CHAPTER 4

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

4.1 INTRODUCTION

In the field of composite materials, the composition, dispersion of reinforcements, and their morphology are pivotal factors influencing their tribological properties. This chapter investigates the tribological characteristics of Copper-Graphite-TiC composites under dry sliding conditions. The study explores the tribological behavior across various parameters including sliding distance, applied load, sliding velocity, and the weight percentage of TiC. Worn surfaces of the composites have been examined under SEM attached with EDS and AFM. Obtained results have been correlated with the topographical study of worn surfaces.

4.2 WEAR & FRICTION BEHAVIOR UNDER DRY SLIDING

4.2.1 Influence of sliding distance

Figures 4.1 (a-d) and 4.2 (a-d) illustrates influence of sliding distance on the wear volume and COF, respectively for Cu, Cu-Gr composite and T1.5 to T4.5 composites at various loads of 10 N to 40 N. Fig. 4.1 indicates that wear volume increases linearly with the sliding distance for all the compositions. Which may be due to the domination of adhesive component of wear leading to sticking of surface over time and with extended sliding distances. Also, for pure Cu samples there is a sharp increase in wear volume due to large amount of adhesion with the counter disc. However, under higher applied loads and sliding distances, the interfacial temperature on the composite pin surface experiences a rise due to frictional heating during sliding. In such conditions, the asperities of the soft matrix phase tend to deform, and the contact points are predominantly formed by hard particles in case of TiC reinforced composites which restricts wear at lower values even at higher applied loads. TiC reinforcement particles results in the achievement of a steady state wear condition at an earlier stage. This can be attributed to a reduction in adhesive forces due to reinforcement of hard particles. Chourasiya et al. (2021) have also reported similar results.

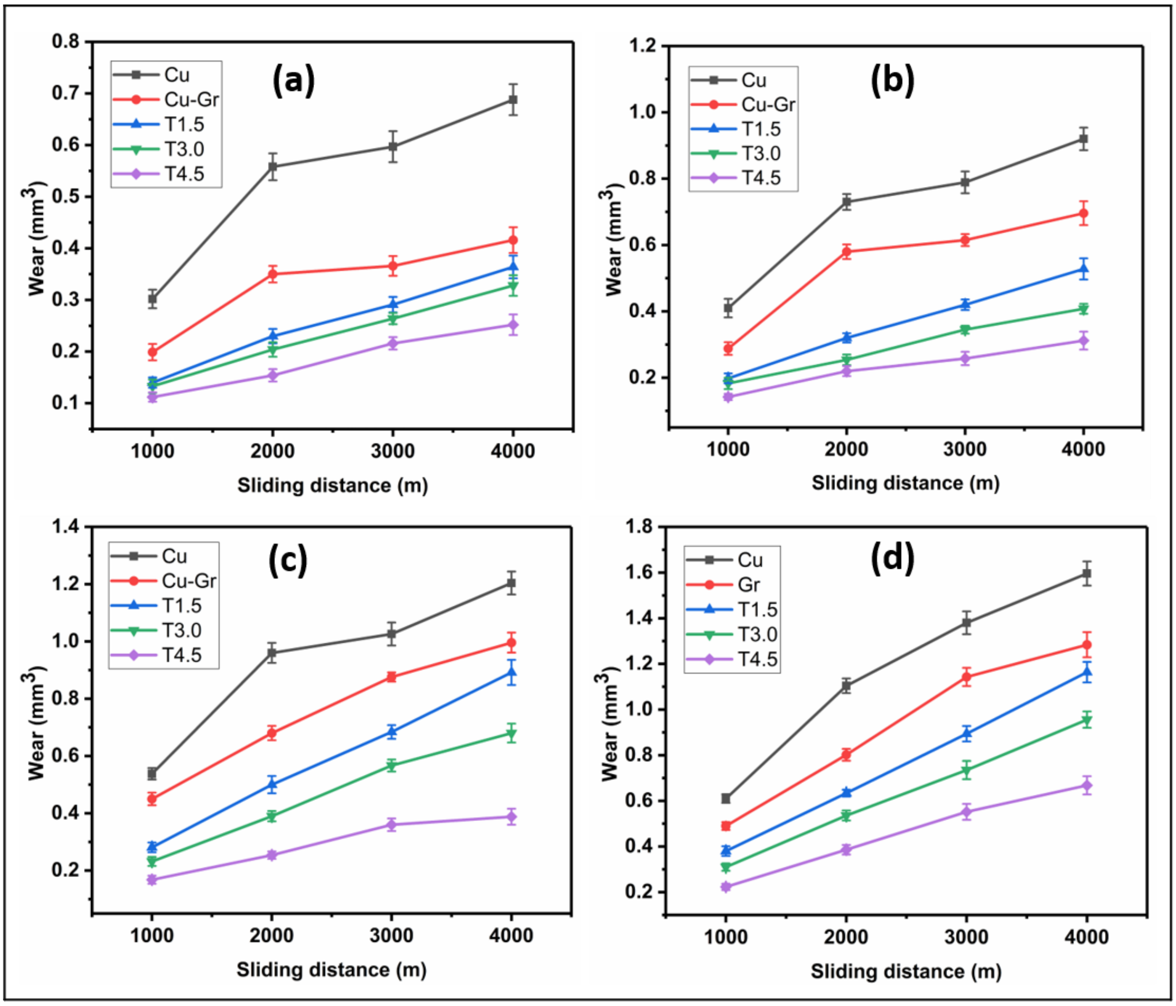

Fig. 4.1 Influence of sliding distance on wear volume at various applied loads (a) 10 N (b) 20 N (c) 30 N (d) 40 N

In Fig. 4.2, the impact of sliding distance on the coefficient of friction (COF) for both Cu and composites is shown. The observed variations in COF are closely linked to the adhesion occurring between the surfaces in contact. As the sliding distance extends, the temperature at the pin contact area rises causing increased softening of the material leading to more deformation of the composites. However, the Cu-Gr and T1.5- T4.5 composite depicted less COF than pure Cu at each sliding distance implying better wear resistance.

