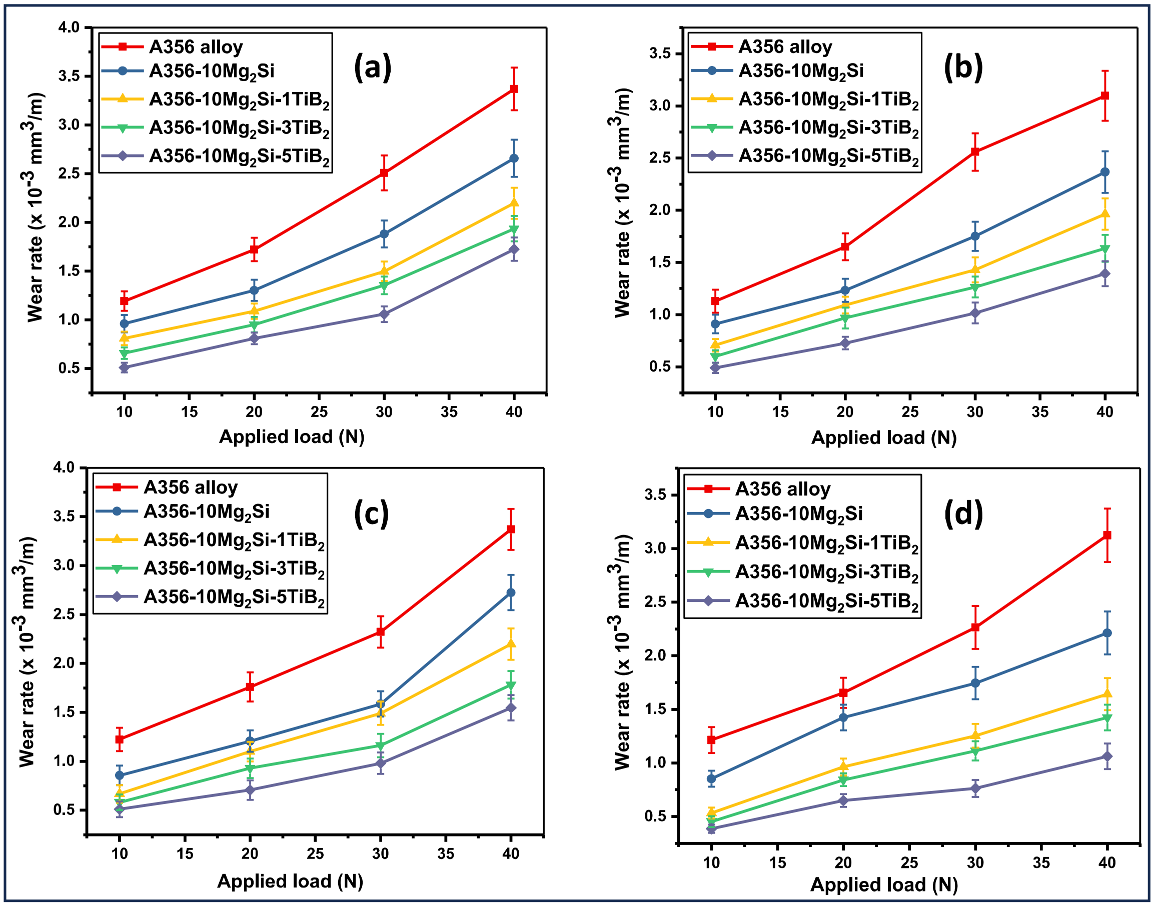


Fig. 5.6 Influence of applied load on wear rate at sliding distance of (a) 1000 m (b) 2000 m (c) 3000 m (d) 4000m

Figures 5.8 presents the influence of applied load on specific wear rate of A356 alloy and A356-Mg_2Si-TiB_2 hybrid composites. Figure clearly shows that initially specific wear rate is high because of interaction of asperities on contact surfaces. However, with increase of the applied load surface temperature of the pin surface increases and an oxide layer is formed which reduces the surface contacts ultimately decreases the specific wear rate. At high applied loads, cracks are generated in the formed oxide layer and get detached which increases the specific wear rate. However, the increase in the specific wear rate of hybrid composites is much lower than that of alloy and single reinforced composites due to their higher hardness and strength, which is in line with Archard's wear law.

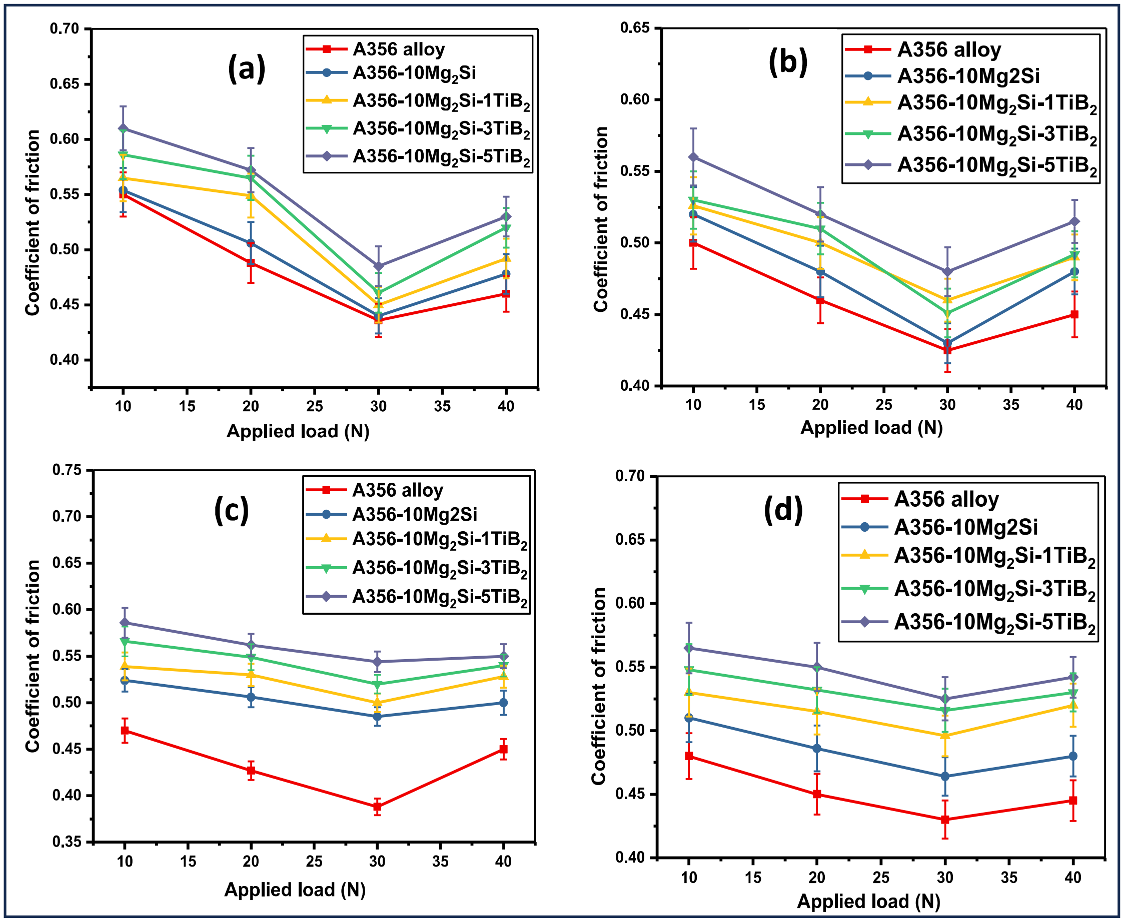


Fig. 5.7 Influence of applied load on COF at sliding distance of (a) 1000 m (b) 2000 m (c) 3000 m (d) 4000 m

