CHAPTER 5

TRIBOLOGICAL BEHAVIOUR OF ZA ALLOY AND COMPOSITES IN LUBRICATING SLIDING CONDITION

5.1 INTRODUCTION

The relation between materials microstructure, topographical features, lubricant characteristics, and general environmental features significantly affects the overall performance of tribological systems. In the applications, where materials are used under lubricating conditions, pores present on the surface are important as these microcavities may retain lubricant and supply in the event of restricted supply of lubricants. This will not only reduce coefficient of friction but will also reduce wear loss [Bondi et al., 2019]. Finally, it will also extend the application range of the composite. In the subsequent sections, the effect of sliding distance, applied load and vol.% ZrB_2 particles on tribological behaviour of ZA alloy and ZA/ZrB_2 composites has been discussed in lubricating conditions using SAE20W40 motor oil.

5.2 INFLUENCE OF SLIDING DISTANCE

The influence of sliding distance on tribological behaviour of ZA alloy and composites is shown in Figs 5.1 and 5.2. Running-in wear region seems to be existing in the below 1000 m but lack of data at lower distance is the bottleneck (Fig. 5.1). Thereafter, almost a linear increase in wear i.e. steady state wear is observed with increase in sliding distance for all the compositions and all the loads (Fig. 5.1(a - e)). But ones applied load goes to 30 N and above, bulk wear increases at a faster pace for composites with lower amount of ZrB_2, however, with highest amount of reinforcement bulk wear remains stable even for maximum distance and largest load tested. With sliding distance travelled, surface continuously keeps getting damaged even after the presence of lubrication, however, severity of damage is reduced. With sliding distance rise in surface temperature takes place, which affects the lubricant film. Continuity of the film breaks and metal to metal contact takes place increasing the bulk wear. Presence of lubrication reduces the COF, but once lubricating film breaks due to temperature rise hard particles come in contact with the counterface and causes increase in COF (Fig 5.2) [Gautam et al., 2015]. Further, soft matrix of composite also interacts more with the hard counter surface of the steel disc, leading to the removal of more material and increase in COF value. COF values of alloy and composites increases by ~36% for alloy and ~ 26% for C9.0 composites respectively when sliding distance increases from 1000 to 5000 m.

Figure 5.3 shows the SEM image of the worn surface of the C9.0 composite at varying sliding distances and a constant load of 50 N. This can be seen that at a lower sliding distance (1000 m), only the sliding track of the sample is visible, which signifies very less wear, while with an increase in sliding distance (2000 m), delamination starts and a further increase in the sliding distance leads to shallow ploughing along with wear grooves, which signifies an increase in wear. Similar observations are also suggested by the AFM image (Fig. 5.4) and average surface roughness value (Ra) curves (Fig. 5.5). AFM image shows the surface topography (unevenness given in terms of the height of peak and valley). It increases from 180 nm to 350 nm as sliding distance increase from 1000 m to 5000 m and Ra values increase from 1.15 ± 0.01 µm to 1.31 ± 0.02µm. AFM analysis of wear sample &

Ra values suggest an increase in wear with an increase in sliding distance and results are in agreement with the trend shown in Figs. 5.1 and 5.2.

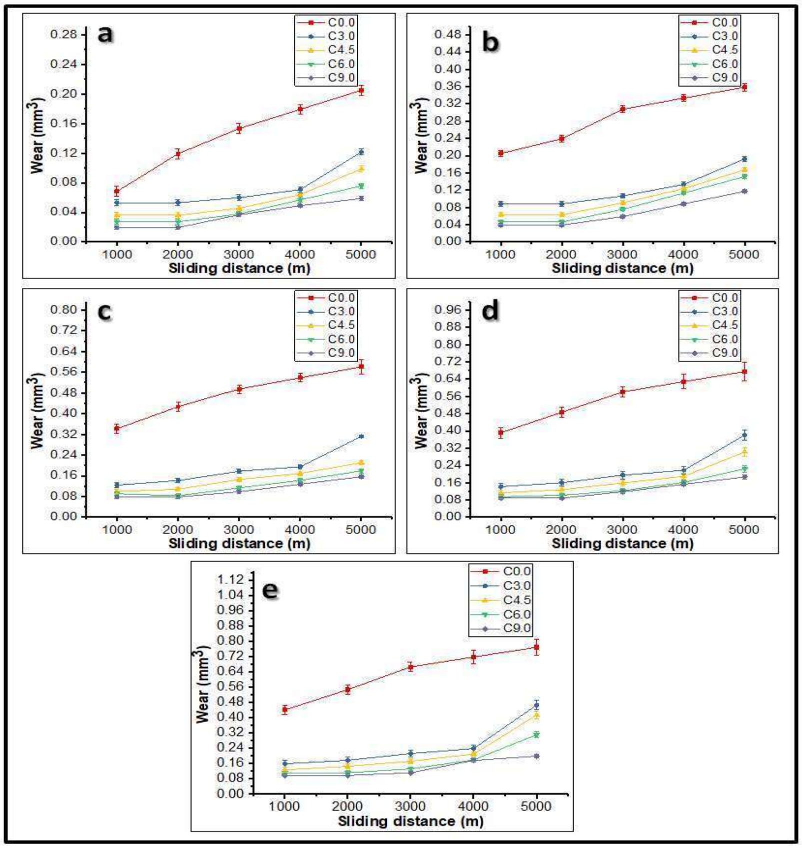

Fig. 5.1 Effect of sliding distance on wear at applied load of (a) 10 N (b) 20 N (c) 30 N (d) 40 N (e) 50 N