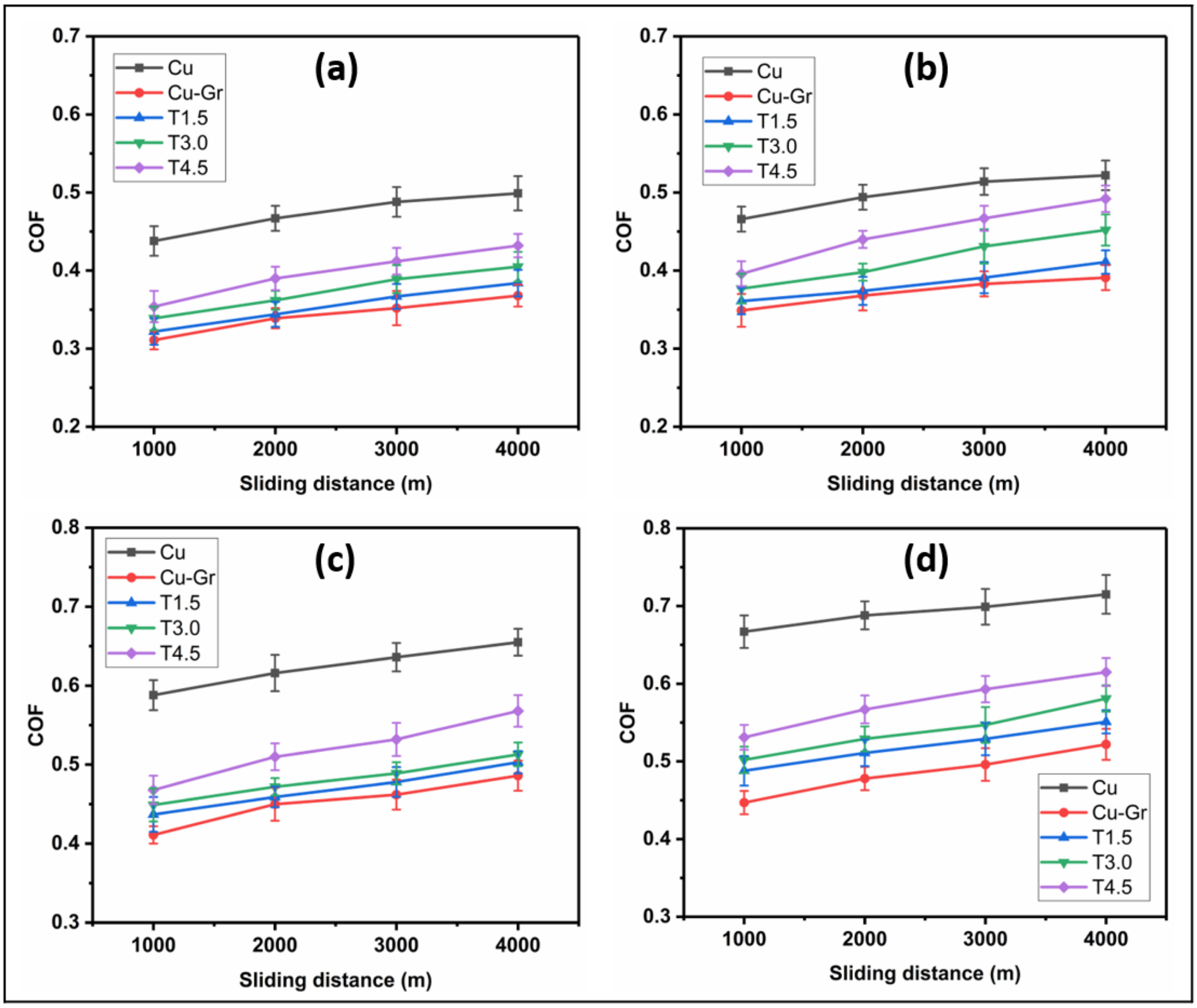

Fig. 4.2 Influence of sliding distance on COF at various applied loads (a) 10 N (b) 20 N (c) 30 N (d) 40N

SEM and AFM analysis were conducted to study the worn surface of composites in order to better comprehend the wear mechanism. Figures 4.3 (a-d) portrays the SEM image of worn surfaces of T3.0 composites with different sliding distance of 1000 m-4000 m. From the worn surface it is inferred that at lower sliding distances less wear is observed compared to higher ones. At shorter sliding distances, the worn surface displays shallow ploughing and minimal delamination.

