CHAPTER 5

TRIBOLOGICAL PERFORMANCE OF COPPER-GRAPHITE-TIC COMPOSITES IN LUBRICATING SLIDING CONDITIONS

5.1 INTRODUCTION

The performance of tribological systems is greatly influenced by the interaction among the microstructure of materials, topographical features, properties of lubricants, and environmental factors. However, in applications involving lubricated conditions, the presence of pores on the material surface holds significance. These tiny cavities can play a crucial role by retaining lubricants and providing a continuous supply in situations where the lubricant flow is constrained. In this chapter, the influence of sliding distance, sliding velocity, applied load and wt.% of TiC particles on tribological behaviour of Cu-Gr-TiC composite is discussed under lubricating conditions by using SAE20W40 motor oil. The worn surface examination under SEM and AFM have been carried out along with analysis of topographical features.

5.2 WEAR & FRICTION BEHAVIOR UNDER LUBRICATING SLIDING

5.2.1 Influence of sliding distance

Figure 5.1 (a-d) depicts the influence of sliding distance on wear volume of Cu sample, Cu-Gr composite and T1.5 to T4.5 composites at varying applied loads of 10 N to 70 N. Wear of samples steadily increases with the sliding distance for all the compositions and all the loads [Gautam et al., 2015]. However, at larger loads (70 N) a sharp increase in wear is observed. The matrix of composite interacts more with the hard counter surface of the steel disc, leading to more material removal with extended sliding distances. The increase in wear of all samples is in the range of approximately 120%–150% with the rise of sliding distance from 2000 m to 8000 m. When the sliding distance is raised the increase in wear may take place owing to increase in contact duration between pin samples and counter disc which leads to the plastic deformation of samples along with the removal of hard particles from matrix material that overall reduces the effect of lubrication and, hence, rise in wear volume. Further after 6000 m the rate of increase in wear was slower because of combined effect of the porosity and lubrication.

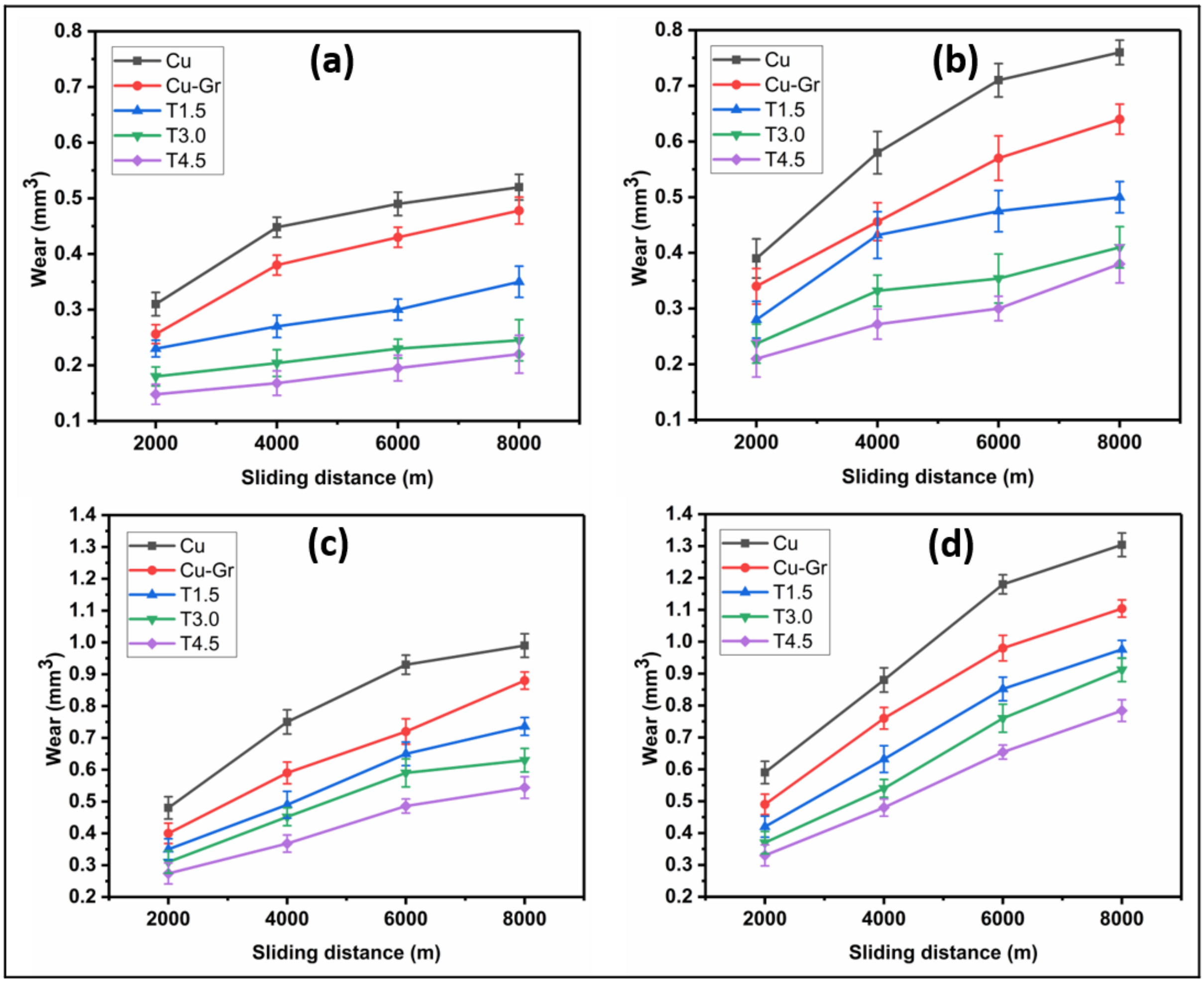

Fig. 5.1 Influence of sliding distance on wear volume at various applied loads (a) 10 N (b) 30 N (c) 50 N (d) 70 N

Figure 5.2 (a-d) illustrates the variation of COF value of pure Cu, Cu-Gr composite and T1.5 to T4.5 composites with increasing sliding distance at varying applied loads (10 N to 70 N). It is found that COF of all composition rises with the increase in distance travelled during wear test while after certain distance (6000 m) it start stabilizing.

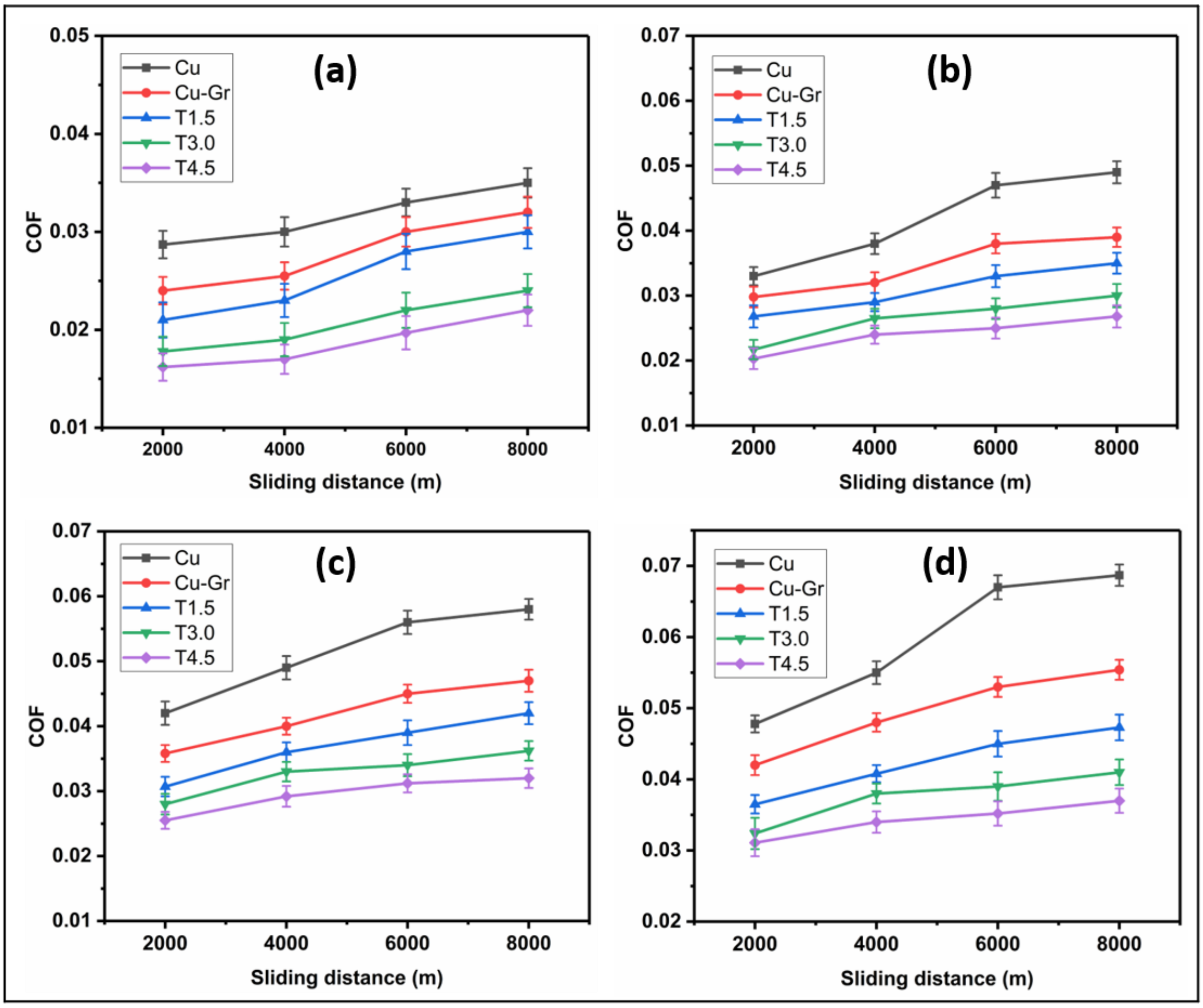

Fig. 5.2 Influence of sliding distance on COF at various applied loads (a) 10 N (b) 30 N (c) 50 N (d) 70N

As the distance increases, the pin sample interact more with the hard surface thereby causing more material removal and hence surge in coefficient of friction value. However, for the T1.5- T4.5 composites less rise in coefficient of friction is observed as compared to pure copper and graphite reinforced composite. The TiC reinforced composites depicting less surge in COF at higher sliding distance may be attributed to their better lubricant retaining property owing to high porosity.