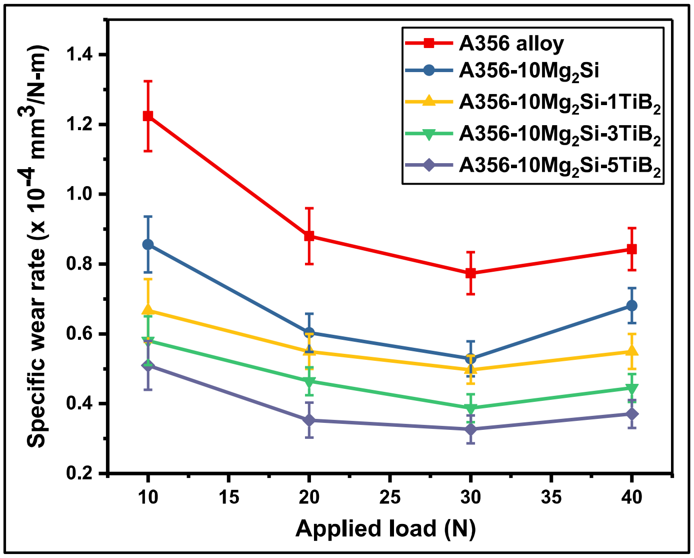


Fig. 5.8 Influence of applied load on specific wear rate at sliding distance of 3000m

Worn surfaces of hybrid composite A356-10Mg_2Si-3TiB_2 under different loads are presented in Figs. 5.9 (a-d). With rise of applied load from 10 N to 40 N, worn surfaces of hybrid composite changes from shallow ploughing to deep ploughing and subsequently, plastic deformation and delamination occur. It is also observed that severe delamination occurs when applied load is more than 30 N. However, hybrid composite can resist delamination even at higher load of 30 N. Large deformation of composites during sliding wear results in crack nucleation especially at the site of reinforcement particles. Voids are formed during plastic deformation of matrix around the reinforcement particles. Some of these cracks and voids, propagate to the surface and start fragmenting causing delamination [128]. Severe wear regime is started beyond 30 N of applied load owing to the higher contact area of mating surfaces at higher load. Higher friction heat generated at higher load softens the matrix phase that leads to higher penetration of hard asperities on disc surface increasing the wear rate[120]. EDS analysis is also carried out to understand the changes takes place during sliding. Fig. 5.10 (a-b) present the SEM image of worn surface and EDS spectra of the whole area of micrograph of A356-10Mg_2Si-3TiB_2 hybrid composite. It confirms the formation of the MML layer by indicating that the worn surface includes a layer including Fe and O in addition to Al, Si, Mg, Ti, and B. The existence of MML lowers the COF and wear rate [129].

Figure 5.11 displays the AFM images of worn surfaces to further analyse worn surfaces to measure the unevenness of worn surface which consists of peaks and valleys. The figure demonstrates that increasing the applied load from 10 N to 40 N increases peaks and valley height from 2 µm to 4 µm. This can be due to the increasing wear rate with applied load as surface roughness increases. This is also aligned with the results of wear rate.

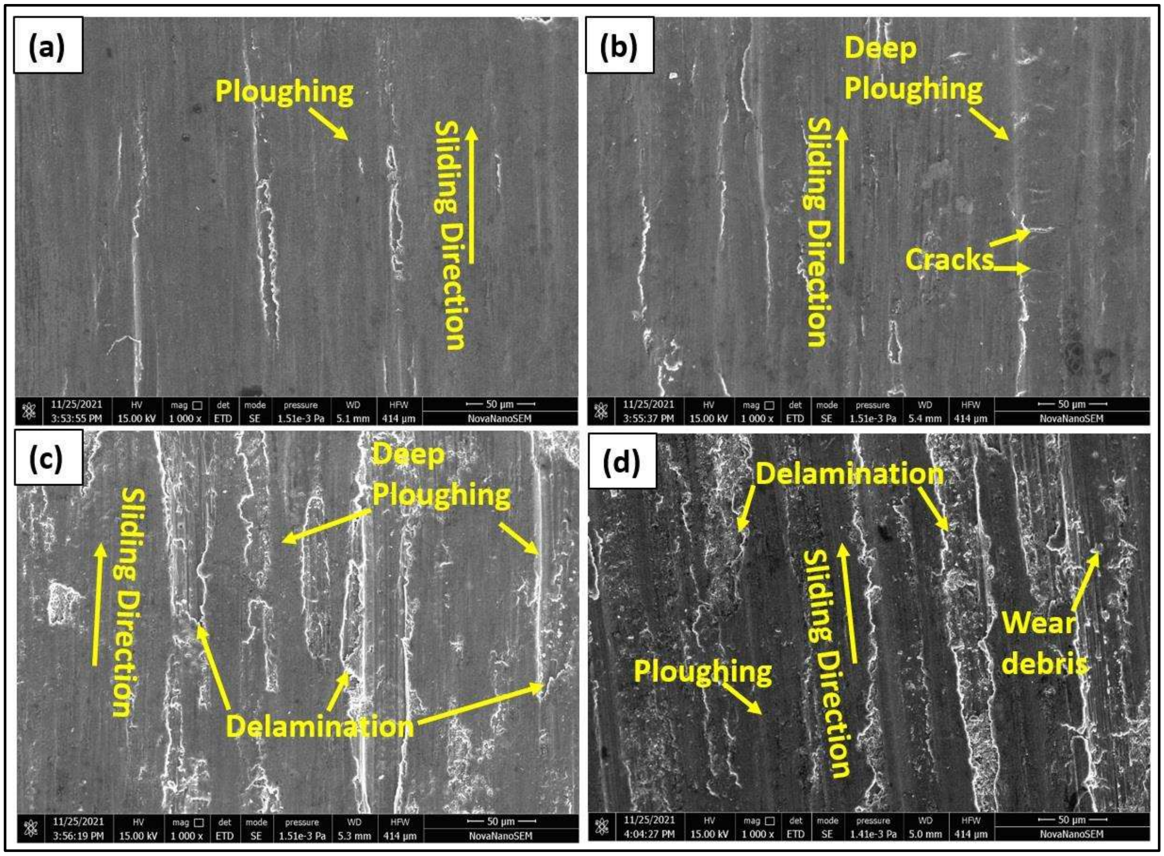
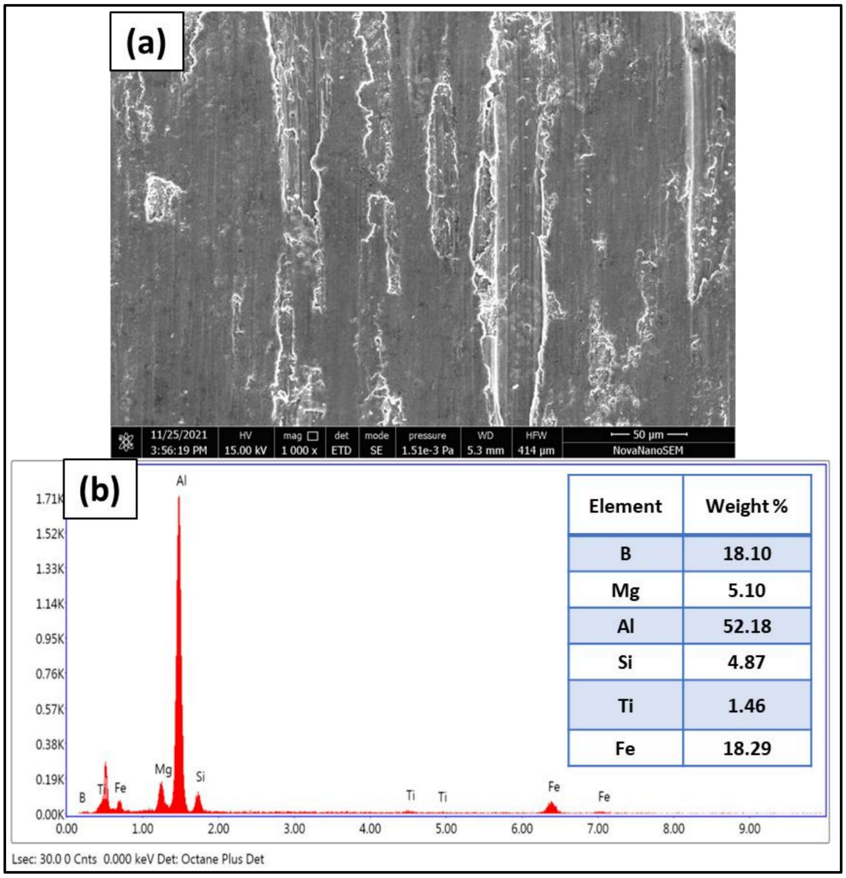