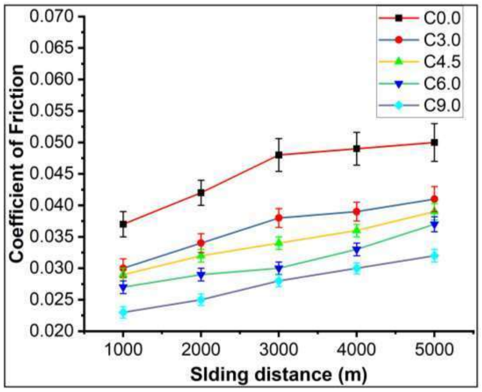

Fig. 5.2 Influence of sliding distance on COF at constant applied load of 50 N

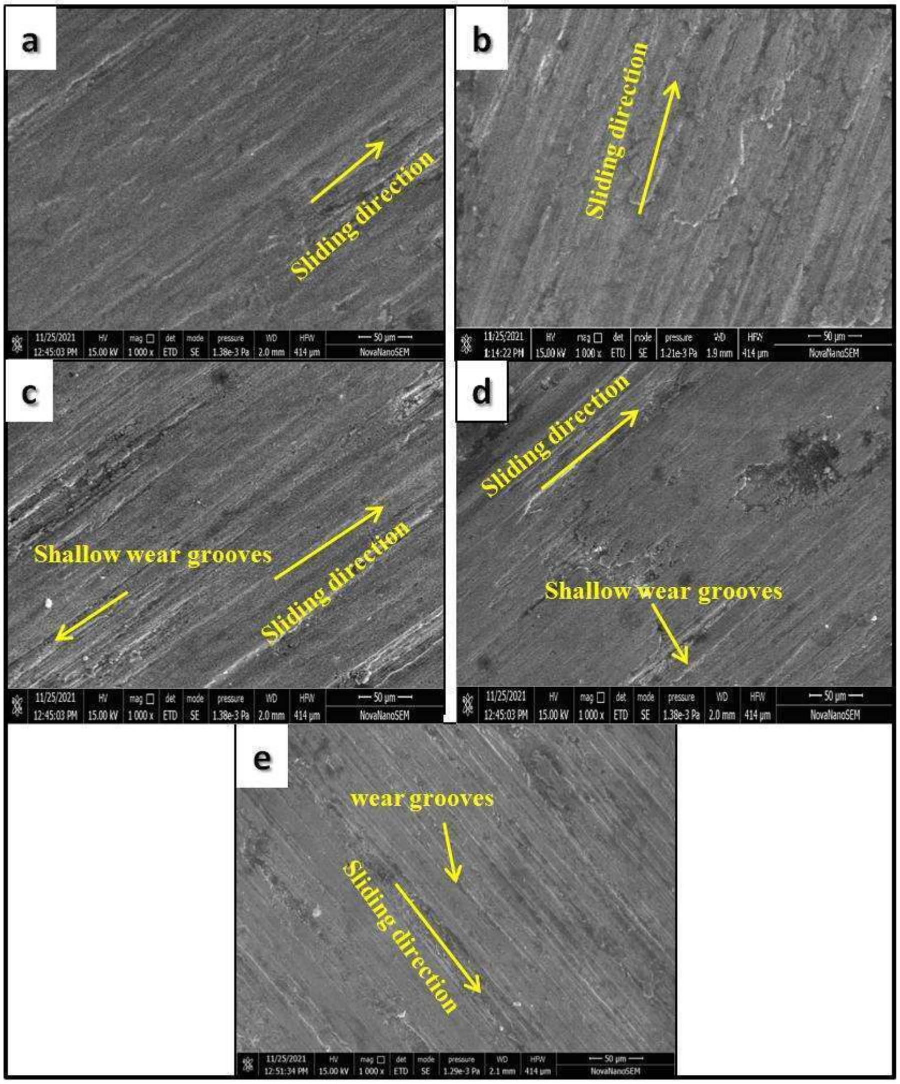

Fig. 5.3 SEM image of worn surface at constant load of 50 N of C9.0 composite at sliding distance (a) 1000 m (b) 2000 m (c) 3000 m (d) 4000 m (e) 5000 m

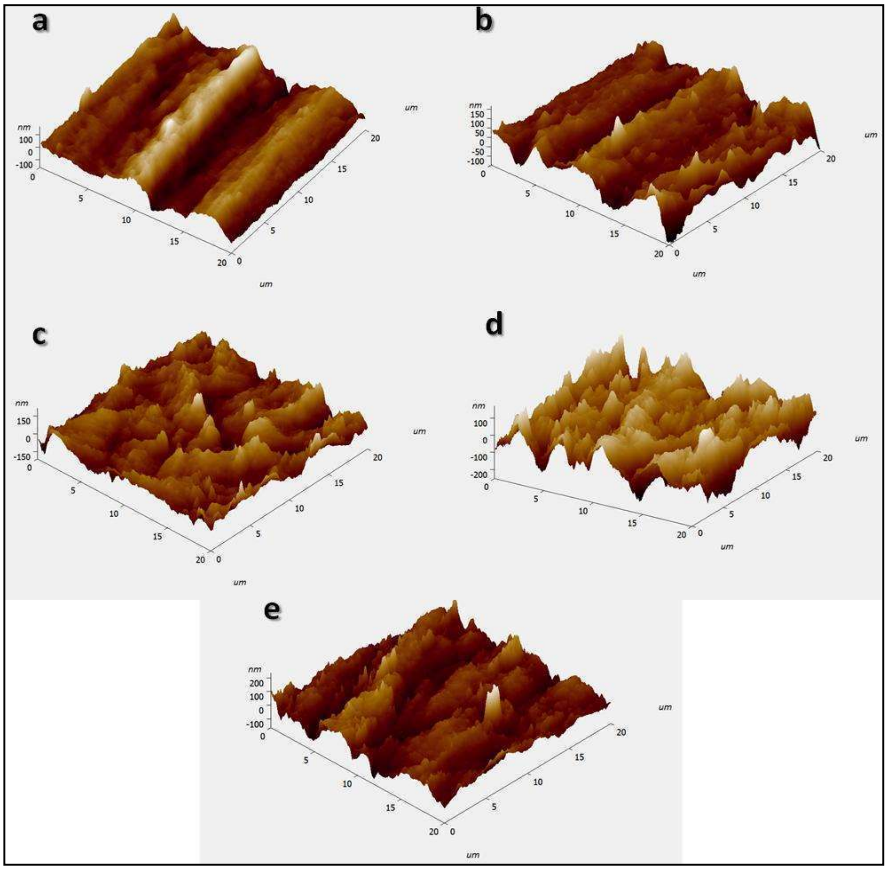

Fig. 5.4 AFM image of worn surface at constant load of 50 N of C9.0 composites at sliding distance of (a) 1000 m (b) 2000 m (c) 3000 m (d) 4000 m (e) 5000 m