Figures 5.3 (a-d) shows the SEM image of worn surfaces of T3.0 composites with different sliding distance of 2000 m-8000 m and a fixed load of 70 N.

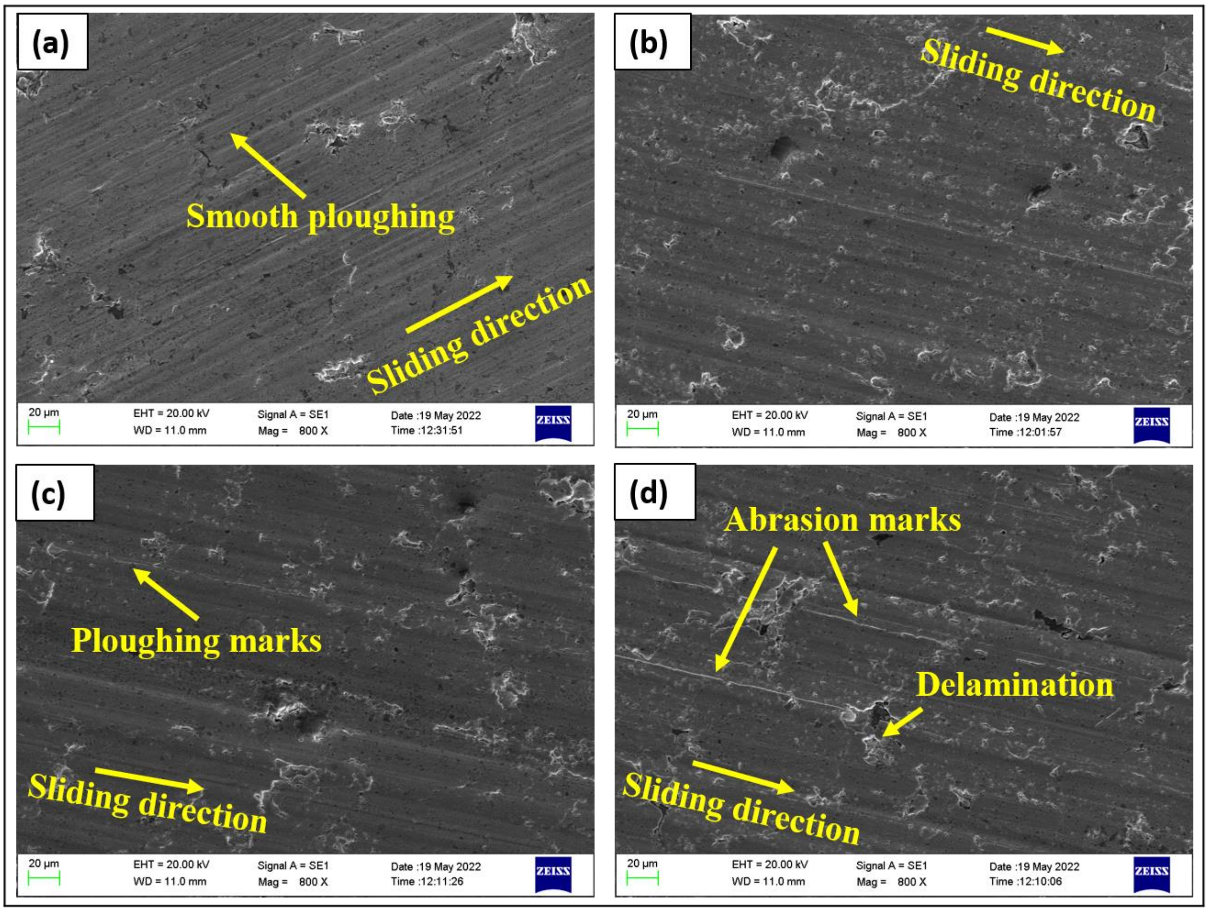

Fig. 5.3 SEM images of worn surface of T3.0 composite at load of 70 N and sliding distance of (a) 2000 m (b) 4000 m (c) 6000 m (d) 8000 m

At initial sliding distance of 2000 m smooth ploughing is observed depicting less wear. As the distance is raised more ploughing marks are seen on the composite sample. Also at higher sliding distance, a large amount of abrasion marks exists. However, more delamination of matrix material occurs at distance of 8000 m implying more wear loss. The identified features on the worn surfaces are consistent with the results drawn from the wear analysis.

Figure 5.4 illustrates the 3D AFM image of worn surfaces of T3.0 composite with different sliding distance from 2000 m to 8000 m for 70 N applied load. It is observed that average peak and valley of worn surface rises from 600 nm to 1.4 μm with the sliding distance. These values of surface roughness are found to be in similar trends with the result of wear.

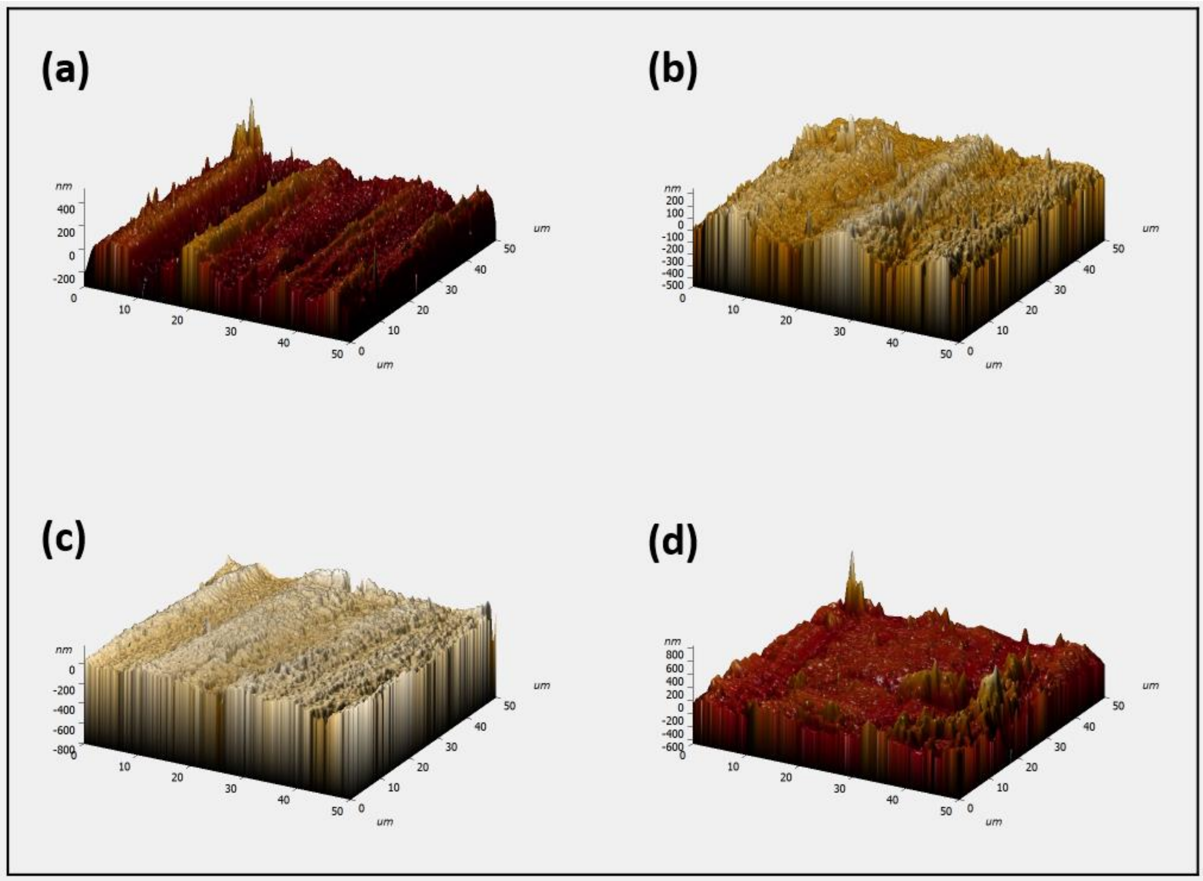

Fig. 5.4 AFM image of T3.0 composite at 70 N load and sliding distance of (a) 2000 m (b) 4000 m (c) 6000 m (d) 8000 m

5.2.2 Influence of sliding velocity

Figure 5.5 (a-d) illustrates the impact of sliding velocity on wear rate at various applied loads. It is seen that wear rate that takes place at 0.75 m/s is much higher than that at 3 m/s in presence of lubricant oil for each loading condition. This trend is followed by all the samples. This can be attributed to the phenomena where the pin sample and counter surface are in contact for longer periods of time at low sliding velocities. For all compositions, the amount of percentage decrement in the wear rate from low to high velocity is approximately in the range of 20–30. However, the T4.5 composite (4.5 wt.% of TiC) was having lowest wear rate at each velocity signifying enhancement in wear resistance than other composites. T4.5 composite has relatively high surface pores compared to others. These pores/microcavities are important because they have the ability to retain lubricants, ensuring a continuous supply in cases where lubricant access may be limited. At high velocity these surface pores release more lubricant during wear test. As a result, a continuous thick film is generated leading to least wear rate at 3 m/s sliding velocity.