Fig. 5.9 SEM images of worn surface of A356-10Mg_2Si-3TiB_2 hybrid composite at 3000 m of sliding distance and applied load of **(a)** 10 N **(b)** 20 N **(c)** 30 N **(d)** 40 N



Element	Weight %
B	18.10
Mg	5.10
Al	52.18
Si	4.87
Ti	1.46
Fe	18.29

Fig. 5.10 **(a)** SEM image of hybrid composite (C3) worn surface at applied load 30 N, **(b)** EDS spectrum of whole area of SEM image.

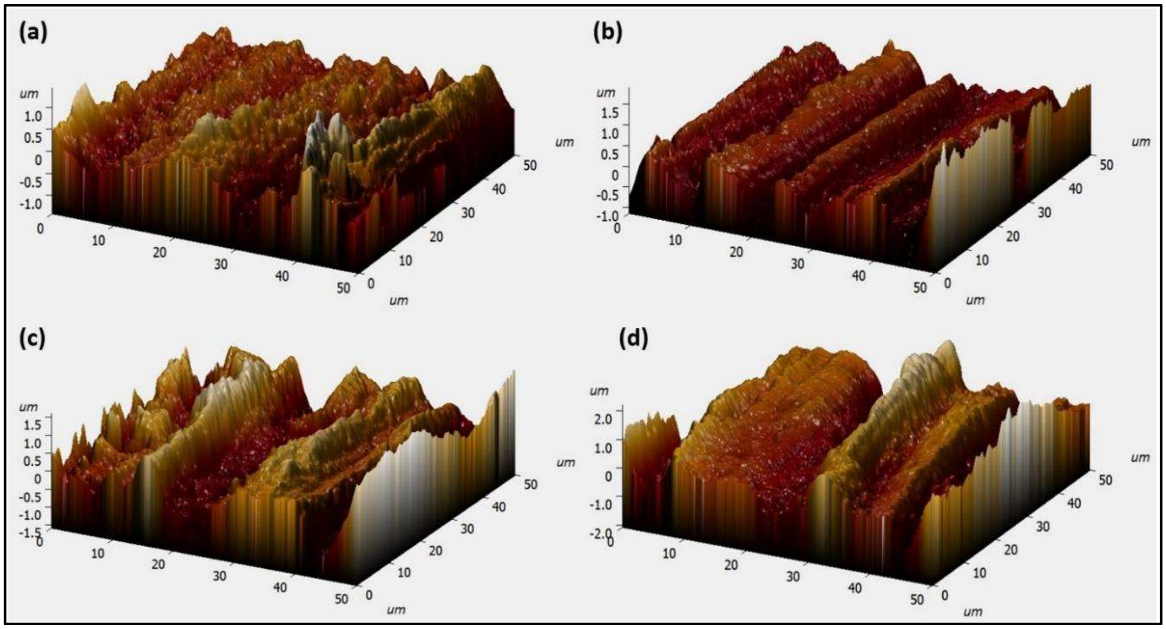


Fig. 5.11 AFM image of A356-10Mg_2Si-3TiB_2 hybrid composite at 3000 m of sliding distance and applied load of **(a)** 10 N **(b)** 20 N **(c)** 30 N **(d)** 40 N

5.2.3 Influence of Sliding Velocity

Figure 5.12 (a-d) presents the effect of sliding velocity on wear rate at various applied loads. The figure indicates that the wear rate increases as the sliding speed increases from 0.75 m/s to 3 m/s for all compositions. This can be caused by an increase in temperature which softens the pin surface resulting in higher wear rate. The wear rate of hybrid composites was significantly less compared to that of single-reinforced composites. The development of an oxide film on pin surface of the composite owing to temperature rise at higher sliding velocity leads to reduction in delamination. Whereas, in case of alloy due to softening of matrix phase of oxide layers become unstable thus wear rate increases.

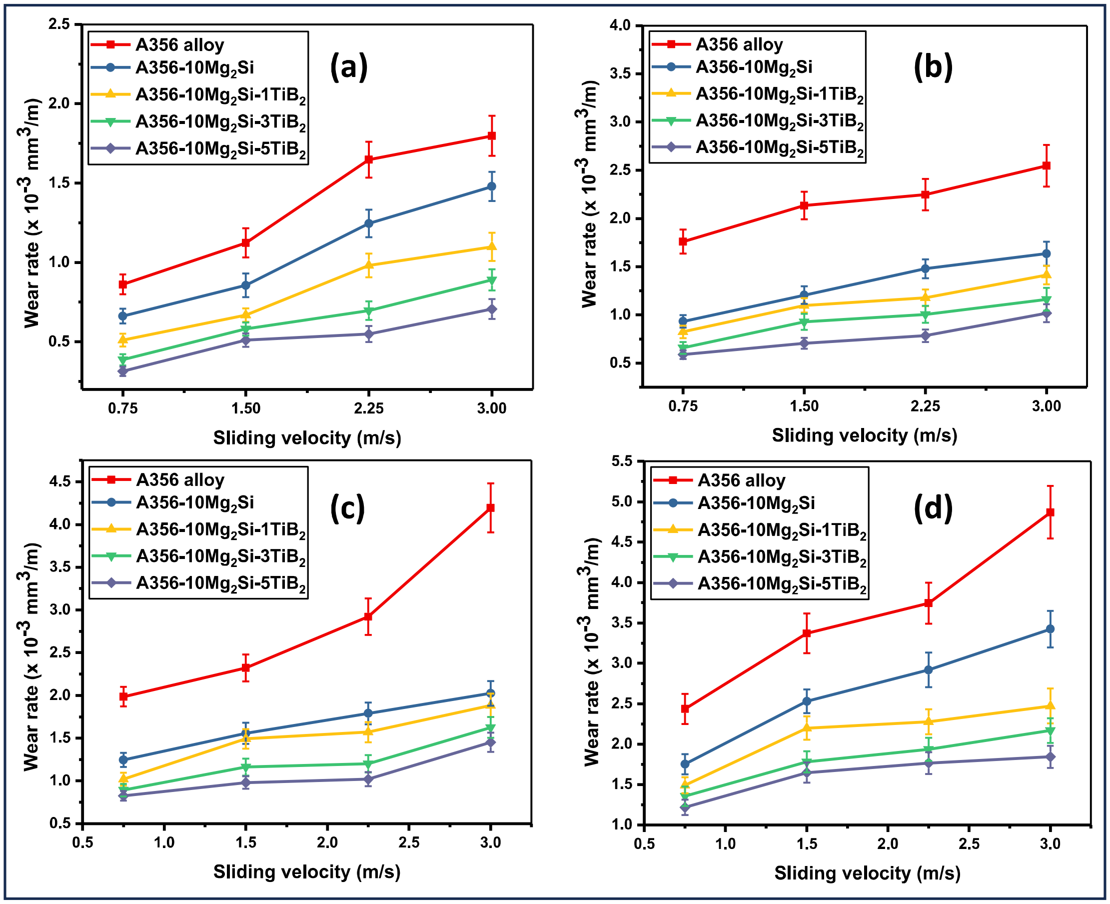


Fig. 5.12 Influence of sliding velocity on wear rate at sliding distance of 1000 m and different applied loads (a) 10 N (b) 20 N (c) 30 N (d) 40 N