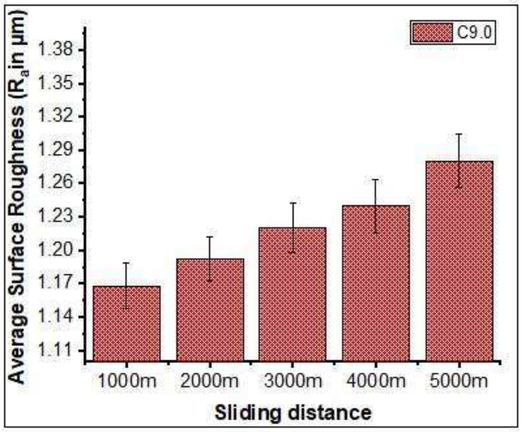

Fig. 5.5 Average surface roughness value (Ra in µm) of C9.0 composite at 50 N load

5.3 INFLUENCE OF APPLIED LOAD

Figures 5.6 and 5.7 show the influence of applied load on wear rate and specific wear rate of ZA alloy and ZA/ZrB_2 composites. Figure 5.6(a-e) shows an increase in wear rate with increasing applied load in alloy and all composites. At lower load, the effect of lubrication is more prominent as lubricant form a protective layer, and at lower load, the breaking of local film thickness does not take place, while at higher load, the lubricant layer starts breaking and increases the contact between pin sample and counter surface. This results in an increase in wear. Further, with an increase in load, penetration of hard particles asperities is enhanced and reduces the effect of lubrication in such regions. After larger sliding distance and at higher load, the hard asperities may be removed and fill the microcavities restricting the retention of lubricant and that leads to increase in wear [Ebner et al., 2018]. Composites show much lower wear than alloy, which may be due to the high hardness of composites having the hard ZrB_2 particles, which offer resistance to wear. Also, with increase in particles reinforcement, porosity increases. On one hand, presence of these micro-pores reduces the contact surface between pin sample and counter surface, on the other hand retention of lubricants in these micro-pores provides self-lubricating effect that reduces the wear. Further, reinforced particles provide improved load-bearing capacity, so even with the increase in load, there is not much increase in wear. This can also be observed that with increase in sliding distance, wear rate tends to become stable and steady state wear is observed. Figure 5.7 for specific wear rate with varying load for all the sliding distance shows a much clearer picture.

The effect of varying load on COF for alloy and all composites is given in Fig. 5.8, which indicates increase in COF for all the compositions with an increase in applied load.

While in the case of alloy, the rise in COF is very significant compared to composites. The COF for alloy increases from 0.022 ± 0.003 to 0.050 ± 0.006, as the load rises from 10 N to 50 N, while for composite with 9 vol.% ZrB_2, the value of COF increases from 0.016 ± 0.001 to 0.030 ± 0.002. This indicates that composite shows much less increase in COF with applied load as compare to base alloy. An increase in applied load leads to larger contact of hard particle asperities with counterface and breaking of lubrication layer also adds to it. This finally increases the area of contact between two surfaces and higher COF is observed.

Figure 5.9 presents the SEM image of the worn surface of the C3.0 composite having 3 vol.% of ZrB_2 at constant sliding distance of 4000 m. This can be observed that with increasing load, the wear grooves and shallow plowing increases. Further, as discussed above, at higher load, breaking of lubricant film increases the contact area between two surfaces that results in more delamination and grooves. Further, the worn surfaces of C3.0 composite was also examined under AFM to analyze the 3D profile (given in Fig. 5.10). AFM image shows that unevenness (the total height of peak to valley) of C3.0 composite increases from 200 nm to 600 nm as load increases from 10 N to 50 N, which indicates an increase in wear with increasing load. Average surface roughness value (Ra) is shown in Fig. 5.11, which clearly indicates an increase in average surface roughness from 1.16 ± 0.02 μm to 1.30 ± 0.03 μm of C3.0 composite with an increase in load. This behaviour indicates that the surface and subsurface deformation of the worn surface increases with increase in applied load, which increases the wear & friction. These results are in agreement with wear and friction results with the applied load (cf. Figs. 5.6 and 5.8).