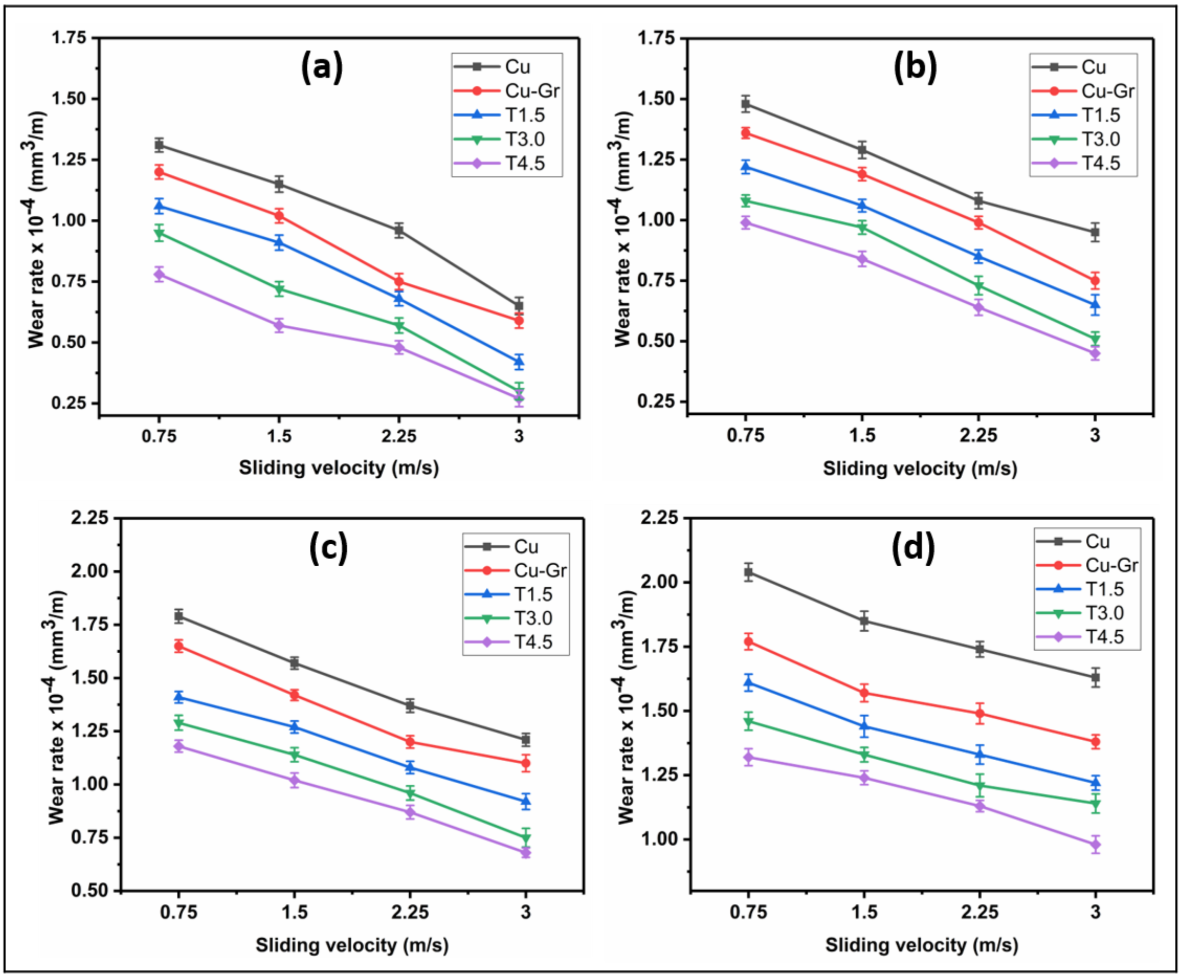

Fig. 5.5 Influence of sliding velocity on wear rate at sliding distance of 8000 m and various applied loads (a) 10 N (b) 30 N (c) 50 N (d) 70 N

Figure 5.6 (a-d) shows the influence of sliding velocity on COF Cu, Cu-Gr and T1.5-T4.5 composites at applied loads of 10-70 N. From the graphs, it is observed that as magnitude of sliding velocity is raised, the COF value of all compositions gets reduced.

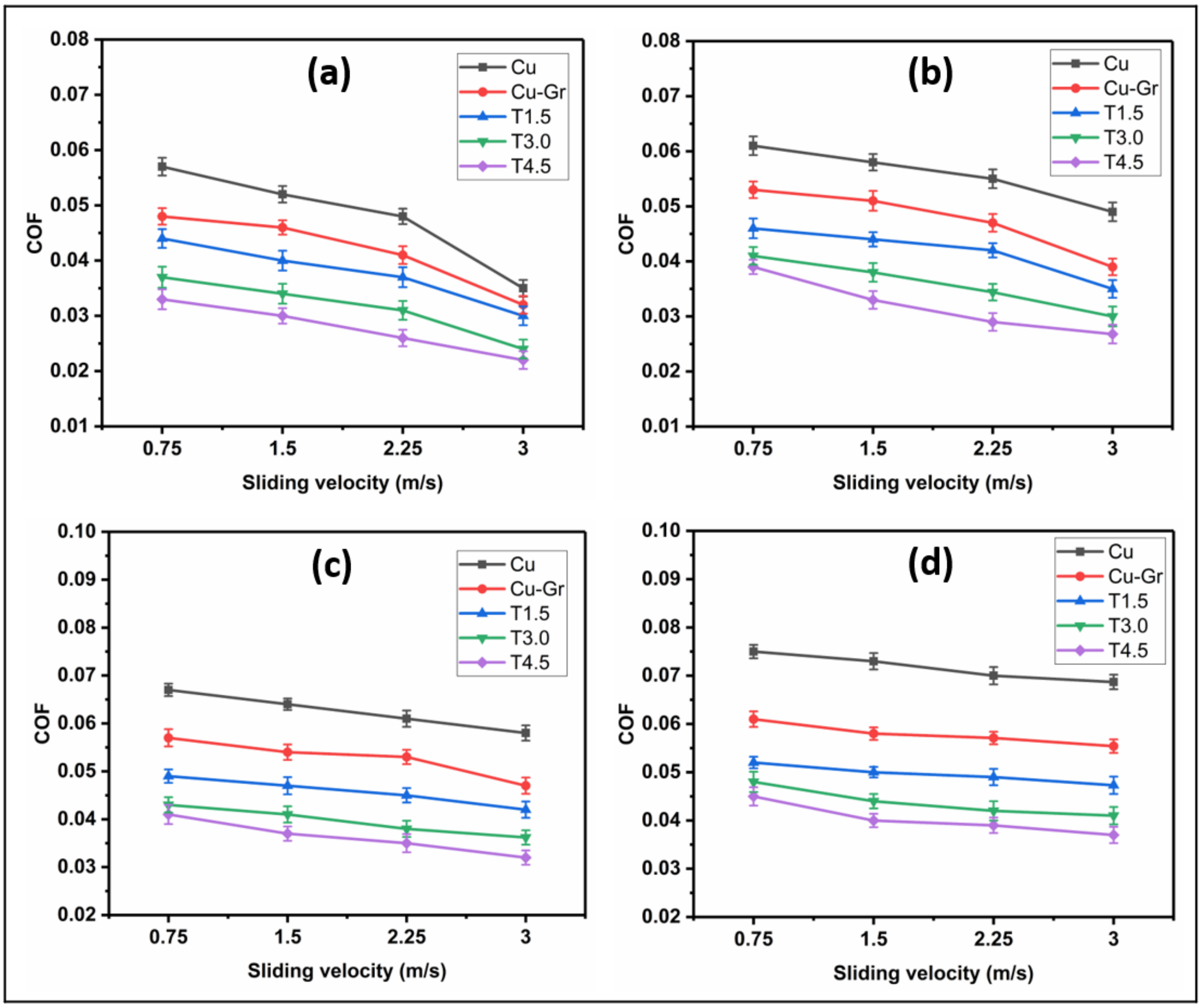

Fig. 5.6 Influence of sliding velocity on COF at sliding distance of 8000 m and various applied loads (a) 10 N (b) 30 N (c) 50 N (d) 70 N

For Cu-Gr composite at higher velocity, lubricating oil reduces the area of contact between the counter disc and pin sample which causes a decrease in COF. Also, at high sliding velocities, the COF is also observed to be decreasing for the T1.5–T4.5 composites. The decrement in COF value of T1.5, T3.0 and T4.5 composites with the increase in velocity from 0.75 m/s to 3 m/s for 70 N load and 8000 m sliding distance are 9%, 14.5% and 18%, respectively. At the contact surface between pins and counter disc, high velocity leads to a phenomenon of mixed lubrication. Also, at higher velocities a substantially thick lubricant film forms that isolates the mating surfaces from each other. Consequently, the contact frictional features get lessened.