Sliding velocity also affects the COF as displayed in Fig 5.13. The figure clearly presents that the COF of alloys and composites decreases with increasing sliding velocity under all applied loads. Due to the gradual increase in temperature, a thin oxide layer developed on pin surface at low sliding velocity, which breaks after a certain sliding distance. Thus, COF decreases slightly at lower sliding velocity. However, pin temperature rises rapidly at higher sliding speeds, develops a thick oxide film on pin surface of the hybrid composite, considerably reducing the COF in hybrid composites. Whereas in alloys reduction of COF is lower than the hybrid composites.

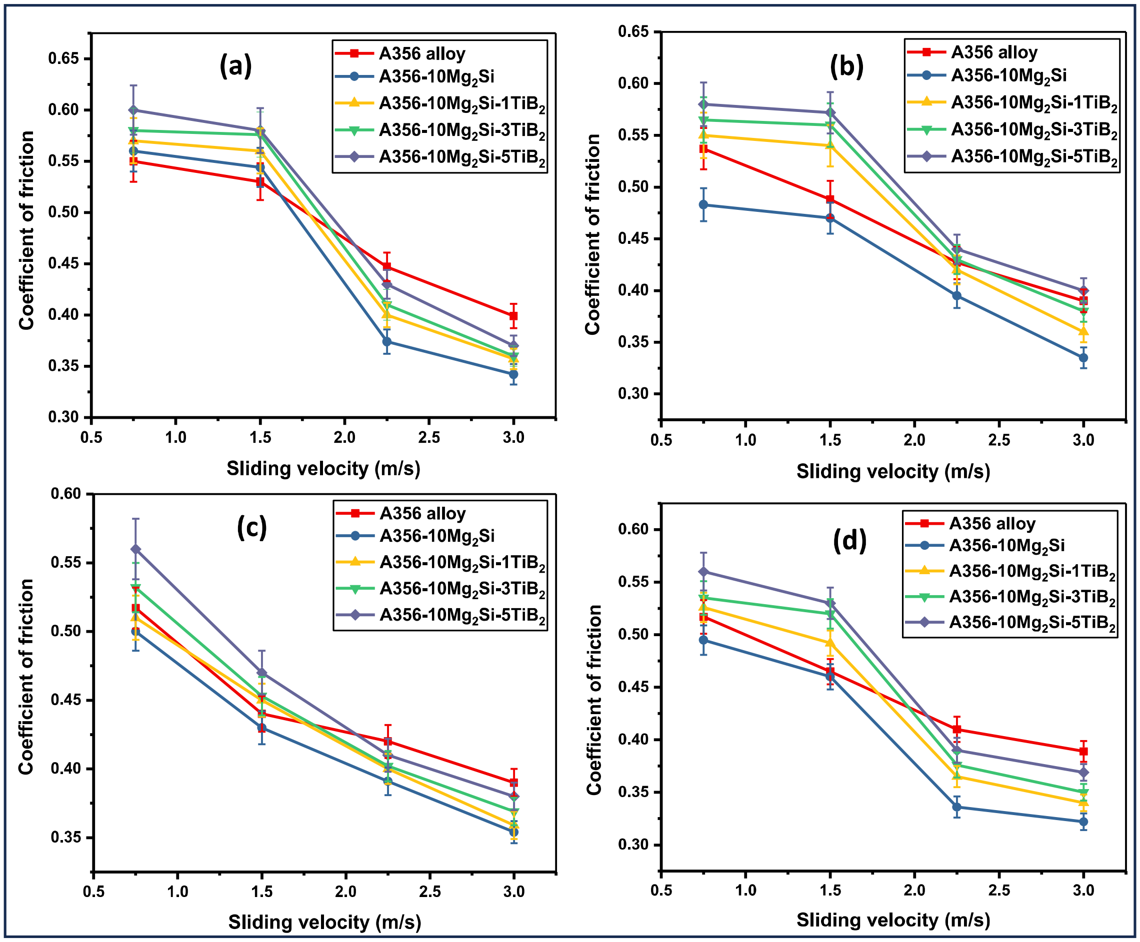


Fig. 5.13 Influence of sliding velocity on COF at sliding distance of 1000 m and different applied loads **(a)** 10 N **(b)** 20 N **(c)** 30 N **(d)** 40 N

Worn surfaces of hybrid composite A356-10Mg_2Si-3TiB_2 under different sliding velocity in range of 0.75 m/s to 3 m/s are presented in Figs. 5.14 (a-d). It is evident that at lower sliding speed dominant wear mechanism is abrasive wear because of smooth surface with shallow ploughing and very less delamination observed as presented in Fig. 5.13 (a). With increase of sliding speed, ploughing become deeper and delamination increases and dominant wear mechanism is delamination as shown in Figs 5.13 (b-d). This can be due to the large frictional heat generated results in higher wear rate.

Figure 5.15 (a-d) displays 3D AFM images of worn surfaces of hybrid composite A356-10Mg_2Si-3TiB_2 at various speed ranges of 0.75 m/s to 3 m/s. Peak to valley height increases from 2.5 µm to 4 µm with increasing sliding velocity from 0.75 m/s to 3 m/s. This can be owing to the deep ploughing and large delamination at high sliding speed increasing the surface roughness.