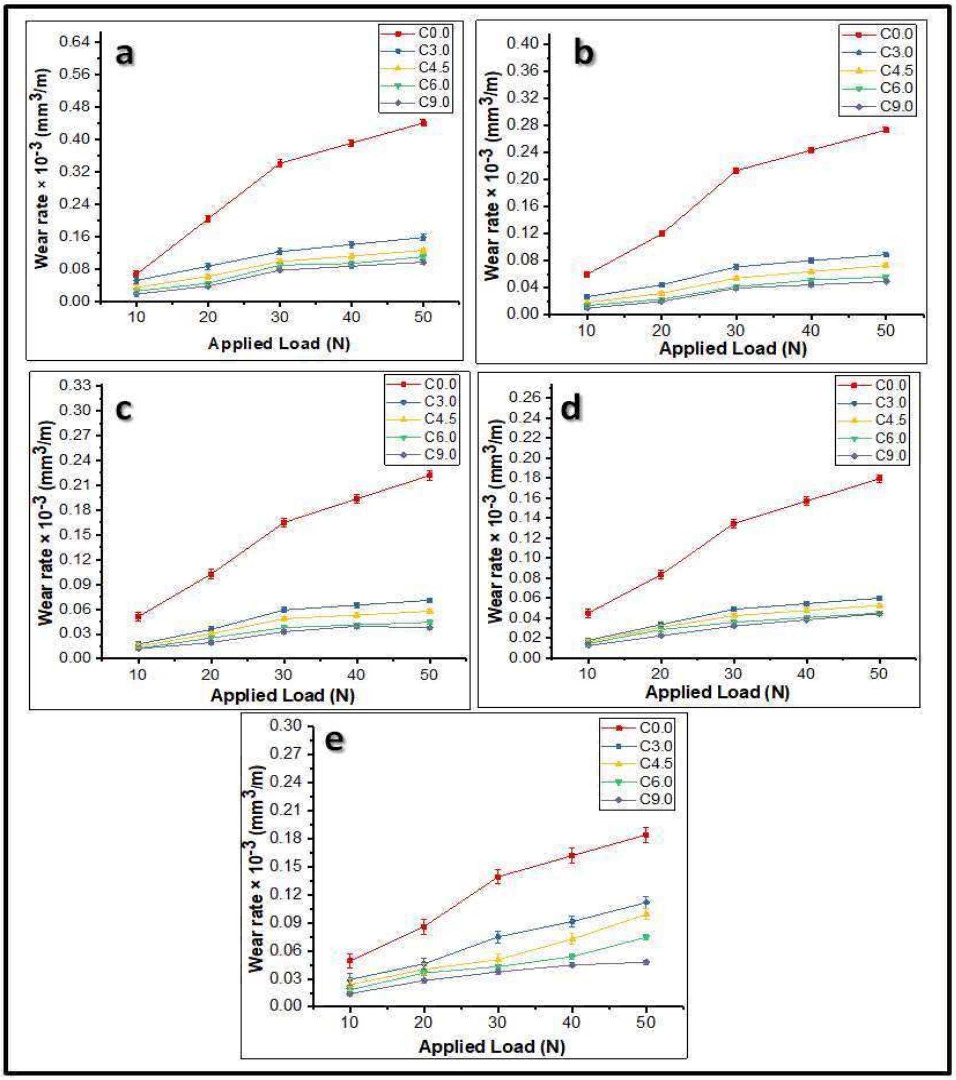

Fig. 5.6 Influence of applied load on wear rate at sliding distance of (a) 1000 m (b) 2000 m (c) 3000 m (d) 4000 m (e) 5000 m

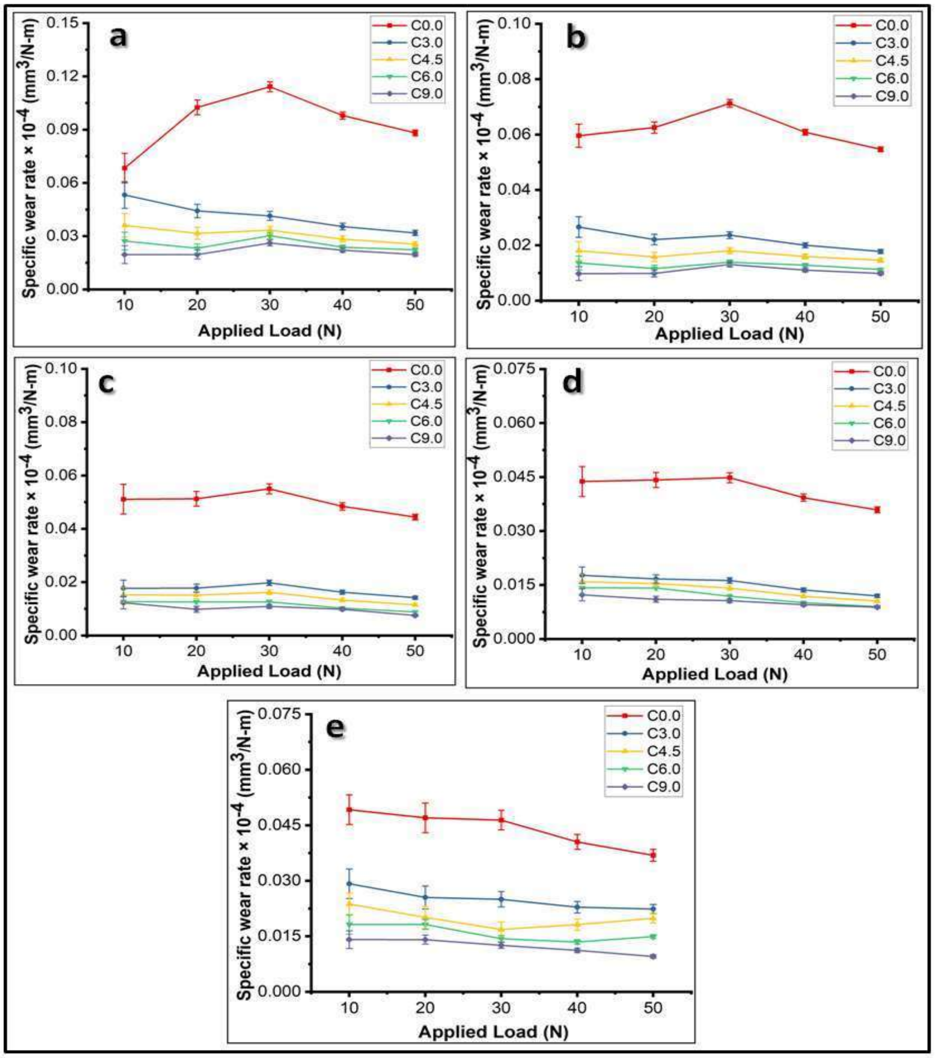

Fig. 5.7 Influence of applied load on specific wear rate at sliding distance of (a) 1000 m (b) 2000 m (c) 3000 m (d) 4000 m (e) 5000 m