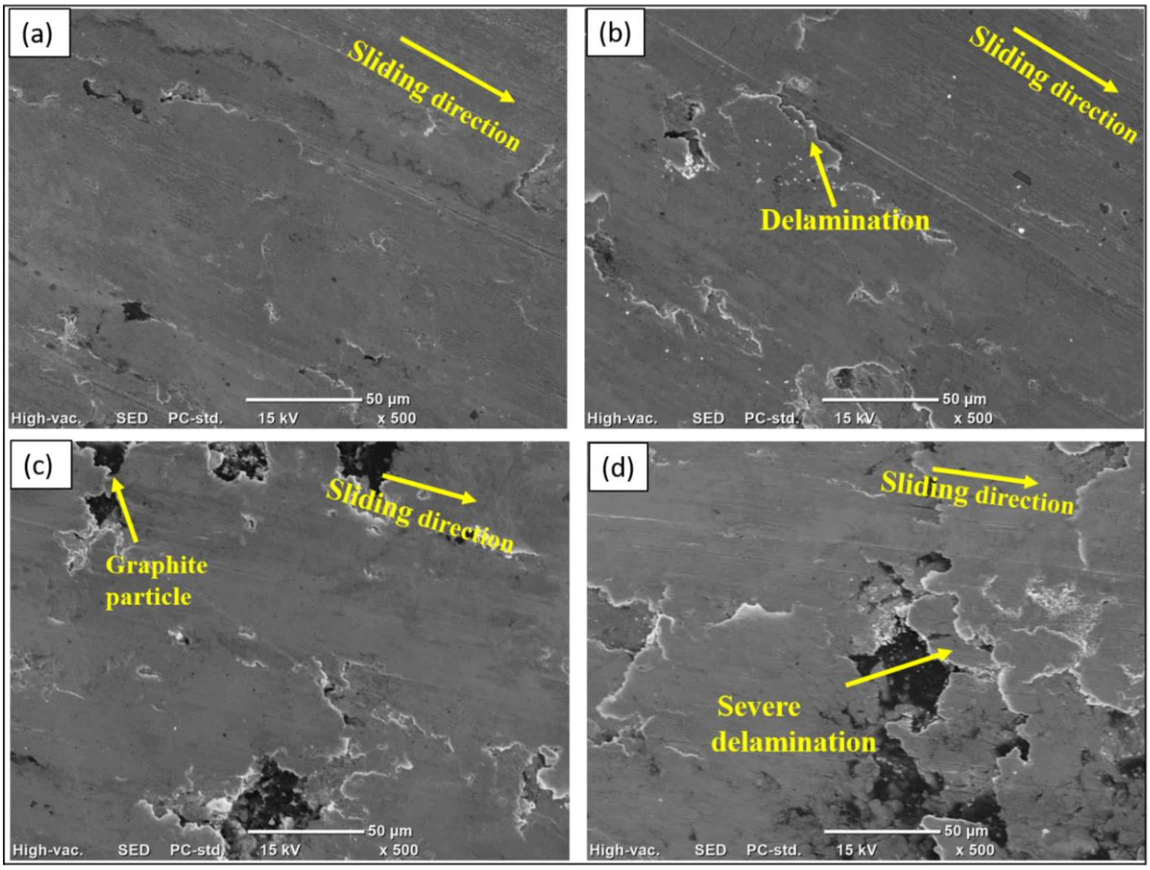

Fig. 4.3 SEM images of worn surface of T3.0 composite at load of 30 N and sliding distance of (a) 1000 m (b) 2000 m (c) 3000 m (d) 4000 m

The temperature at the interface of composite pin sample and the counter face increases when sliding wear occurs that causes softness to the composite sample. However, at larger distances interfacial temperature is high which combined with softness of the composite pin causes greater deformation and significantly impacts the surface features of the composite pins. Therefore, at larger sliding distance of 4000 m, the worn surface exhibits extensive delamination and development of cracks. These observed features on the worn surfaces align with the findings from the wear behaviour as depicted in Fig. 4.1.

Figure 4.4 illustrates the Atomic Force Microscopy (AFM) image depicting the worn surface of T3.0 composite under a 30 N load, with varying sliding distances. The micrograph distinctly shows that as the sliding distance is increased from 1000 m to 4000 m, there is a noticeable rise in peak and valley heights, increasing from 500 nm to 1 μm. The findings of AFM are in line with those obtained in SEM of worn surface at varying sliding distances implying more wear at higher distances.