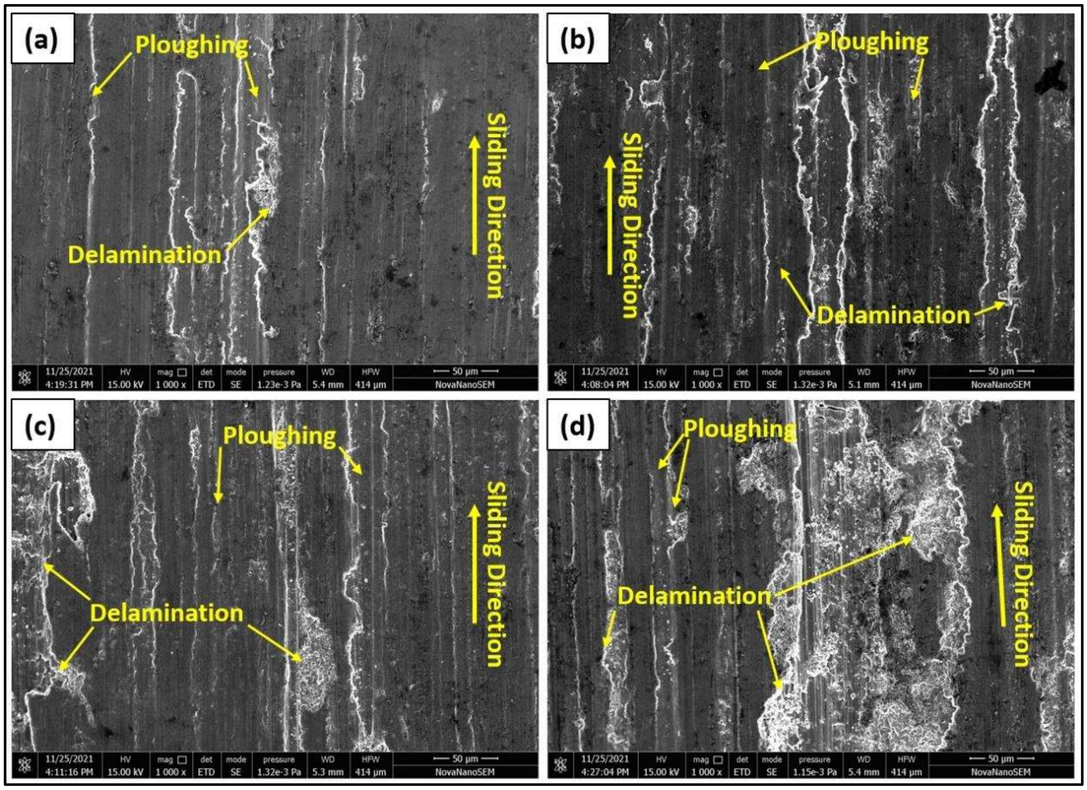


Fig. 5.14 SEM image of worn surface of A356-10Mg_2Si-3TiB_2 hybrid composite at 30N applied load and different sliding speed of (a) 0.75 m/s (b) 1.5 m/s (c) 2.25 m/s and (d) 3 m/s

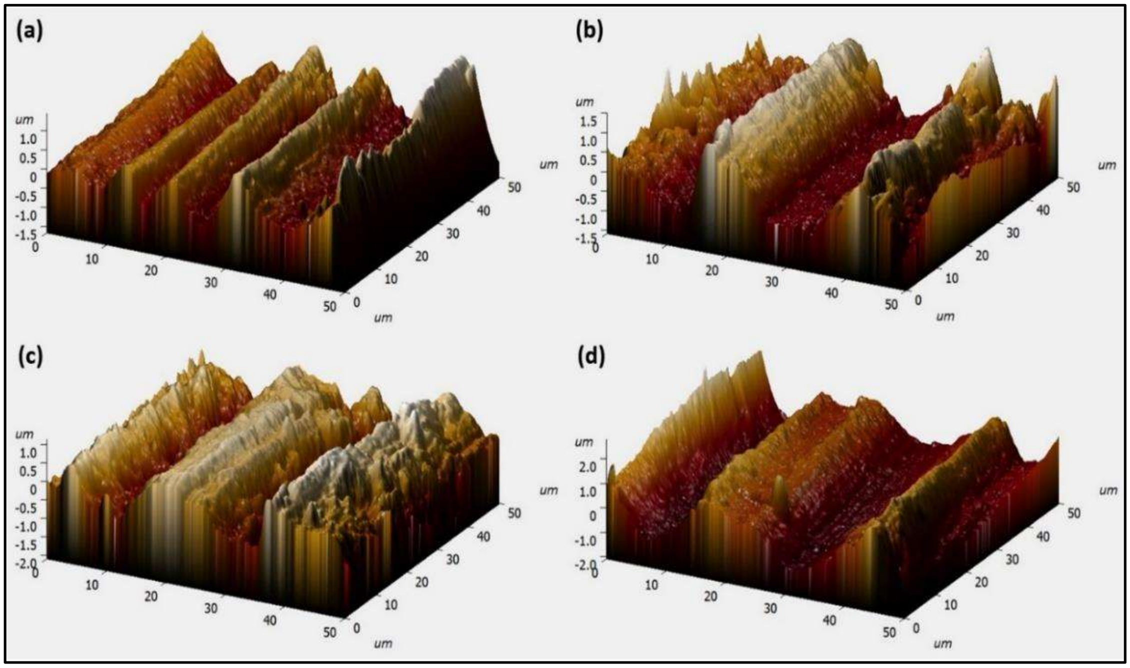


Fig. 5.15 AFM image of A356-10Mg$_2$Si-3TiB$_2$ hybrid composite at sliding speed of (a) 0.75 m/s (b) 1.5 m/s (c) 2.25 m/s (d) 3 m/s

5.2.4 Influence of TiB$_2$ Content

Figures 5.16 and 5.17 presents the influence of TiB$_2$ amount on wear rate and COF. Fig. 5.16 shows that the wear rate in composites is much lower than A356 alloy. It is decreasing continuously with increase of TiB$_2$ phase in the composites and maximum decrease in wear rate is observed in the composite of A356-Mg$_2$Si with 5wt.% TiB$_2$ particles. While, the COF showed the trends which was contrary to wear rate. That means the COF value is high in composites than the base alloy and it continuously increases with the TiB$_2$ particles in hybrid composites as presented in Fig. 5.17. Maximum value of COF is observed in the A356-Mg$_2$Si-5TiB$_2$ hybrid composite. The reduction in wear rate could be owing to various factors. First, refinement of Mg$_2$Si phase as the TiB$_2$ particle acts as heterogeneous nucleation site for the Mg$_2$Si phase. Another, TiB$_2$, itself increases the dislocation density, refines matrix phase increases grain boundary region and results in increasing the hardness and ultimately enhancing the load bearing capacity and wear properties [130]. Moreover, the presence of evenly dispersed refined Mg_2Si phase and TiB_2 particles which acts as load-bearing phase protect matrix phase. These particles lower the surface contact between matrix and disc during dry sliding process. The insitu formed reinforcement particles have a clean interface and good bonding with base alloy and reduce particle detachment and wear rate. The dissimilarity in thermal coefficient of base material and reinforcing materials create a strain field in the composite [91]. These strain fields decrease the crack propagation rate, ultimately decreasing the wear rate of hybrid composite. These things are strengthened with increase of TiB_2 particles content. However, the COF increases owing to increase in the particle contribution during wear of the composites[131].