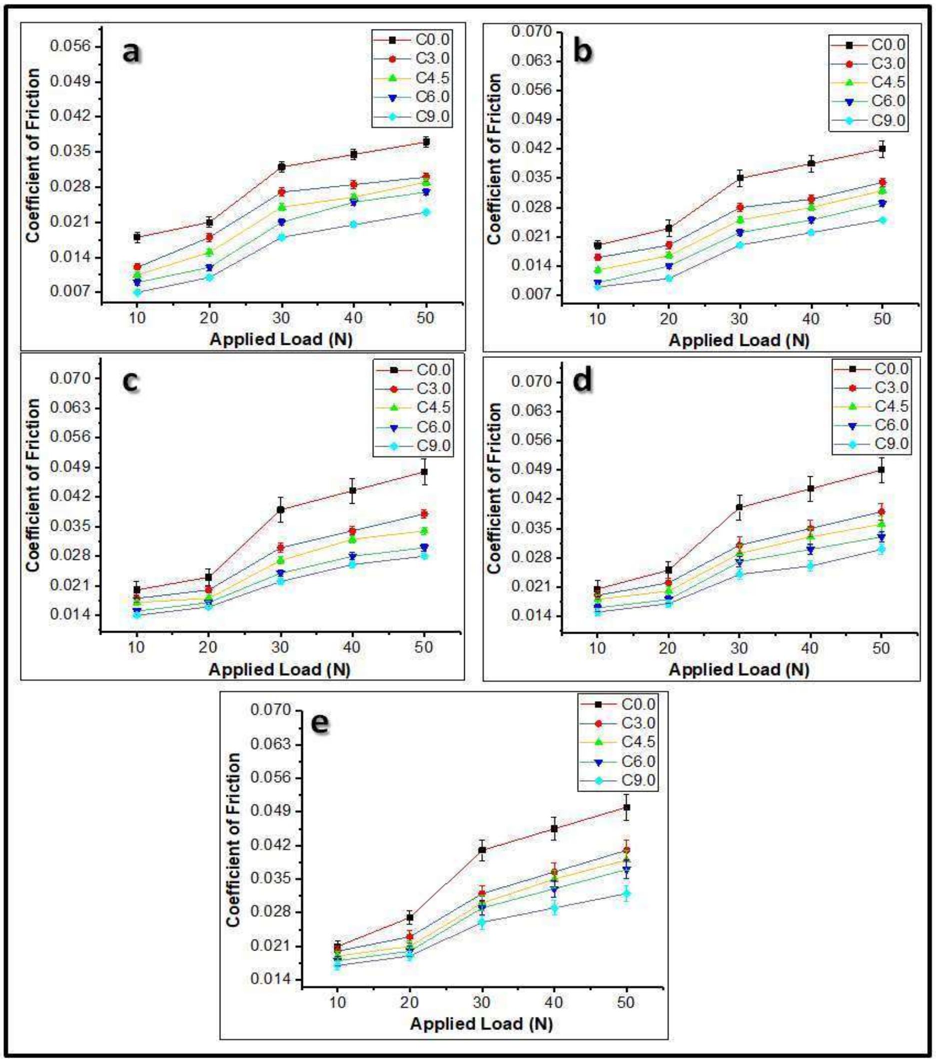

Fig. 5.8 Influence of applied load on COF at sliding distance of (a) 1000 m (b) 2000 m (c) 3000 m (d) 4000 m (e) 5000 m

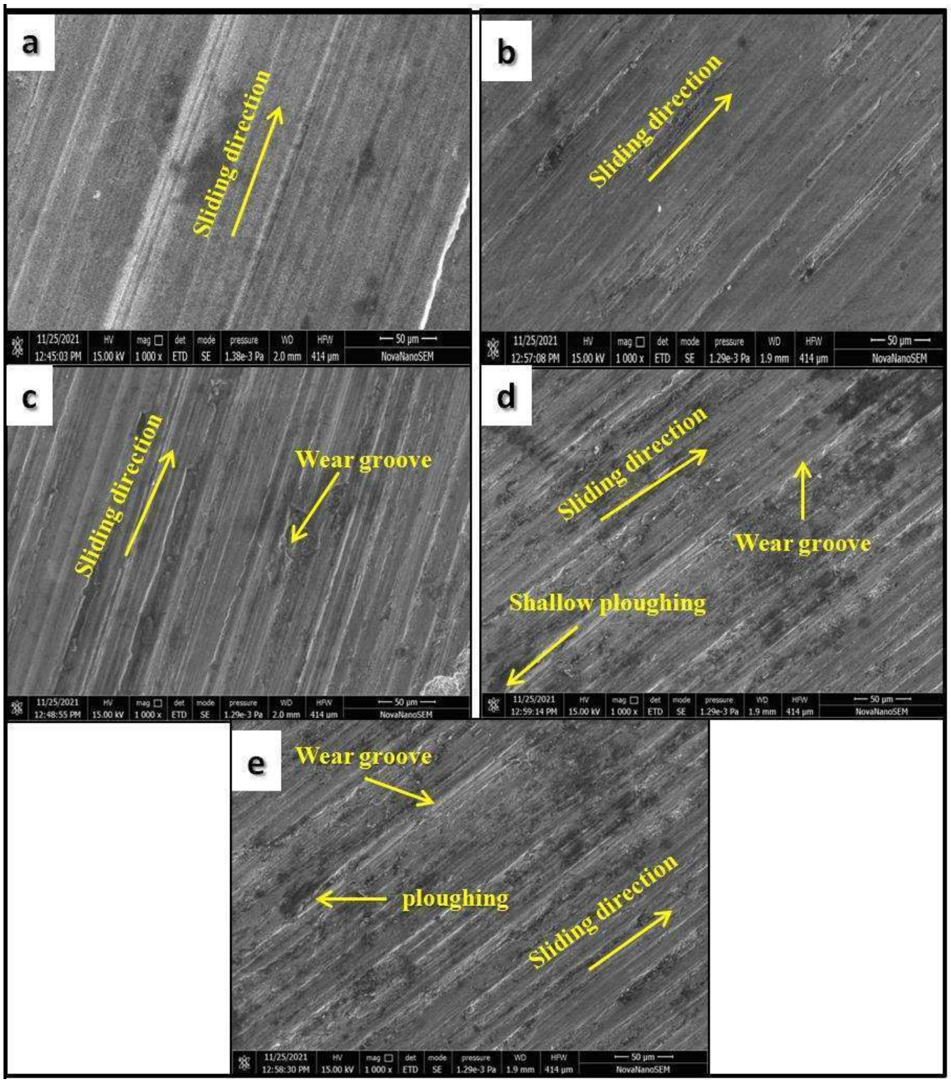

Fig. 5.9 SEM image of worn surface of C3.0 composite for constant sliding distance of 4000 m at (a) 10 N (b) 20 N (c) 30 N (d) 40 N (e) 50 N