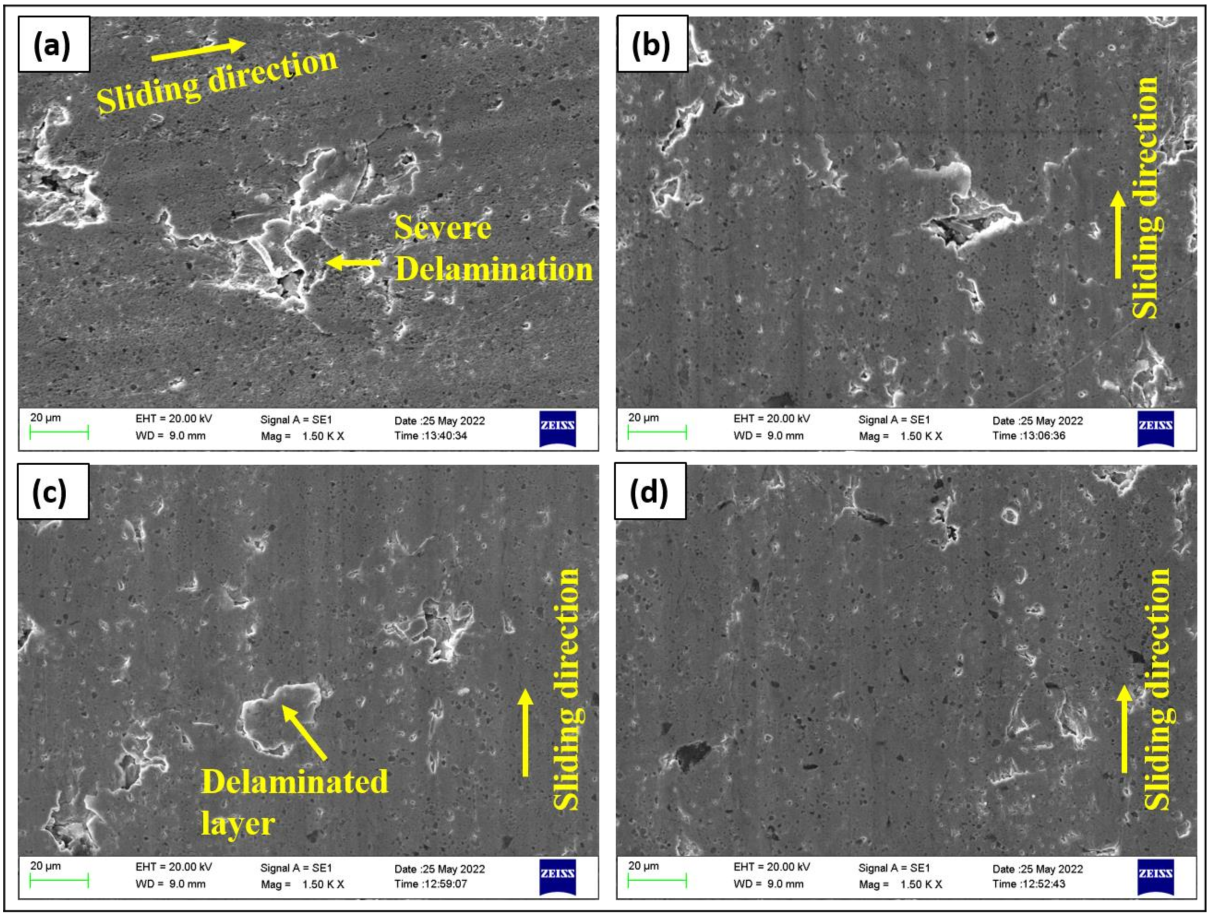

Fig. 5.7 SEM image of worn surface of T3.0 composite at 70 N load and 8000 m of sliding distance and sliding velocity of (a) 0.75 m/s (b) 1.5 m/s (c) 2.25 m/s (d) 3 m/s

Figures 5.7 (a-d) depict the worn surfaces of the T3.0 composite under varying sliding velocity from 0.75 m/s to 3 m/s at fixed load of 70 N. It is seen that at low velocity severe delamination occurs with multiple abrasion grooves on the surface. However, as the velocity increases, it observed a drastic reduction in the intensity of delaminating wear. At 3 m/s sliding velocity, a smooth surface is seen with finer debris particles.

AFM was employed to assess the unevenness and surface roughness of the worn-out surfaces. Figures 5.8 (a-d) illustrate the 3D AFM images of worn surface of T3.0

composite at different sliding velocity 0.75 m/s to 3 m/s. The AFM images vividly illustrate fluctuation of surface roughness from 1.6 µm to 600 nm of valley depth to peak height. This observation is consistent with the findings related to wear rate.

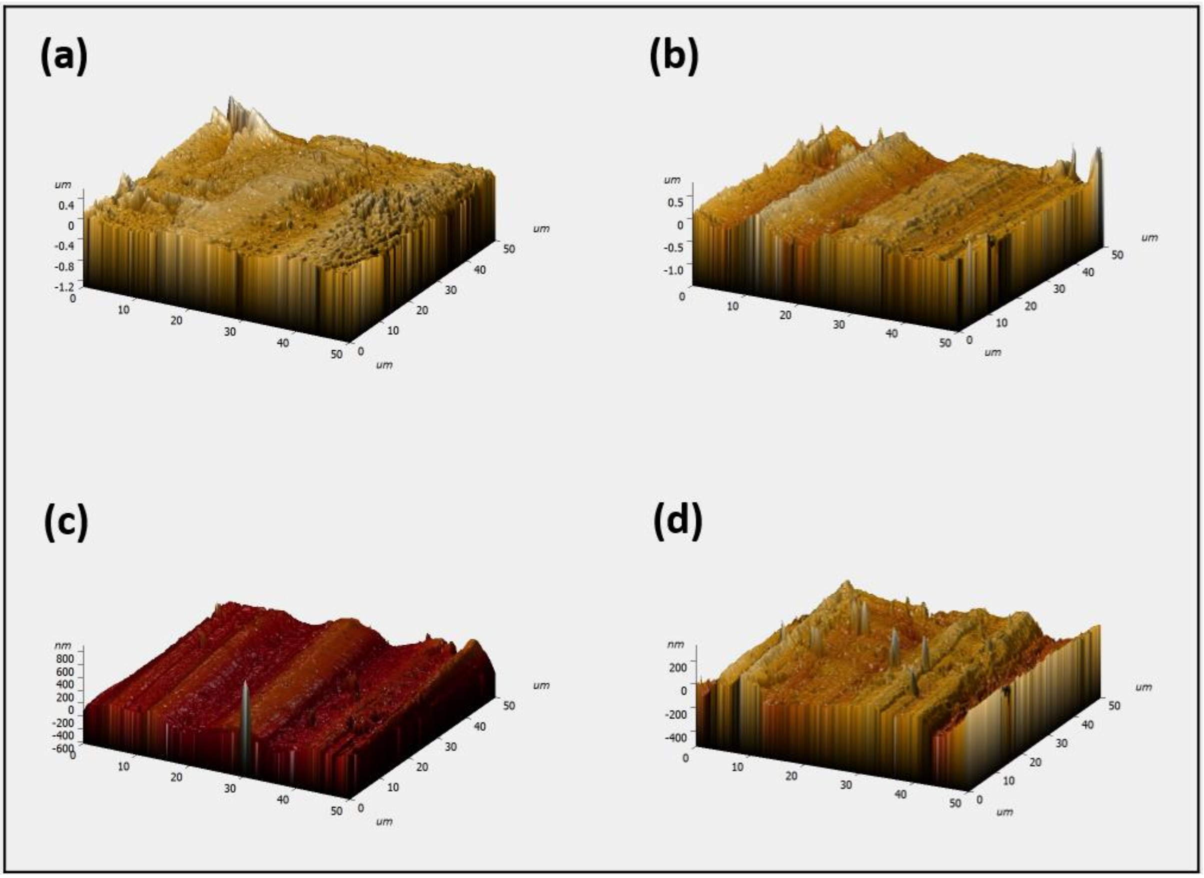

Fig. 5.8 AFM image of T3.0 composite at 70 N load and 8000 m of sliding distance and sliding velocity of (a) 0.75 m/s (b) 1.5 m/s (c) 2.25 m/s (d) 3 m/s

5.2.3 Influence of load

Figures 5.9 (a-d) show the effect of load on wear rate of various compositions at varying sliding distance 2000 m - 8000 m. It is clearly depicted that the rise in wear rate of all compositions occurs with increasing load. Further, the T4.5 composite having maximum amount of TiC particles has the lowest wear rate for each applied load [P. Sahoo and J.M. Koczak, 1991] Many researchers have reported similar outcomes in their prior literature

[Ghasali et al., 2017, A.K. Yadav] The lubricant forms a protective layer at lower loads, hence, the low wear rate.

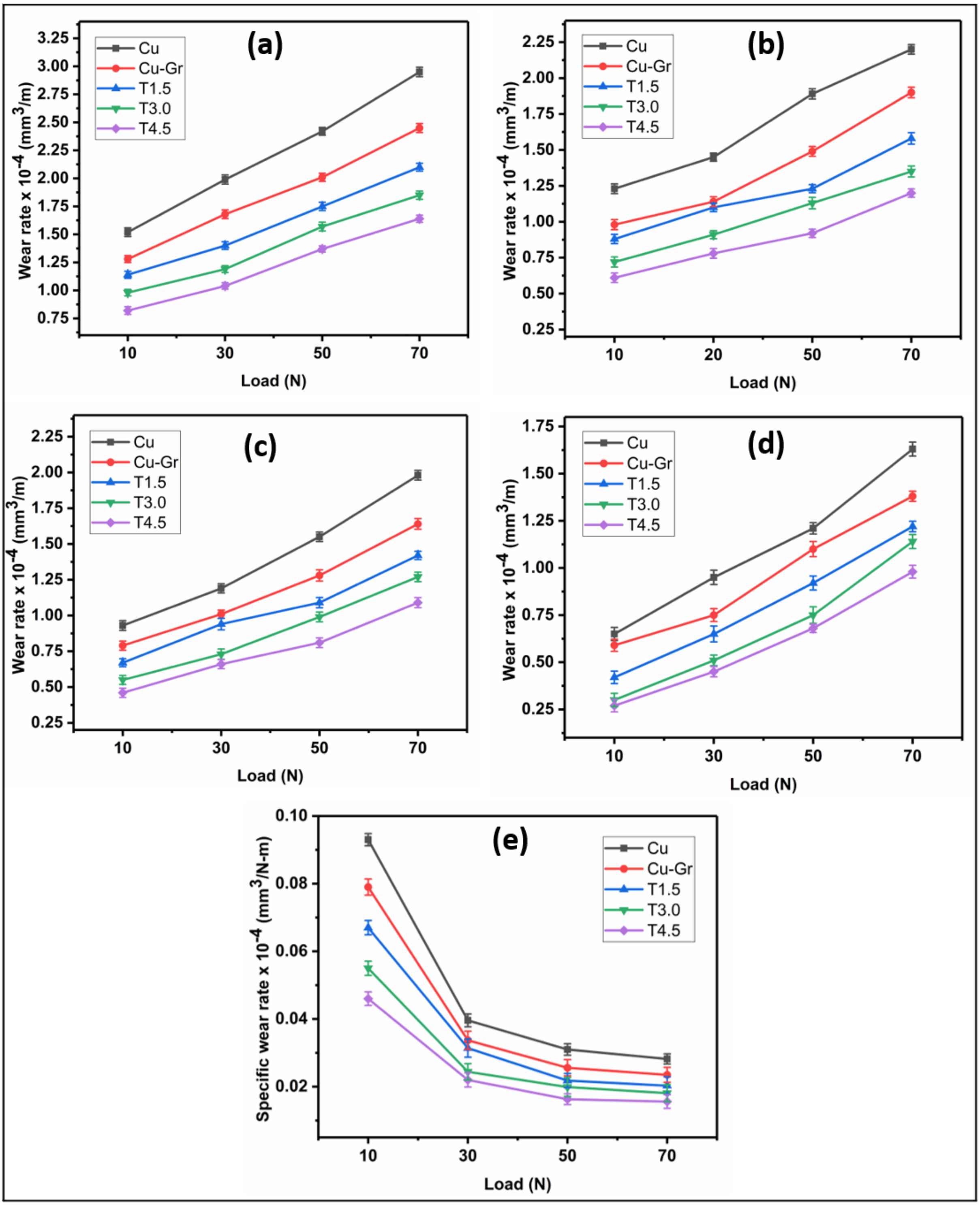

Fig. 5.9 Influence of applied load on wear rate at sliding velocity of 3 m/s and sliding distance of (a) 2000 m (b) 4000 m (c) 6000 m (d) 8000 m and (e) Specific wear rate at 6000 m sliding distance