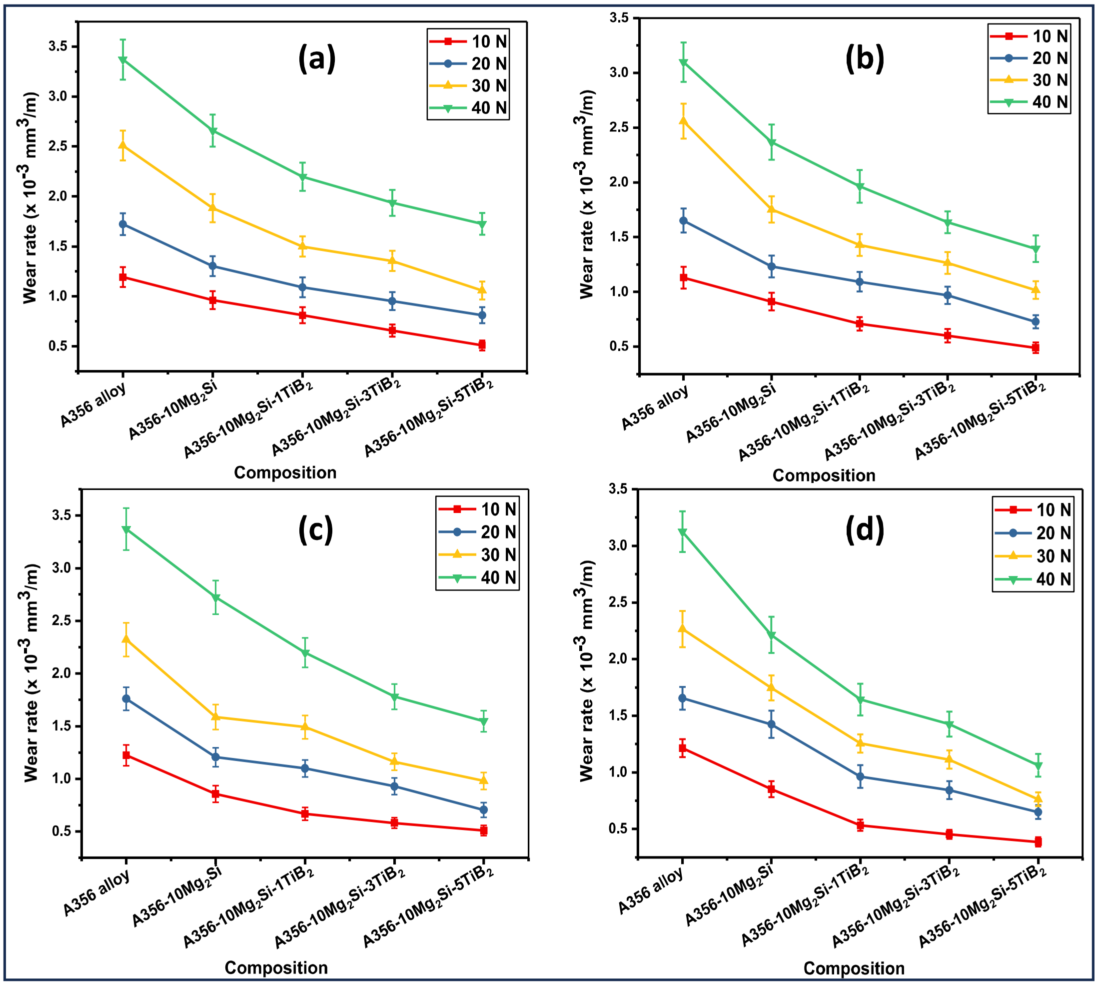


Fig. 5.16 Influence of TiB_2 content on wear rate at constant sliding velocity of 1.5 m/s and different sliding distance of **(a)** 1000 m **(b)** 2000 m **(c)** 3000 m **(d)** 4000 m

Figure 5.18 shows the wear coefficient of composites with varying TiB_2 composition at a constant sliding distance of 3000m. We can observe that increasing TiB_2 content decreases the wear coefficient up to 3 wt.% of TiB_2 particles beyond that it shows an almost similar wear coefficient. It indicates that increasing TiB_2 content increases the wear-resistant properties of composites This helps in optimizing the composition of composite for specific applications where wear is concern.

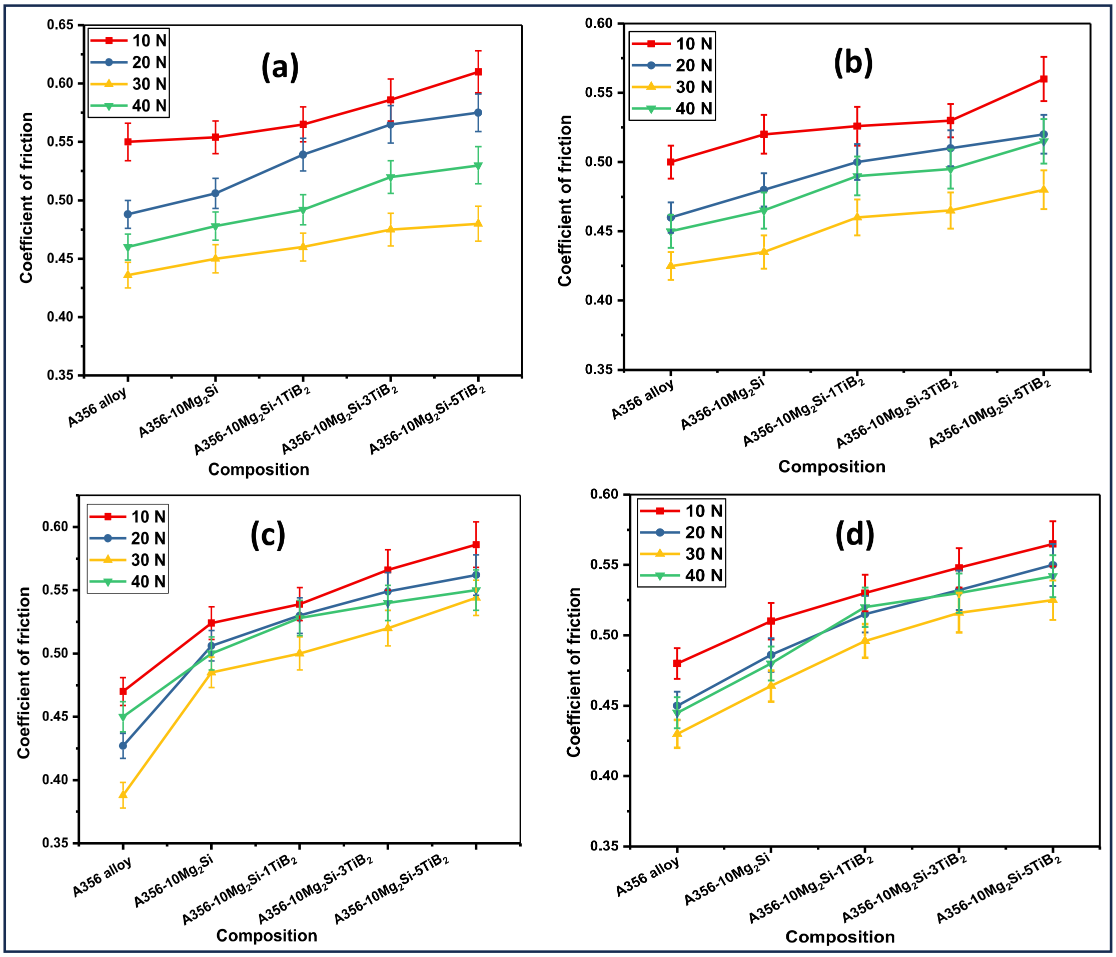


Fig. 5.17 Influence of TiB_2 content on COF at constant sliding velocity of 1.5 m/s and different sliding distance of (a) 1000 m (b) 2000 m (c) 3000 m (d) 4000

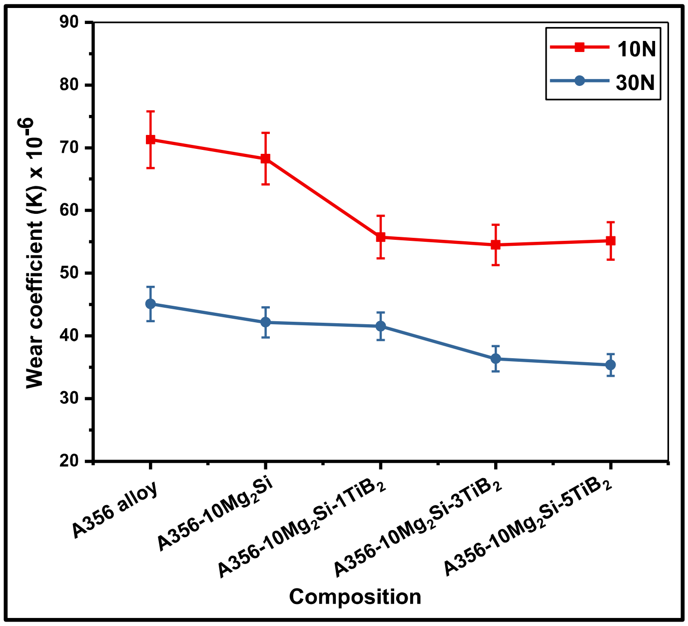


Fig. 5.18 Influence of TiB_2 content on wear coefficient at constant sliding distance of 3000 m

Fig. 5.19 (a-e) shows the SEM images of wear surfaces for matrix A356 alloy and A356-Mg_2Si-xTiB_2 hybrid composites with varying amount of TiB_2 particles at fixed applied load of 30N and sliding distance of 3000 m. Figure shows that the wear surface of base alloy has high amount of delamination, local plastic deformation and deep ploughing, however, these features of worn surfaces are decreased in composite A356-10Mg_2Si and it is further decreased in the A356-Mg_2Si-xTiB_2 hybrid composites with increase of TiB_2 content.