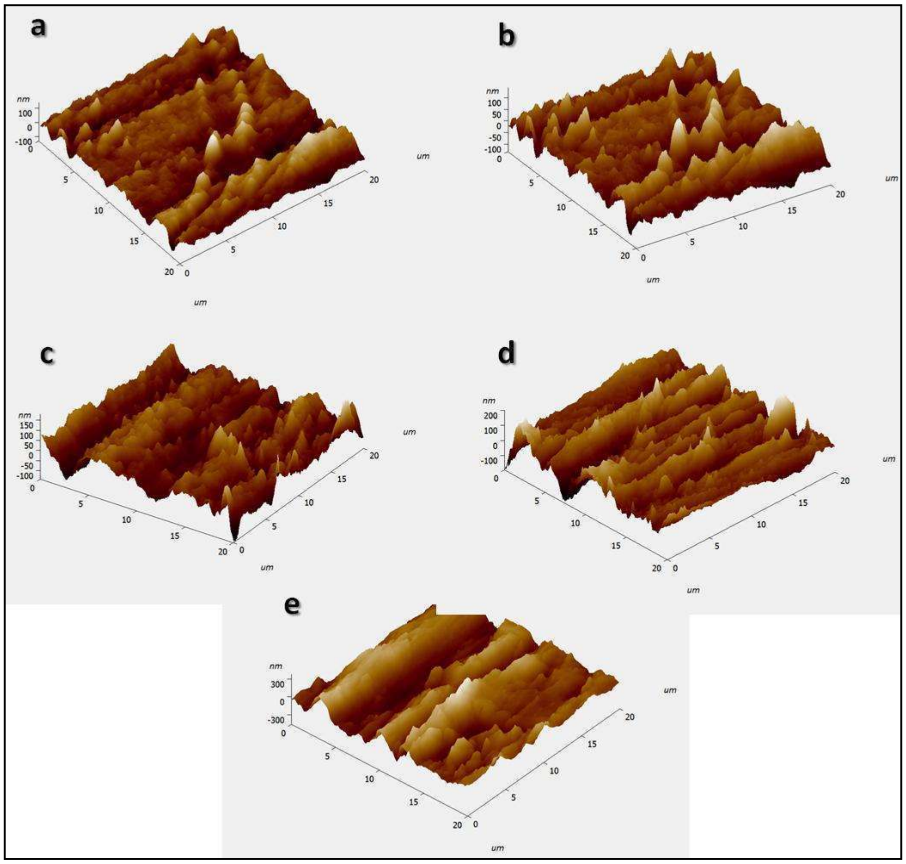

Fig. 5.10 AFM image of worn surface of C3.0 composites for constant sliding distance of 4000 m at (a) 10 N (b) 20 N (c) 30 N (d) 40 N (e) 50 N

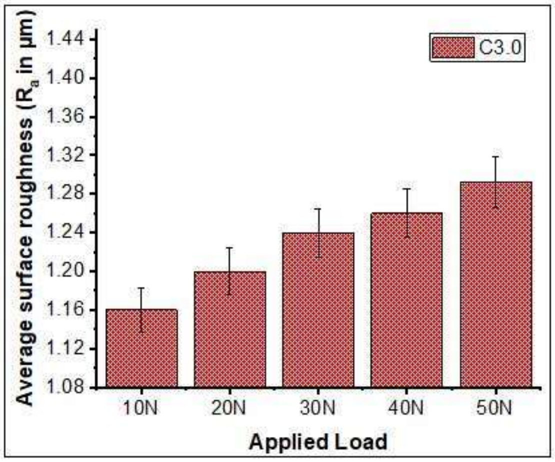

Fig. 5.11 Influence of applied load for constant sliding distance of 4000 m for C3.0 composite on average surface roughness value (Ra in µm)

5.4 INFLUENCE OF ZrB_2 REINFORCEMENT

Figures 5.12 (a & b) and 5.13 show the effect of ZrB_2 reinforcement on wear, wear coefficient and COF for 5000 m sliding distance and 50 N applied load. Tests have been conducted for other parameters also but since the nature of curves is similar, hence, only above parameters have been chosen to include in the present work. Further, at higher load and sliding distance tribological behaviour of composites and alloy is clearly distinguishable. This can be clearly observed that with addition of *insitu* ZrB_2 particles, significant decrease in wear and wear coefficient takes place. This effect increases with amount of reinforcement as seen in composites from Fig. 5.12(a & b). Both wear volume and wear coefficient decrease with rise in ZrB_2 vol.%. This reduction in wear volume is for various reasons. Reinforcements of ZrB_2 causes reduction in grain size of matrix by creating hindrance in the movement of the solidification front, presence of particles acts as nucleation sites, and further increases dislocation density and due to finer grain size, more hindrance in movement of these dislocations takes place. These collectively increase the hardness of composites. Both matrix and ZrB_2 particles possess a different coefficient of thermal expansion (CTE), and during solidification, stress generation takes place, which further provides the hardening of composites [Vineet et al., 2019]. At the same time, the presence of ZrB_2 particles also provides more load-bearing capacity, which tends to decrease wear. Finally, lubrication also plays a vital role in reducing wear. Lubricant creates a film between pin sample and counter surface and helps in wear reduction. Further, reinforcement of particles causes an increase in porosity, and with an increase in vol.% of ZrB_2, there is an increase in porosity level (refer to chapter 3). The presence of porosity acts as microcavities and retain the lubricant, thus causing it to behave [Boidi et al., 2019] just like self-lubricating materials and further lowers the wear. Figure 5.13 shows the effect of ZrB_2 particles on the COF of alloy and composites. COF shows linear decrease with increase in vol.% ZrB_2 particles from 0 to 9 vol.%. Composite with 9 vol.% ZrB_2 show ~ 40% less COF compared to ZA alloy. This may have occurred due to the application of lubricant in which porosity also helps by retention of lubricants in micro-pores as already discussed in case of wear. For any smooth and flat surface, even micro-shaped pores cause reduction in the COF. This effect may be related to an enhancement in hydrodynamic load-carrying capacity which is promoted by micro bearing effect produced by the surface pores. The incorporation of lubricating oil creates a boundary layer between mating surfaces that reduces the contacting surface and COF is reduced [Ebner et al., 2018].