However, for all the compositions it is seen that as the load is raised high wear rate occurs because at high loading condition the prominent lubricant film starts to break and the contact area of sample pins gets exposed against the counter surface. In case of the TiC reinforced composite samples when there is increase in applied load, even though the hardness of samples is more, the plastic deformation of the pins is more. This increase in deformation leads to closing of surface pores which reduce the lubricant retention ability of pin samples and, hence, increase in wear rate. The penetration of hard TiC particles reduces the lubrication effect at higher loads which leads to more wear.

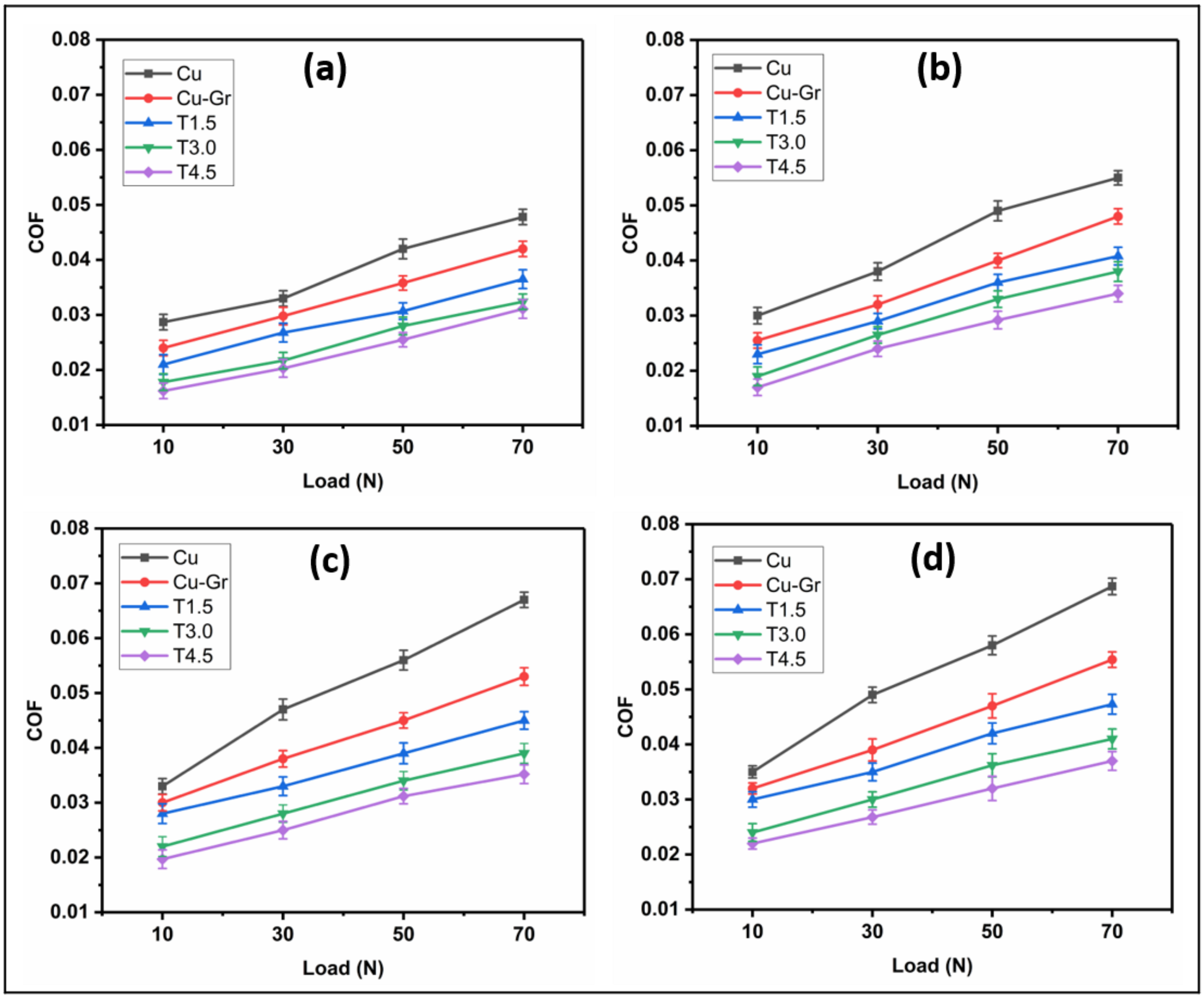

Fig. 5.10 Influence of applied load on COF at sliding velocity of 3 m/s and sliding distance of (a) 2000 m (b) 4000 m (c) 6000 m (d) 8000 m

Figure 5.9 (e) illustrates the effect of load on specific wear rate at 6000 m sliding distance. It is seen that specific wear rate decreases with the load. However, the decrement in specific wear rate is low at higher loads. Further, Figure 5.10 (a-d) depicts the influence of applied loads on COF of all compositions at different sliding distance (2000 m- 8000 m). It is inferred that with 10 N to 70 N rise in load, the increase in the COF is 94% for pure copper sample and 68% for 4.5 wt.% TiC reinforced composite, respectively for sliding distance of 8000 m. It shows composites depict improvement in reducing COF in lubricating environment. Also, higher applied load leads to easy removal of lubricant layer and thereby increasing the COF for all compositions.

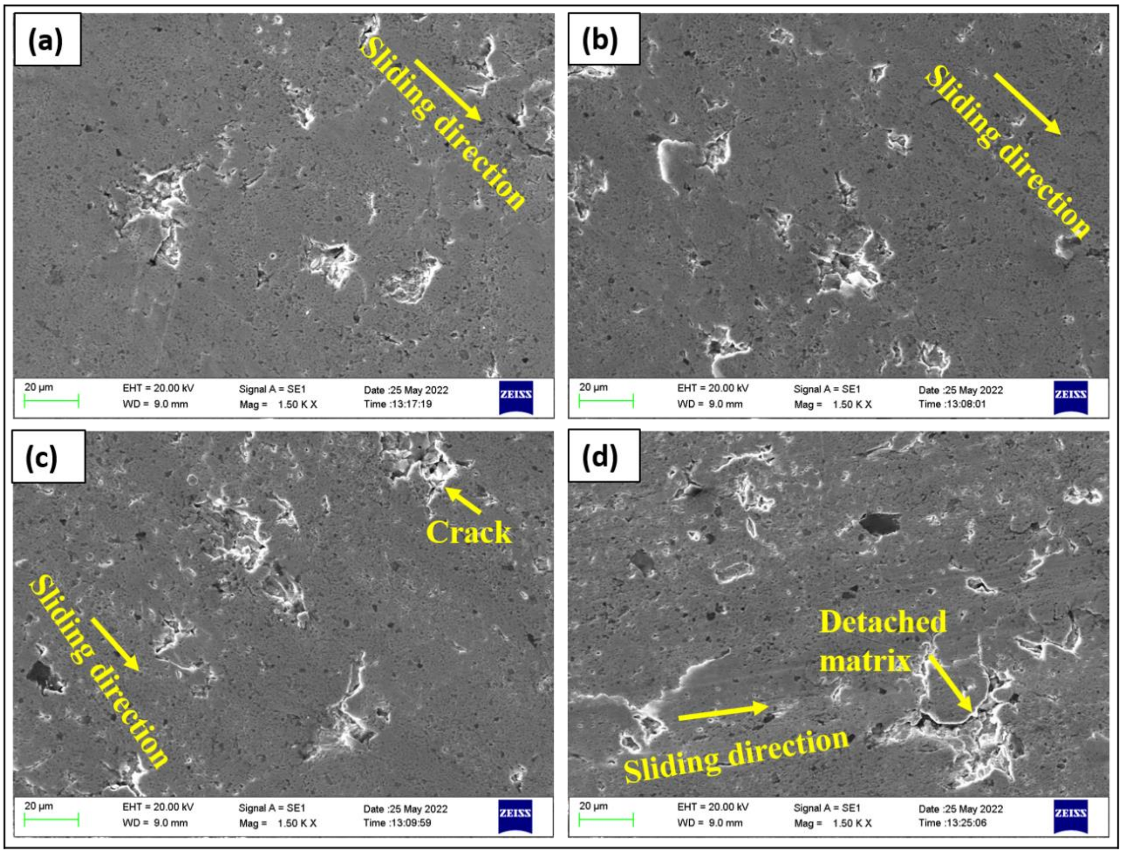

Fig. 5.11 SEM images of worn surface of T3.0 composite at 8000 m of sliding distance and applied load of (a) 10 N (b) 30 N (c) 50 N (d) 70 N

Figure 5.11 shows the SEM image of the worn surface of the T3.0 composite at constant sliding distance of 8000 m. It is inferred that as the applied load is raised, the delamination of the pin sample increases.