The worn surfaces of hybrid composites showing less delamination & plastic deformation and shallow ploughing. The minimum surface features are observed in the hybrid composite having 5wt.% of TiB_2 particles in the A356-10Mg_2Si. Presence of TiB_2 particles and fine Mg_2Si phase in the composite resist the cutting action by the asperities of steel disc during sliding and decrease the wear [132]. These worn surfaces results are also in agreement with the results of wear shown in Fig. 5.16.

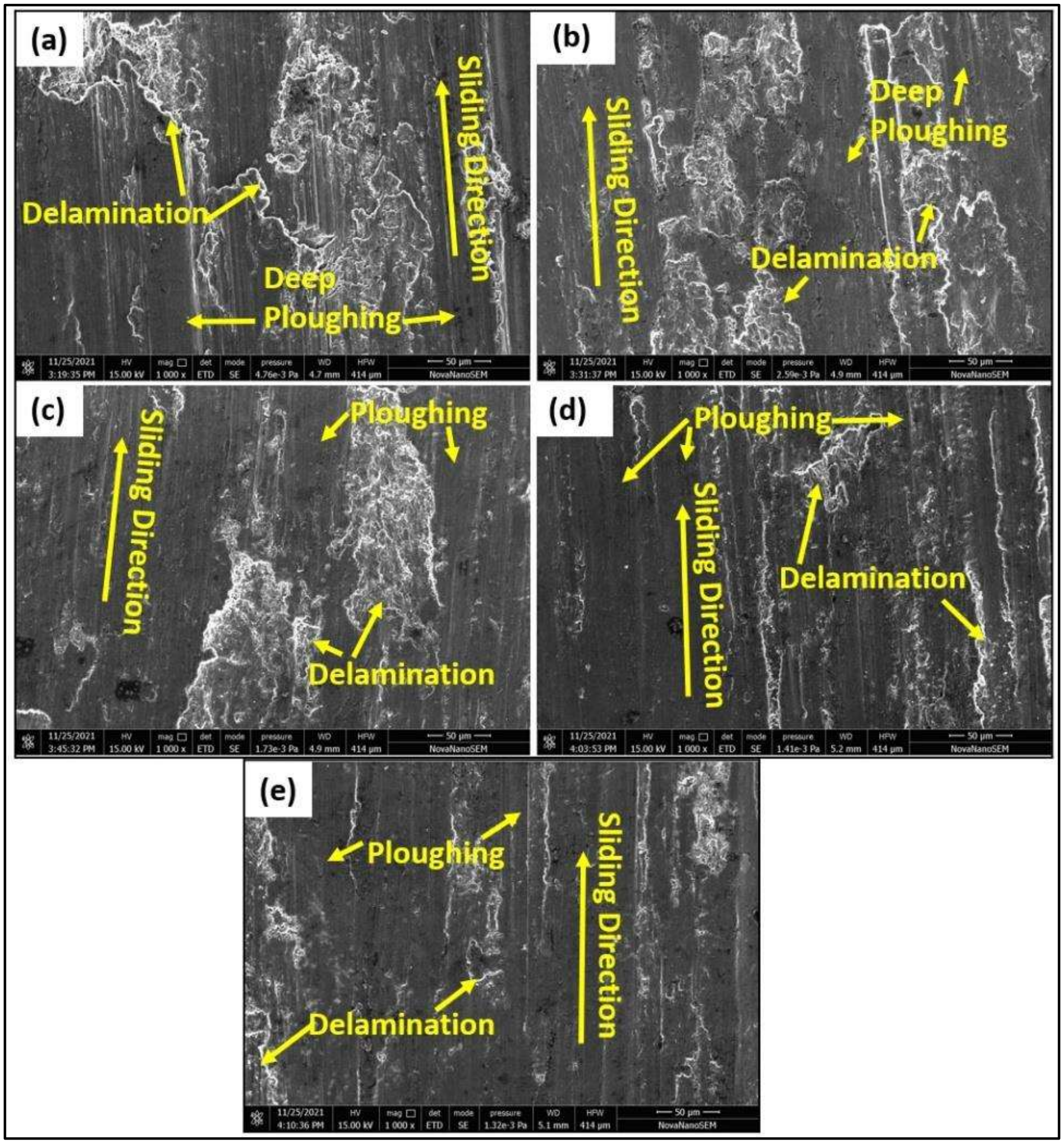


Fig. 5.19 SEM images of worn surface at 30 N load and 3000 m of sliding distance for (a) A356 alloy and A356-10Mg_2Si-xTiB_2 hybrid composite (b) x = 0 (c) x = 1 (d) x = 3 (e) x = 5

Figure 5.20 (a-e) displays the AFM three dimensional micrographs of matrix alloy and A356-Mg_2Si-xTiB_2 composites with different amount of TiB_2 particles. It clearly shows the peaks and valleys on the worn surfaces with varying height. It is observed that the maximum average peaks value is observed in matrix alloy than that of hybrid composites. However, it decreases continuously from 2.5 μm to 400 nm as the amount of TiB_2 particles increases from 0 to 5wt.% in the A356-10Mg_2Si composites.

Minimum value of is observed in the hybrid composite having 5wt.% TiB_2 particles. Decreased peaks value on the surface indicates the less wear of material and it can be due to the presence of TiB_2 particle reinforcement [133]. This result is also in agreement with obtained wear results.