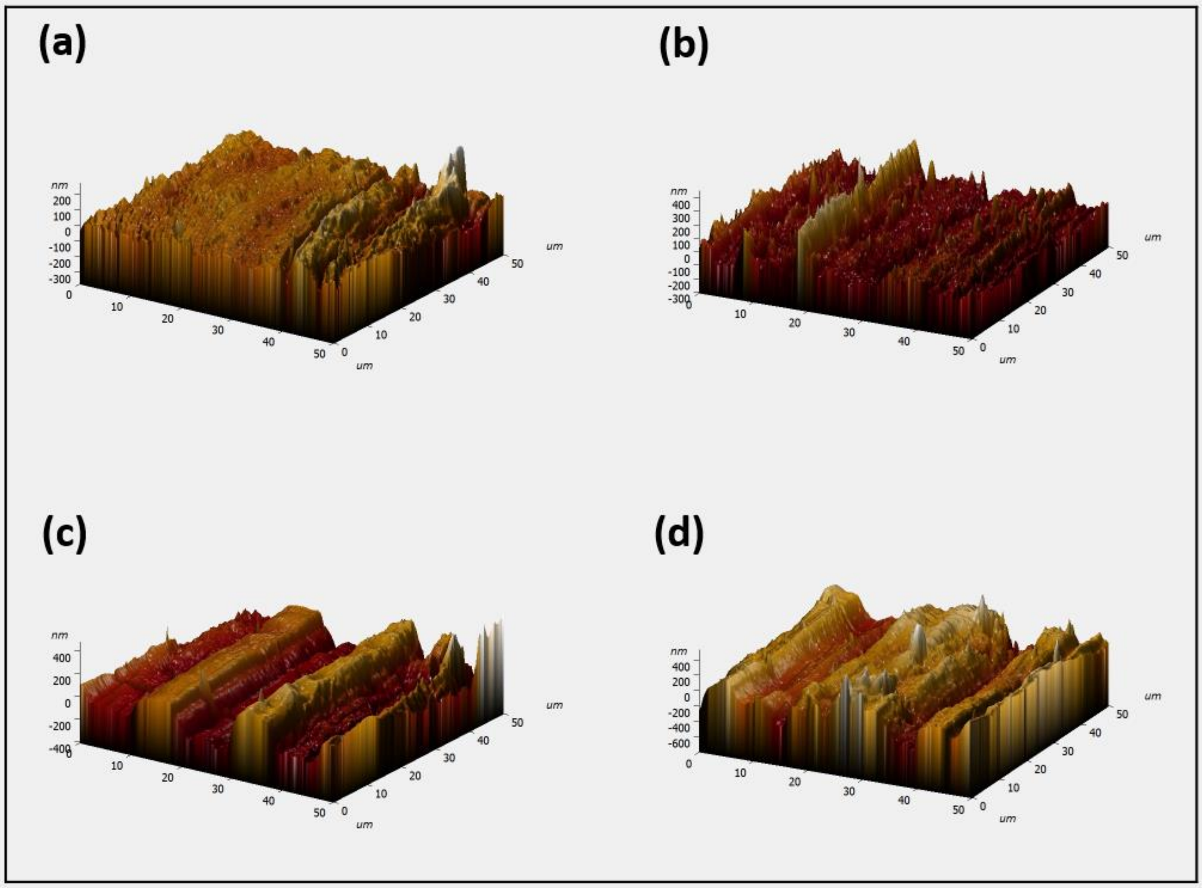

Fig. 4.4 AFM image of T3.0 composite at 30 N load and sliding distance of (a) 1000 m (b) 2000 m (c) 3000 m (d) 4000 m

4.2.2 Influence of sliding velocity

Figures 4.5 (a-d) and 4.6 (a-d) present the effect of sliding velocity on wear rate and COF of Cu, Cu-Gr composite and T1.5-T4.5 composites at various loads of 10 N to 40 N. The Fig. 4.5 suggests for all compositions that the wear rate increases with an increase in sliding velocity from 0.75 m/s to 3 m/s. In the case of Cu-Gr composite, the high velocity causes the graphitic film to break which leads to the absence of lubricative action that causes more wear rate. The temperature of the worn surface may also increase as the sliding velocity rises and the surface softening may take place owing to frictional heating. TiC reinforced composites exhibited a markedly lower wear rate in comparison to Cu and Cu-Gr composite. However, the incorporated hard particles in the composites may also get out of the surface and may work as a third body at the interface which contributes in wear rate. The same phenomenon is also observed by Buytoz et al., (2018).

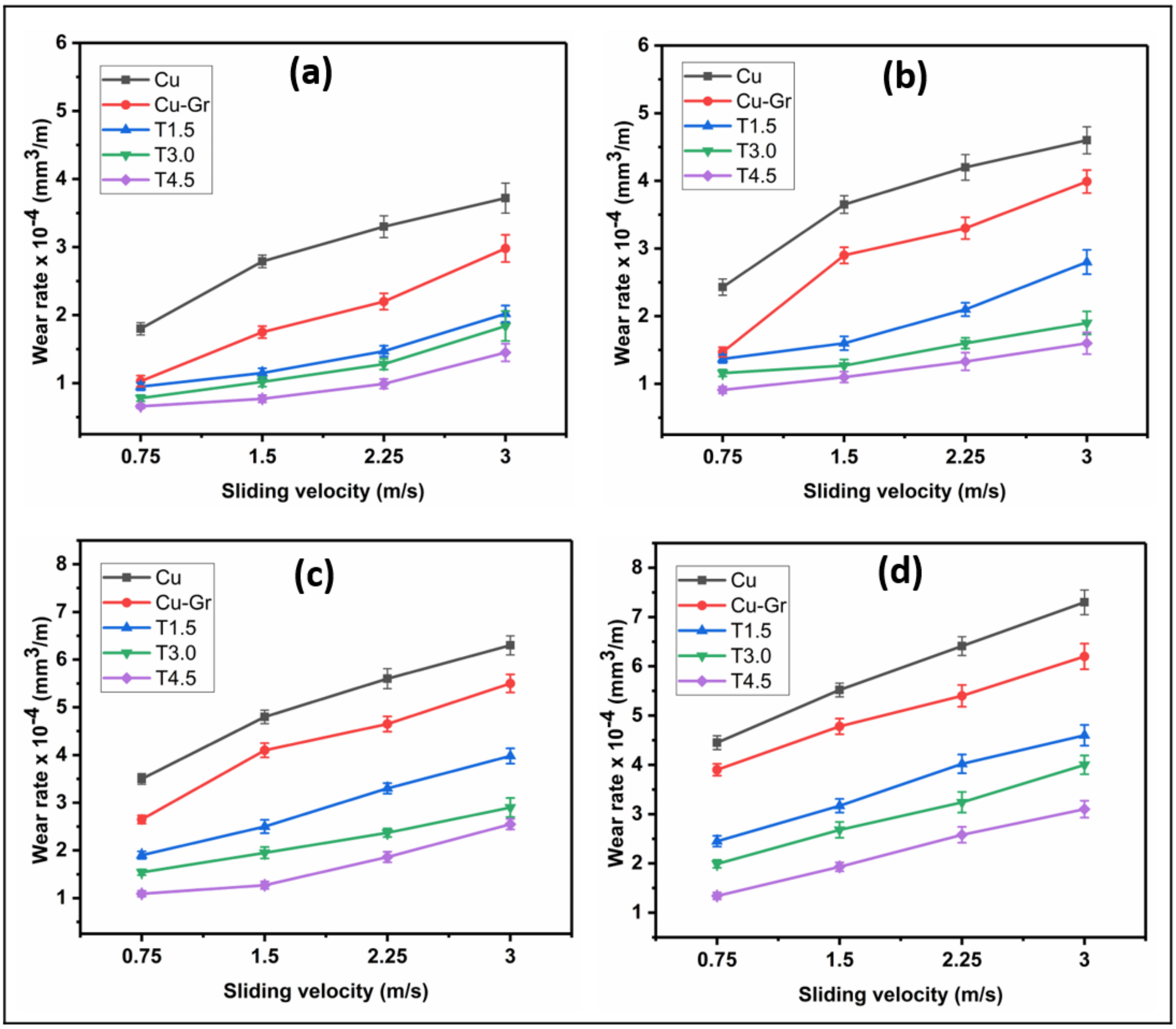

Fig. 4.5 Influence of sliding velocity on wear rate at sliding distance of 3000 m and different applied loads (a) 10 N (b) 20 N (c) 30 N (d) 40 N