Figures 5.14 to 5.16 shows the effect of ZrB_2 reinforcement on the worn surface of the wear sample using SEM, AFM, and Surface profilometer. From Fig. 5.14(a- d) it can be clearly observed that with addition of ZrB_2 particles damage to the surface decreases as vol.% of ZrB_2 increases and for 9 vol.% reinforcement comparatively smoother topography is observed. Figure 5.14(a-d) clearly exhibits decrease in delamination, ploughing and grooves as vol.% ZrB_2 increases. Further, 3D analysis of worn surfaces by AFM in Fig. 5.15 clearly shows that with increase in ZrB_2 content from 0 to 9 vol.% in composites, the average values of peaks and valley decrease from 700 nm to 300 nm, which signifies lower unevenness of the surface with lower surface roughness and less wear of the composite. It becomes, further, clear from average surface roughness value of alloy and composites by surface profilometer studies, which shows that with increase in vol.% of ZrB_2 from 0 to 9 vol.% the average surface roughness value decreases from $1.65 \pm 0.03\mu m$ to 1.30 ± 0.02 μm

(Fig.5.16). These observations are in line with tribological results given in Figs. 5.12 and 5.13.

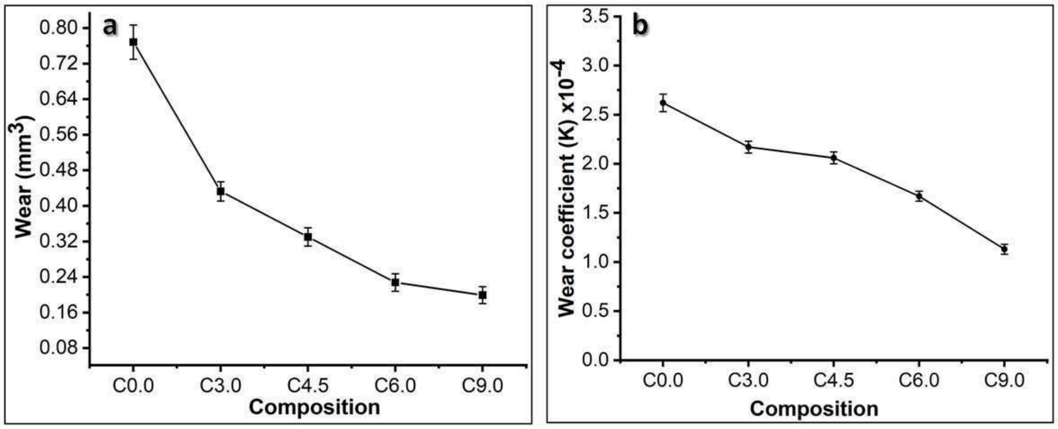

Fig. 5.12 Influence of ZrB_2 content for 5000 m sliding distance and 50 N applied load (a) wear volume (b) wear coefficient