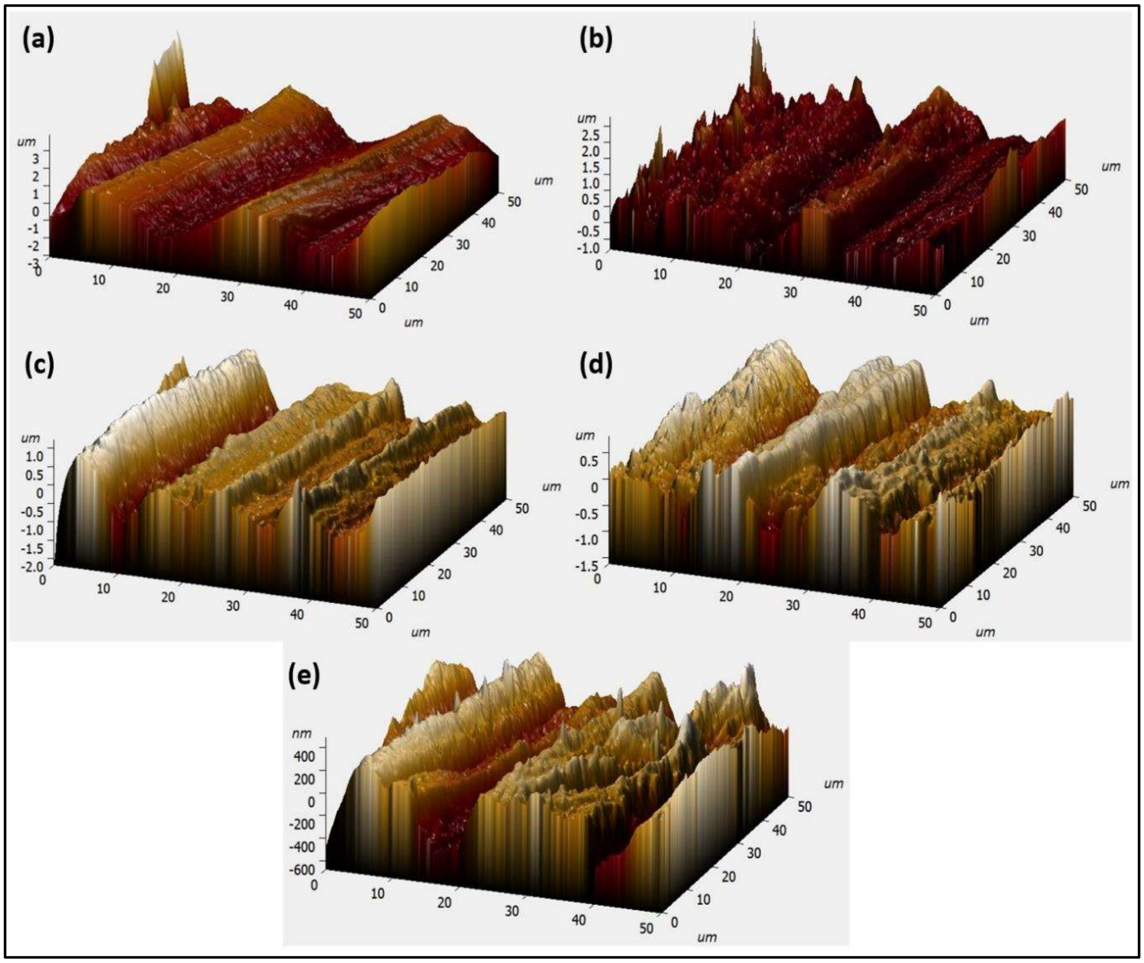


Fig. 5.20 AFM images of worn surface at 30 N load and 3000 m of sliding distance for (a) A356 alloy and A356-10Mg_2Si-xTiB_2 hybrid composite (b) x = 0 (c) x = 1 (d) x = 3 (e) x = 5

5.3 Wear Debris Analysis

The analysis of wear debris is very important to understand the wear mechanism involved. Therefore, these examinations have been performed on different compositions with varying operating parameters using SEM with EDS.

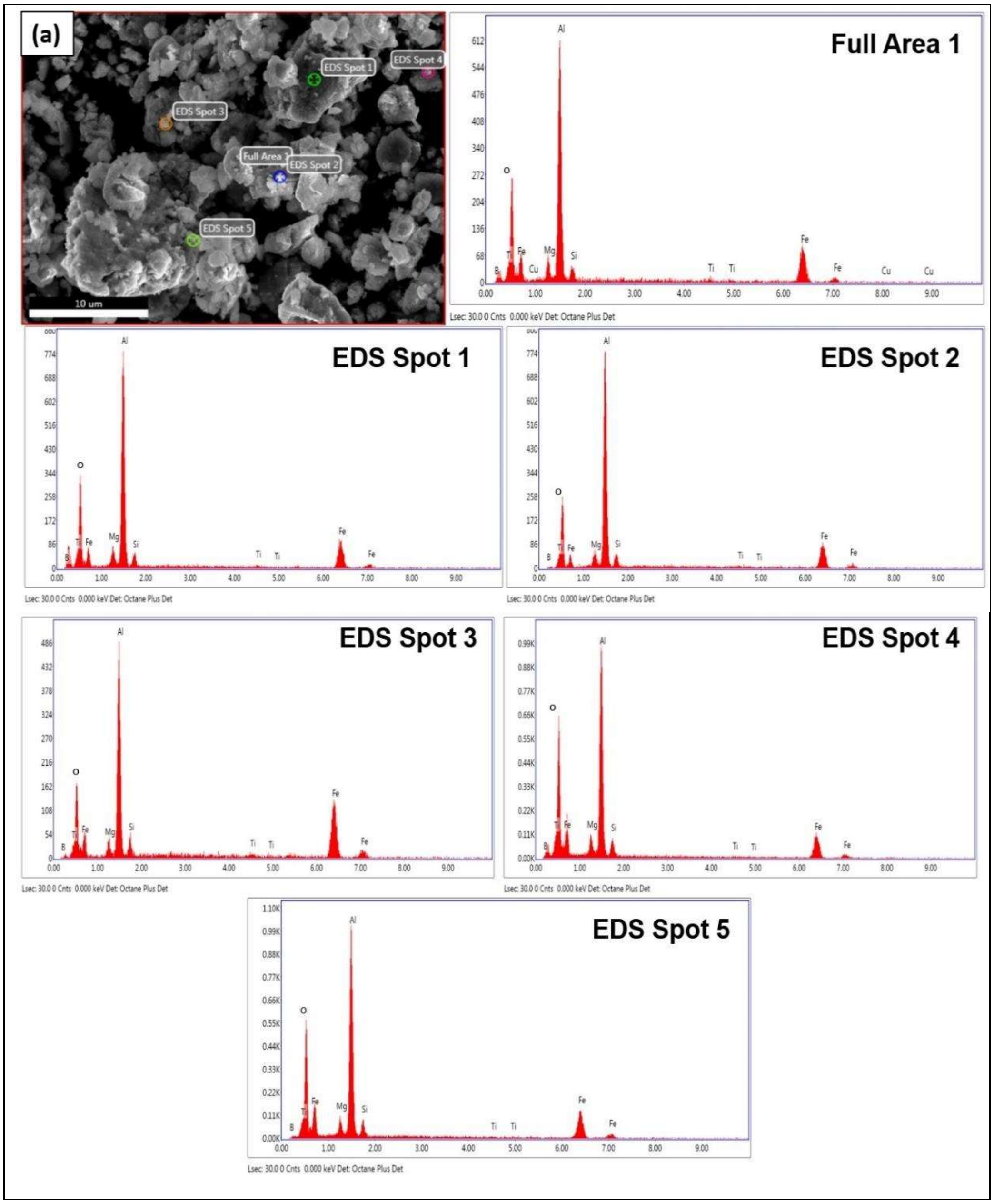


Fig. 5.21 (a) SEM micrograph of Wear debris of hybrid composite at applied load 40 N and corresponding EDS spectrum of whole area and points of SEM image.

Figure 5.21 displays the SEM images of wear debris of A356-10Mg_2Si-3TiB_2 at 40 N load and its EDS spectrum of corresponding points and full area of micrograph. EDS spectrum shows that the wear debris consist of Al, Si, Mg, Ti and B from hybrid composite and Fe from counter face as shown in EDS spectrum and it confirms the broken oxide layer and MML at high load. It may be entrapped between the composite pin and counter face resulting in three body wear at high load which increases the wear rate [134].

5.4 Summary

The following conclusion can be derived from this chapter:

- Wear rate and specific wear rate of hybrid composite decreases as TiB_2 content increases due to increased hardness and grain refinement. However, with increase of applied load and sliding distance, it shows an increasing trend.
- The hybrid composite containing of 5wt.% of TiB_2 particles shows approximately 66.5 % and 56% less wear rate in comparison to A356 alloy and A356-10Mg_2Si composite at 30 N load and 3000 m sliding distance.
- With an increasing amount of TiB_2 particle in the hybrid composites, COF increases, however, it decreases with the increase of applied load and gets minima at 30 N load followed by increase with further increase in applied load. With increase of sliding distance, it exhibits the fluctuating tendency.
- Minimum wear and highest COF are observed in the hybrid composite having 5wt.% TiB_2 particles in A356-Mg_2Si.
- Worn surface analysis under SEM and AFM, and wear debris analysis are in agreement with the observed tribological results.