Figure 4.6 clearly demonstrates that coefficient of friction (COF) for Cu, Cu-Gr and T1.5-T4.5 composites consistently rises as the sliding velocity increases for each of the applied loads. For Cu-Gr composite, at higher speeds, the graphite film that forms at the surface gets detached after some distance. This allows the fresh composite surface to get in contact with the counter surface. Thus, increasing sliding velocity results in forming and breaking of the graphitic film at regular intervals which increases the COF.

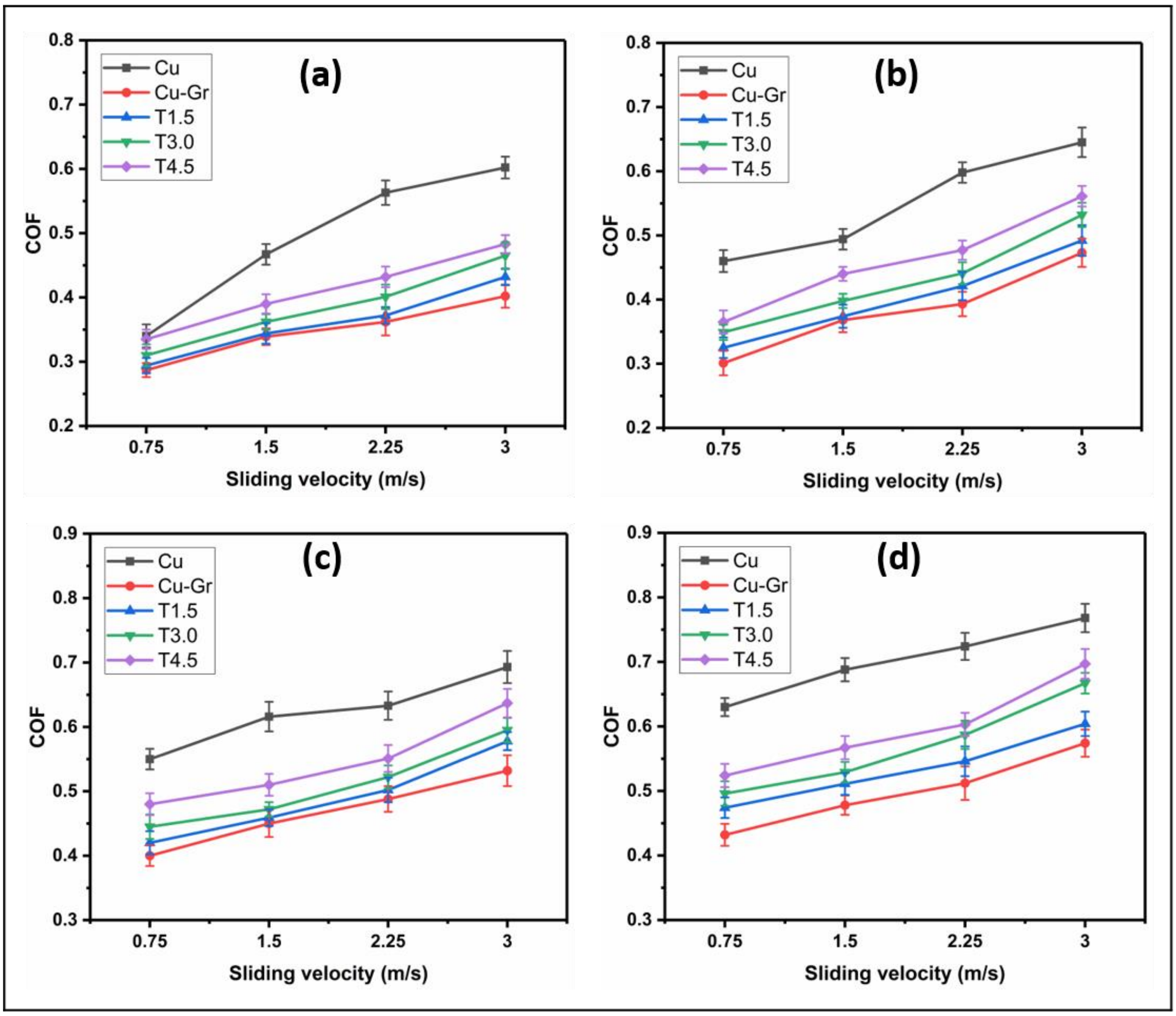

Fig. 4.6 Influence of sliding velocity on wear rate at sliding distance of 3000 m and different applied loads (a) 10 N (b) 20 N (c) 30 N (d) 40 N

The increasing trend of COF is also observed for the T1.5–T4.5 composites at higher sliding velocity. The hard TiC particles get commuted in between the metal surfaces at high-speed conditions. These hard particles get abraded and subsequently increase the COF in TiC-reinforced composites.

Figures 4.7 (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 lower sliding speed of 0.75 m/s, a smooth surface and minimal delamination is observed (Fig. 4.7(a)). However, with rise in sliding velocity, the worn surface exhibits more delamination at different regions. Further at 3 m/s velocity, dominant mechanism of wear becomes delamination owing to the significant frictional heat generated during the process which also results in more wear rate.