Also, at higher load the lubricating film breaks causing direct contact among the mating surfaces. Due to which some cracks are observed leading to higher amount of delamination at larger loads. Further, at load of 70 N the wear is maximum as the matrix material gets detached at some places. The AFM images of worn surface are presented in Fig. 5.12 (a-d) to examine the surface roughness of the T3.0 composite under varying loads. It is seen that as the applied load goes up from 10 N to 70 N, there is a corresponding rise in the average peak height to valley depth, increasing from 400 nm to 1 µm. The SEM image of worn surfaces and surface roughness are found to be in similar trends with the result of wear rate.

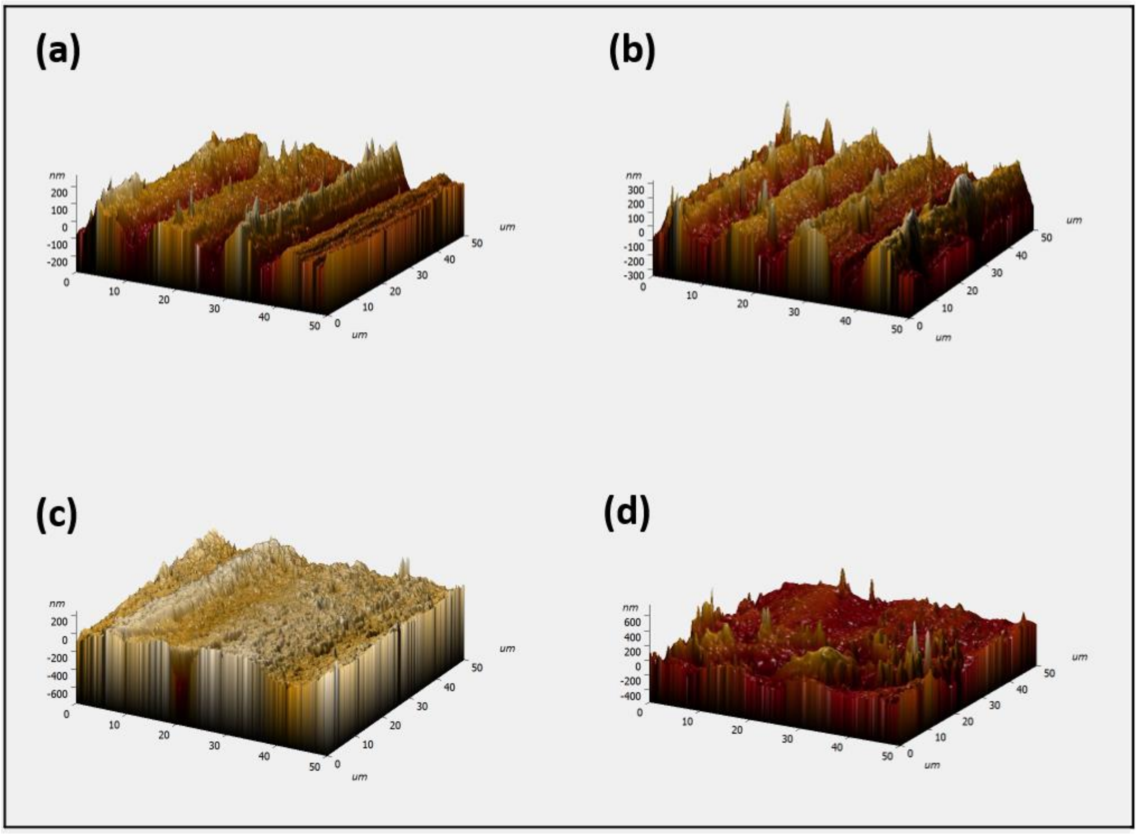

Fig. 5.12 AFM image of T3.0 composite at 8000 m of sliding distance and applied load of (a) 10 N (b) 30 N (c) 50 N (d) 70 N

5.2.4 Influence of TiC content

Figure 5.13 (a-d) shows the effect of reinforcements in copper matrix on the wear rate at various sliding distance 2000 m - 8000 m and 3 m/s sliding velocity. It is seen that the wear rate is reduced with addition of graphite to Cu matrix as well as with rise in the content of TiC particles. It is observed although the composite containing graphite particles has reduced hardness than copper, its wear rate is significantly lower because the graphite has self-lubricating properties [Xiao-Ming et al., 2017, L. Su et al., 2015].

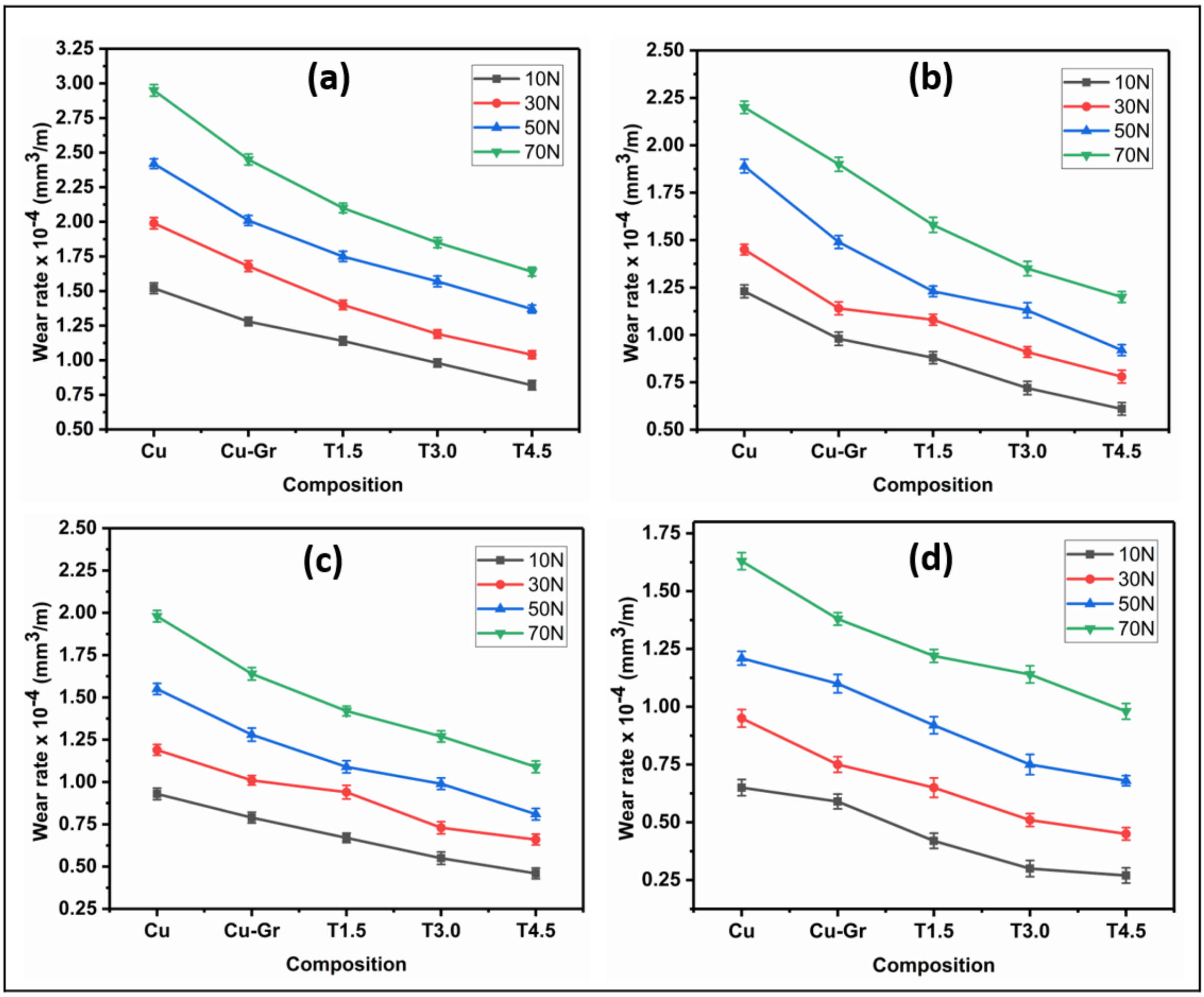

Fig. 5.13 Influence of Gr and TiC content on wear rate at constant sliding velocity of 3 m/s and different sliding distance of (a) 2000 m (b) 4000 m (c) 6000 m (d) 8000 m

Graphite forms a lubricating film when the pin sample is in contact with the hardened steel counter surface. In addition, the lubricating oil also sticks to the sample forming a layer and also helps in isolating the sample from the steel surface. Both graphitic film and oil layer restrict the severe adhesion of ductile Cu against counter surface thus enhances the wear resistance of the Cu-Gr composite. Because of the hard TiC particles that are present in the composite, the wear resistance of TiC reinforced composites improves when weight percentage of TiC is increased. At 70 N load and 8000 m sliding distance, the wear rate of T4.5 composite decreases by 40% in comparison to pure Cu and it has 19.6% and 14% less wear rate than T1.5 and T3.0 composites, respectively. The TiC particles when exposed with the counter disc carry the load and inhibit the surface deformation of matrix material and thus lowering the rate of wear. As the amount of the reinforcing TiC particles is increased (T1.5 to T4.5), the porosity percentage also increases. The pores that are present on the sub surface of the composites let the lubricant to settle onto them. These pores act as a reservoir for the lubricant and during wear test they come out forming a protective layer on the pin sample. Hence, the wear rate reduces with the rise in content of TiC reinforcements.