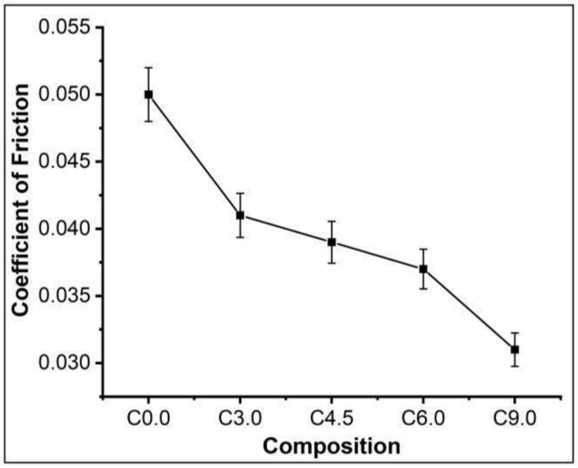

Fig. 5.13 Coefficient of friction for alloy and composites

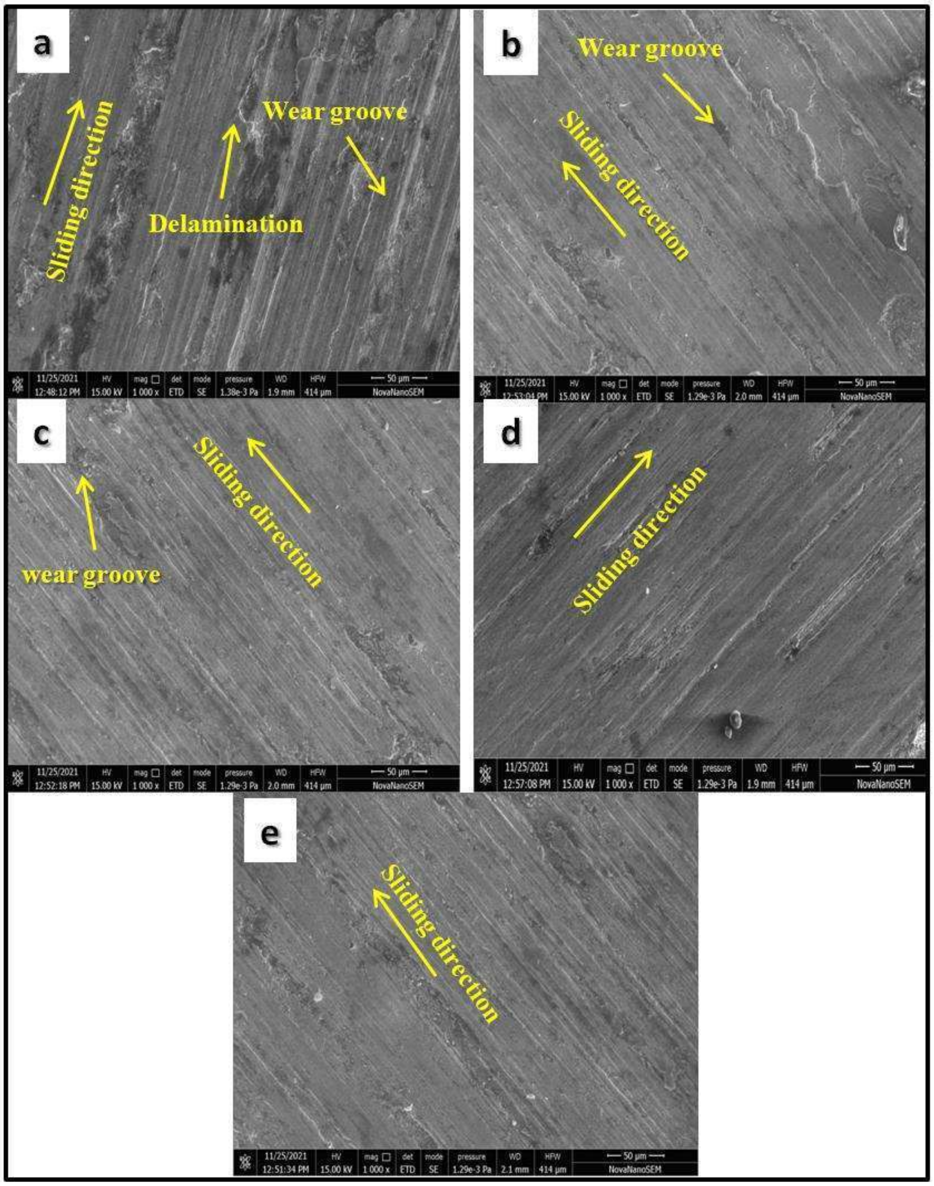

Fig. 5.14 SEM image of worn surface for 5000 m sliding distance and 50 N applied load for (a) C0.0 (b) C3.0 (c) C4.5 (d) C6.0 (e) C9.0

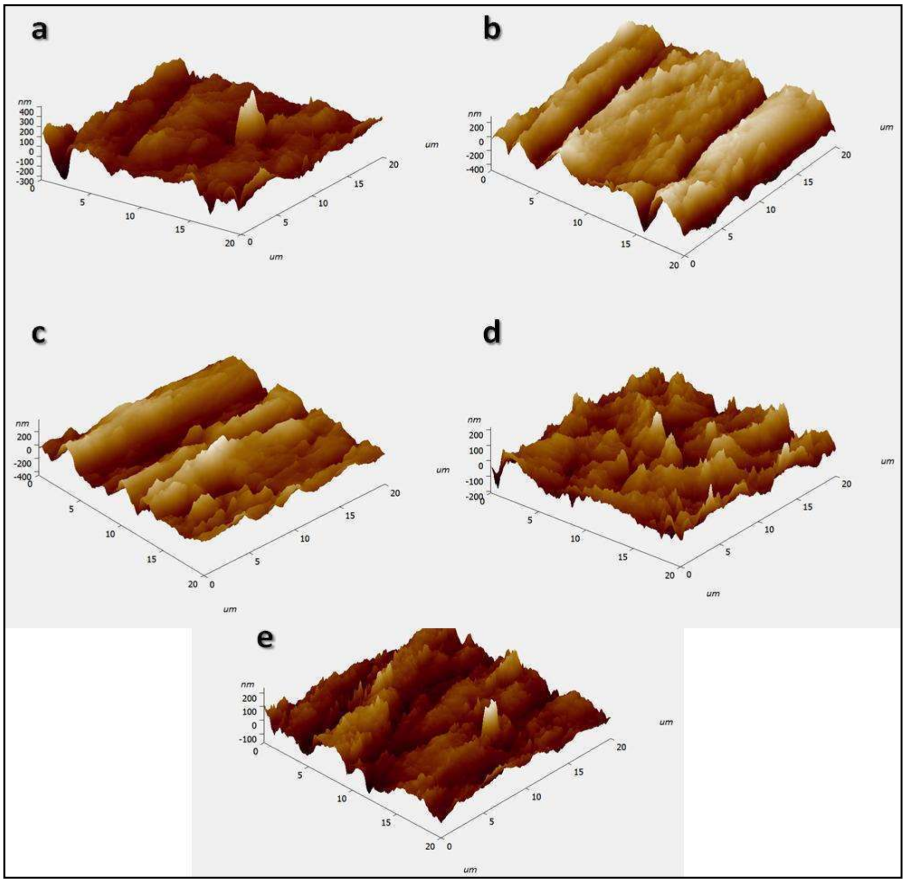

Fig. 5.15 AFM image of worn surface for 5000 m sliding distance and 50 N applied load for (a) C0.0 (b) C3.0 (c) C4.5 (d) C6.0 (e) C9.0

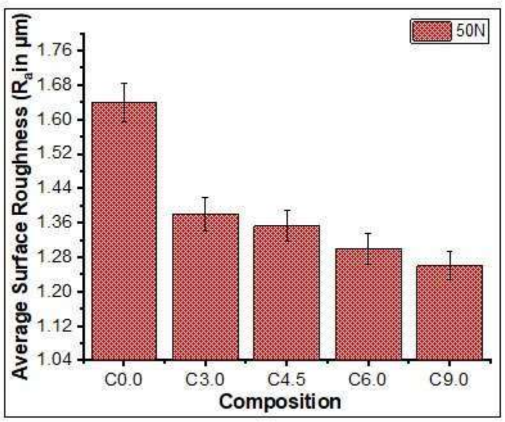

Fig. 5.16 Average surface roughness value (Ra in µm) for 5000 m sliding distance and 50 N applied load for alloy and composites

5.5 CONCLUSIONS

Following can be concluded from the above work:

- Lubrication improves the wear resistance as well as it also reduces the COF.
- Tribological analysis indicates that increase in load from 10 N to 50 N and sliding distance from 1000 m to 5000 m, increases the wear loss by ~268% & ~100% for alloy and ~265% and ~ 159% for C9.0 composite with 9 vol.% ZrB_2.
- The C9.0 composite (consist of 9 vol.% of ZrB_2 particles) shows approximately 97% less wear volume compared to C0.0 (ZA alloy) at 50 N load and 5000 m sliding distance.
- SEM & AFM images and average surface roughness values clearly suggest significant decrease in surface damage for C9.0 composite even at higher load and sliding distance thus overall results in material savings and reduction in COF may help in reductions of frictional losses.
- Low wear and low COF indicates the huge potential of present material system for bush and bearing applications.