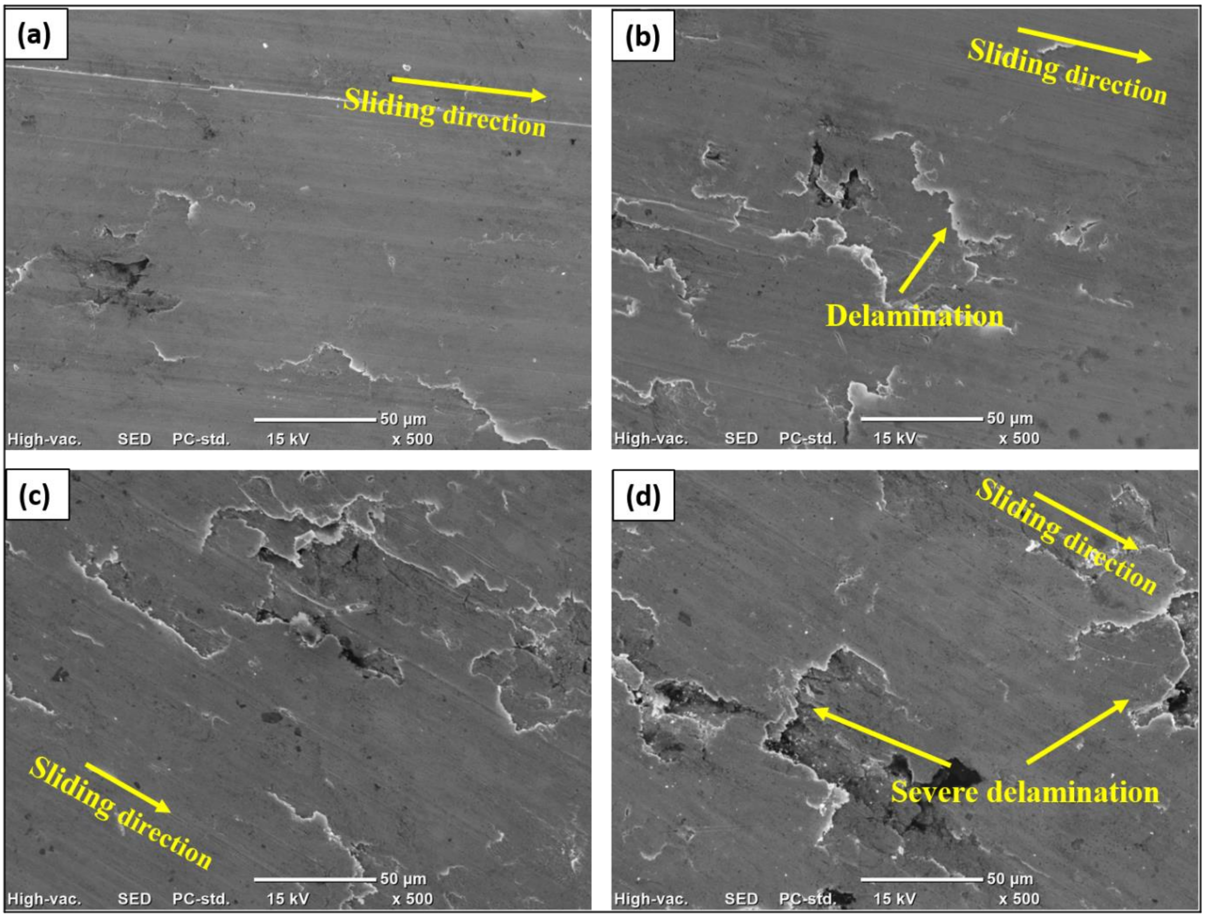

Fig. 4.7 SEM images of worn surface of T3.0 composite at load of 30 N and 3000 m of sliding distance and varying sliding velocity of (a) 0.75 m/s (b) 1.5 m/s (c) 2.25 m/s (d) 3 m/s

To further investigate the worn surfaces of different compositions, the EDS elemental mapping analysis is also done. The EDS elemental mapping of different elements (C, O and Fe) on the worn surface of Cu-Gr composite at different sliding velocities is shown in Figs. 4.8(a) and (b). It is observed that at high sliding velocity (1.5 m/s), the graphite layer gets smeared out from the surface of composite as verified by the content of C which is significantly reduced in the elemental mapping as shown in Fig. 4.8(b).