Figure 5.14 (a-d) demonstrates the variation of COF value with respect to the reinforcements. On application of load, the graphite particles spread at the contacting surfaces. Smeared away graphite creates a transition layer along with the lubricant oil layer that decreases the direct contact of hard steel disc to the composite pins. It causes a substantial decrement in the coefficient of friction. From the Figure 15.4(d) for 70 N applied load and 8000 m sliding distance, it was inferred that T4.5 composite has least COF value of 0.037 which was 32%, 21% and 9.7% less compared to Cu-Gr, T1.5 and T3.0 composites, respectively. Also, the coefficient of friction value gets reduced as the amount of TiC particles is raised. This reduction in COF is due to the influence of lubricant present during the wear test. The porosity value increases with TiC content resulting in more accumulation of lubricant in the pores on the surface. With increase in content of TiC the porosity percentage rises, which in addition with the lubricant oil causes a combined effect in the reduction of the overall COF of the TiC reinforced composites.

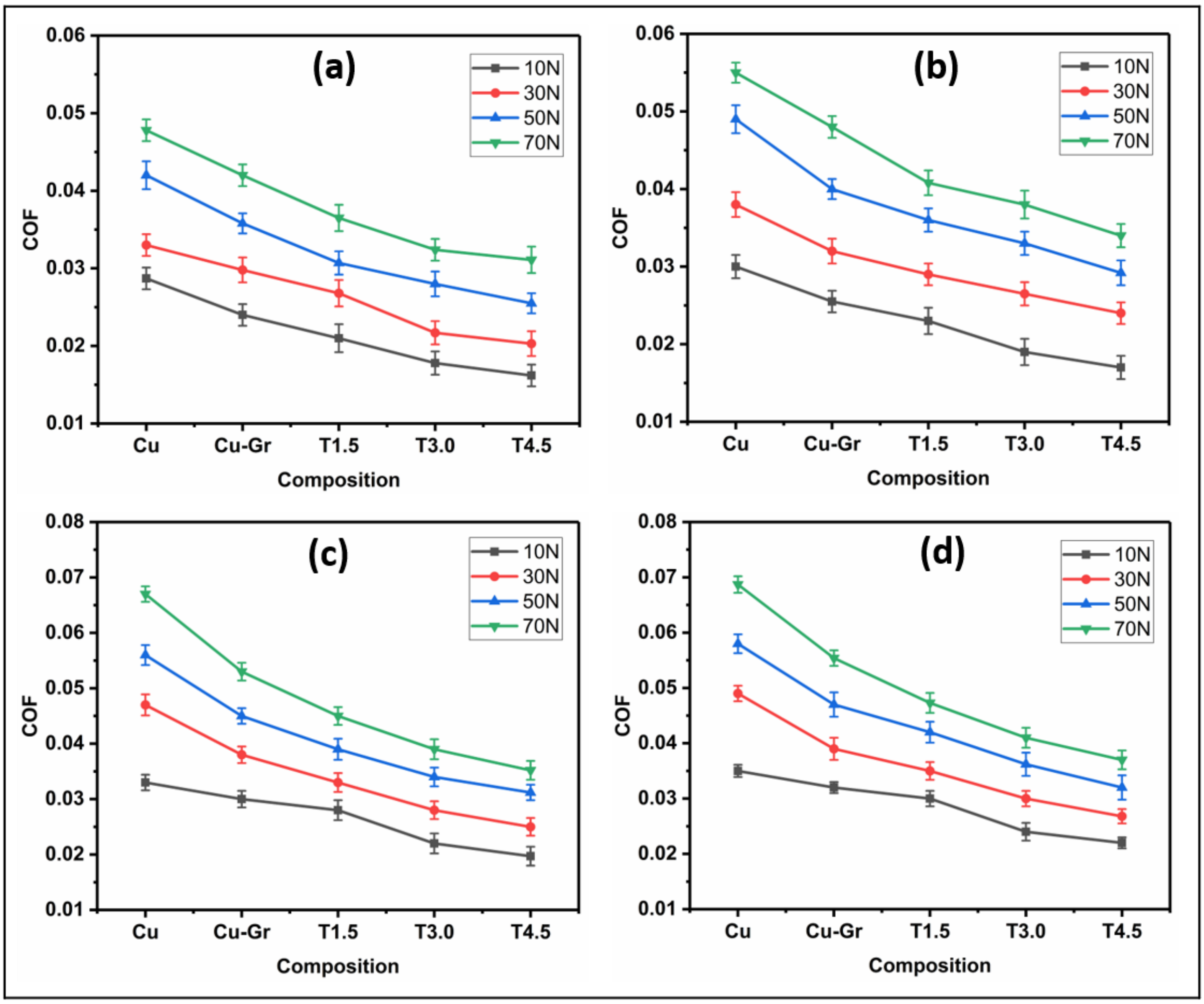

Fig. 5.14 Influence of Gr and TiC content on COF at constant sliding velocity of 3 m/s and different sliding distance of (a) 2000 m (b) 4000 m (c) 6000 m (d) 8000 m

Using Archard's wear equation, the wear coefficient is also determined. Figure 5.15 shows the wear coefficient of Cu, Cu-Gr and T1.5-T4.5 composites at 10 N and 50 N load and constant sliding distance of 8000 m. It was revealed that wear coefficient of Cu and composites decreases with increasing load. It was observed that as the TiC content in the composites increased, there was a corresponding reduction in the wear coefficient. This can be attributed to higher hardness of the composites than Cu that results in lower formation of wear particles. It may be because the surface of composites is protected by the reinforcements during the plastic deformation. However, when TiC content is more than 3 wt.% wear coefficient values are in similar range.

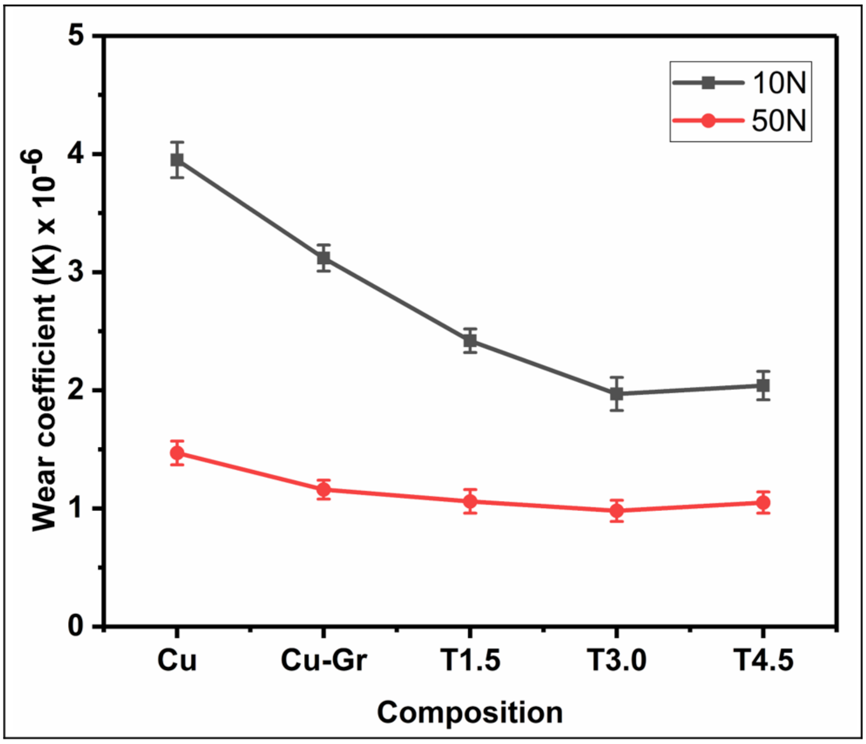

Fig. 5.15 Influence of Gr and TiC content on wear coefficient at constant sliding distance of 8000 m

Figures 5.16 (a-e) depicts the SEM images of worn surfaces for Cu, Cu-Gr and TiC reinforced composites with varying amount of TiC particles at constant applied load of 70 N and sliding distance of 8000 m. The pure copper (Cu) sample depicted many wear grooves and deep ploughing. The abrasion and deep ploughing are dominant in the Cu implying substantial wear of material. The Cu-Gr composite having 5 wt.% graphite depicted smooth ploughing marks which are significantly less severe than Cu thereby confirming less damage. From Figure 5.16 (c) to (e), it is revealed that as the TiC content is increasing, the worn surface is becoming smooth with some amount of delamination. The pores are seen on the samples which enable retention of the lubricating oil and, hence, a smoother surface is obtained.