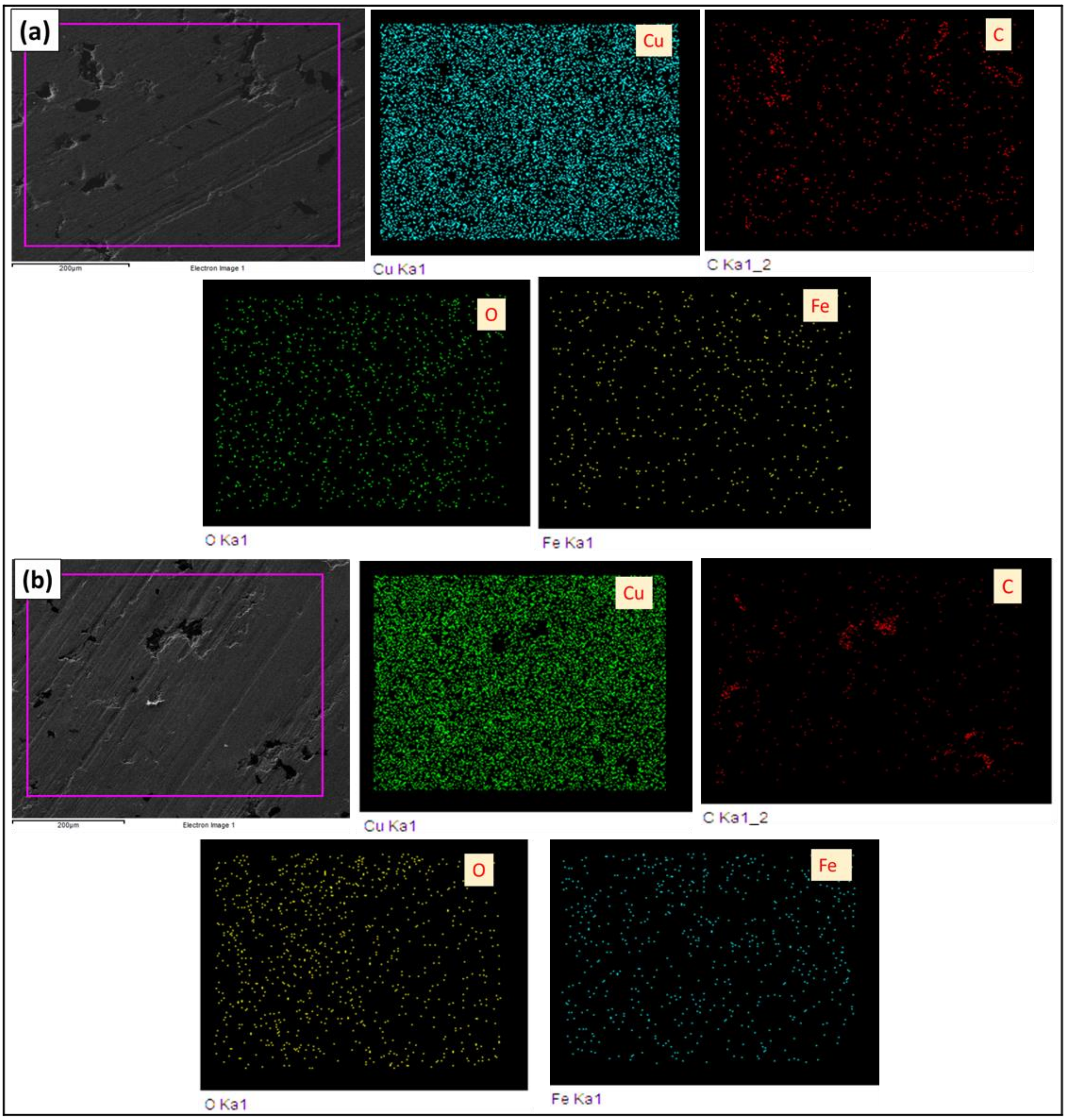

Fig. 4.8 Energy-dispersive spectroscopy (EDS) element mapping of worn surface at 30 N load of Cu-Gr at (a) 0.75 m/s velocity and (b) 1.5 m/s velocity

The improper bonding between the Cu and graphite particles may lead to the removal of this layer at high velocity. This further leads to rise in the Fe concentration since the contact between the disc and Cu matrix increases.