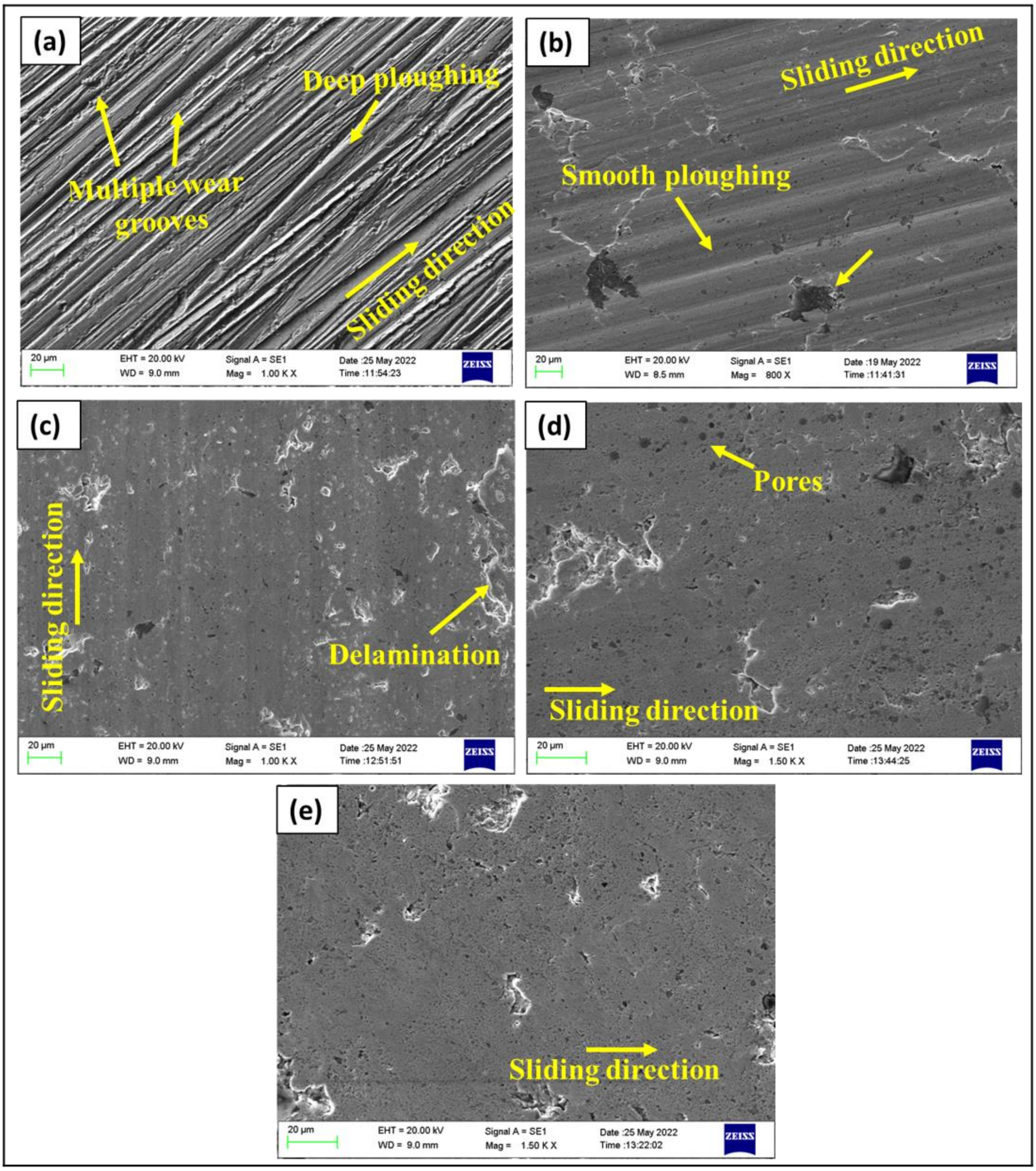

Fig. 5.16 SEM images of worn surface at 70 N load and 8000 m of sliding distance for (a) Cu and composites (b) Cu-Gr, (c) T1.5, (d) T3.0 and (e) T4.5

Figure 5.17(a-e) presents the 3D AFM images of worn surfaces of Cu, Cu-Gr and TiC composites with different amount of TiC particles. The surface roughness and unevenness get reduced with incorporation of reinforcements in the Cu matrix. The average peak-to-valley height exhibits a decrease from 2.0 μm to 0.4 μm as the reinforcement particle content is increased to 4.5 wt.% TiC. These findings align with the observed patterns in wear rate and the condition of the worn surfaces.

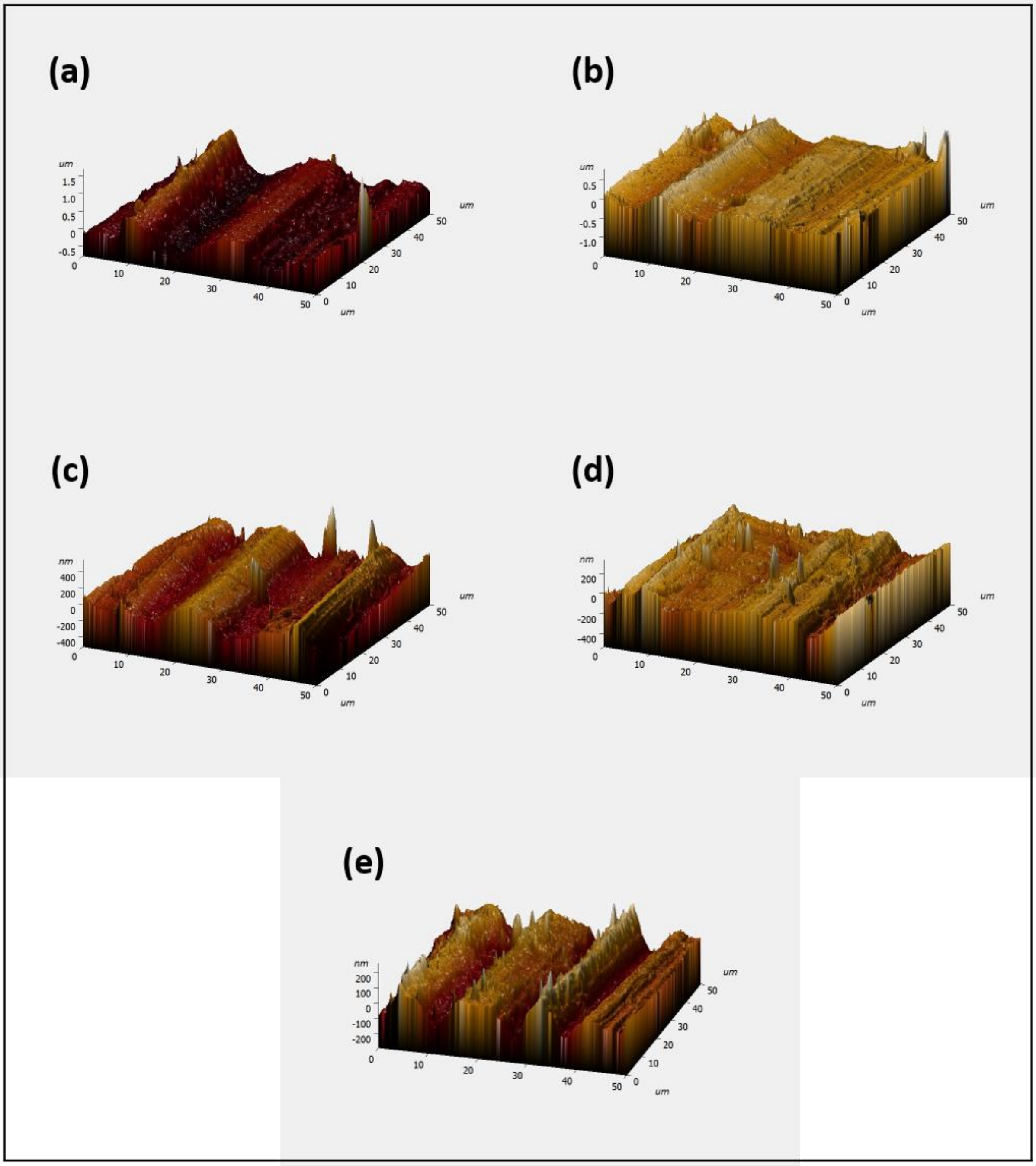

Fig. 5.17 AFM images of worn surface at 70 N load and 8000 m of sliding distance for (a) Cu and composites (b) Cu-Gr, (c) T1.5, (d) T3.0 and (e) T4.5

5.2.4.1 Topographical parameters of worn surface

Surface topographical parameters were also determined for the different AFM micrographs of varying compositions and their values are provided in Table 5.1.

Table 5.1 Topographical parameters of all compositions

Composition	Average roughness S_a (nm)	Root mean square roughness S_q (nm)	Area peak-to valley height S_t (nm)	Skewness (S_{sk})	Kurtosis (S_{ku})
Cu	212.058	265.307	2476.455	0.431	6.953
Cu-Gr	106.325	140.387	2281.216	0.219	4.475
T1.5	75.752	92.374	1067.056	-0.072	2.777
T3.0	46.094	58.364	870.108	-0.108	3.099
T4.5	52.774	66.458	558.959	-0.408	2.993

Surface texture scans of worn surfaces are utilized to measure key topographical parameters that play a pivotal role in determining tribological properties. These parameters have been explained in previous chapter under section 4.2.4.1. However, in lubricating condition the values of the parameters are different. From Table 5.1, it is found that that average roughness, S_a value reduces from 212.058 nm to 52.774 nm with increase in the reinforcement contents. The S_a values are less than the S_q values for respective samples. Additionally, the S_t value exhibits a consistent decrease from the Cu to the T4.5 composite and minimum value of S_t is 66.458 nm for T4.5 composite. A continuous negative skewness values imply cracks, indications of valleys. The negative values of S_{sk} suggest a strong load bearing capacity. The skewness value is more negative as TiC content increases, further indicating an increase in load bearing capability for TiC reinforced composites (S_{sk} for T4.5 composite is −0.408). The kurtosis value S_{ku} is close to 3 for the composites implying that there are relatively fewer high peaks and deep valleys over the scanned area for composites and a bumpy surface exists for the composites. However, for the pure copper Cu sample S_{ku} value is 6.953 which is much higher than 3, as a result its distribution will be having a large number of high peaks and deep valleys with spikes over the surface. Pure Cu has both high S_{ku} value and a high S_t value indicating rougher surface than the composite. It may be due to the strong correlation between these parameters, where peak heights and valley depths are directly related with S_{ku}.

5.3 CONCLUSIONS

The conclusions drawn from this chapter can be summarized as follows:

- In case of lubricating medium, the porosity plays a key role in improving the wear performance by acting as microcavities on surface which increases the retention capacity for the oil.
- The graphite particle inclusion causes a reduction in the wear rate and COF of Cu matrix and further addition of TiC particles results in significant decrease in both wear and COF, which widens the scope of present composites in tribological applications.
- With rise in applied load and sliding distance, the wear and COF of all composition increases. But with increase in sliding velocity, the wear and COF reduces at high velocities due to formation of thick film of lubricating oil that reduces the actual contact between samples and counter disc.
- The minimum wear rate and COF among all compositions was exhibited by the T4.5 composite owing to the influence of both Gr and TiC particles.

- The worn surface analysis illustrates that under lubrication the dominant wear mechanism for pure Cu is abrasion and deep ploughing. Deep ploughing action did not occur for the Cu-Gr composites instead smooth surface is observed. However, for the TiC reinforced composites, wear is a combination of smooth surface and some amount of delamination.
- The topographical parameters depicted better load bearing capacity and less roughness values for 4.5 wt.% TiC reinforced Cu-Gr composite.