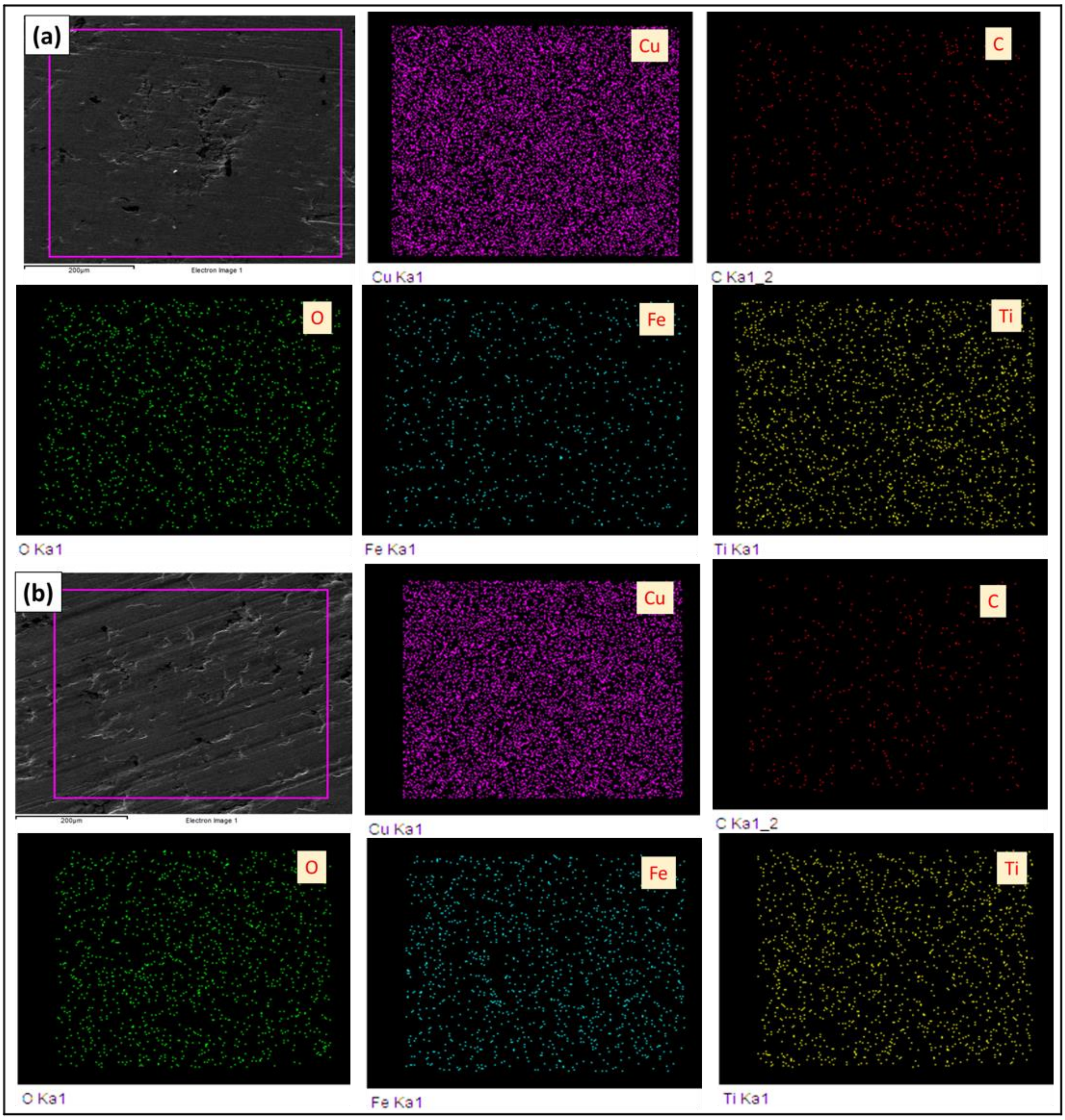

Fig. 4.9 Energy-dispersive spectroscopy (EDS) element mapping of worn surface at 30 N load of T3.0 composite at (a) 0.75 m/s velocity and (b) 1.5 m/s velocity

The EDS elemental mapping of different elements (C, O, Fe and Ti) on the worn surface of T3.0 composite at different sliding velocities is depicted in Figure 4.9(a) and (b). While comparing unstable graphitic conditions present in the C-Gr composite during the test, it is observed that concentrated carbon spots for the T3.0 composite at both the velocities show the stability of graphite film. It is also noticed from Figs. 4.9(a) and (b) that more amount of C is present for the TiC reinforced composite signifying the retention of stable graphitic layer. These TiC particles mechanically interlock the graphite at the interface and suppress its removal from the contact surface which enhances the self-lubrication property and thus reducing the wear [H. Fallahdoost et al., 2016].

Figure 4.10 exhibits AFM images of worn surfaces, providing a detailed analysis of surface unevenness consisting of peaks and valleys.

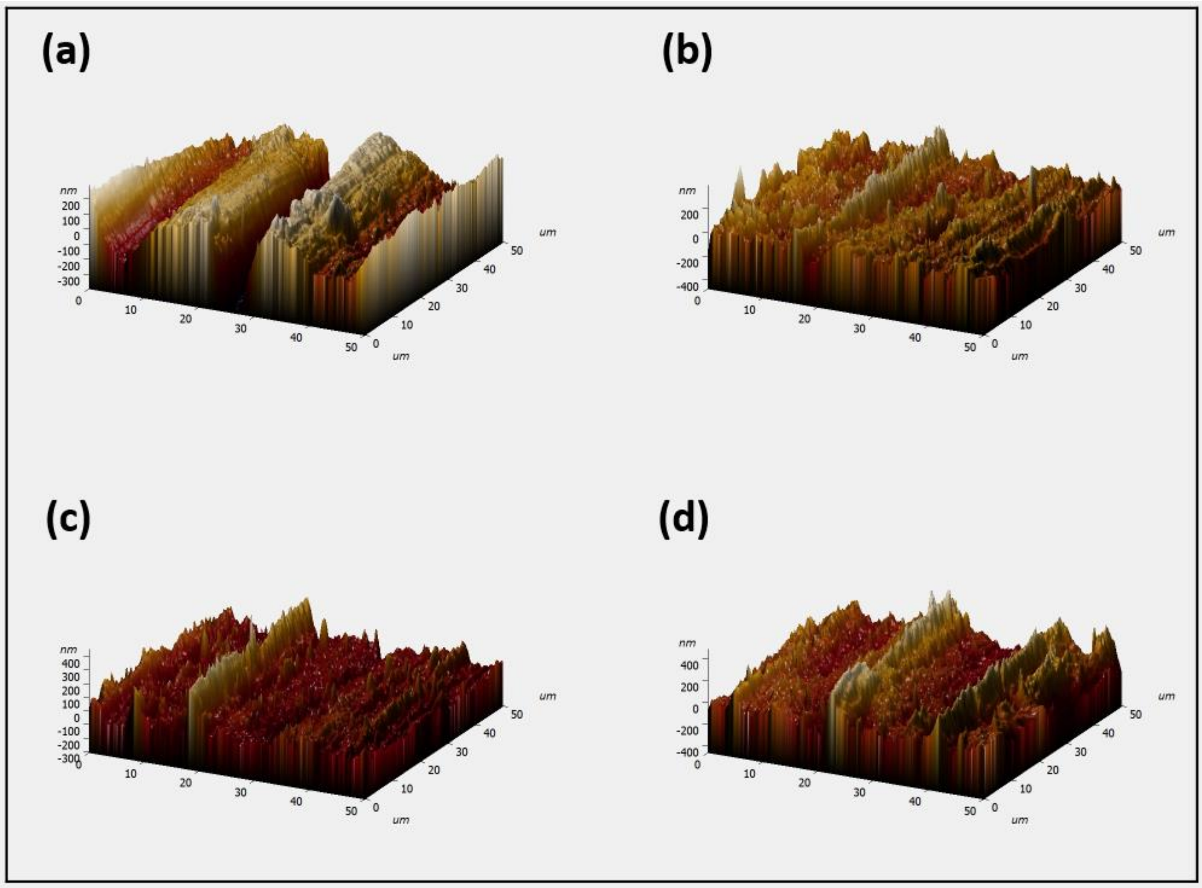

Fig. 4.10 AFM image of T3.0 composite at 30 N load and 3000 m of sliding distance and sliding speed of (a) 0.75 m/s (b) 1.5 m/s (c) 2.25 m/s (d) 3 m/s

The figure demonstrates as the velocity rises from 0.75 m/s to 3 m/s, the average value of peaks and valley increases from 500 nm to 800 nm. It may be attributed to the severe delamination at high velocity causing increased surface roughness. This is also aligned with the results of wear rate.

4.2.3 Influence of load

Figure 4.11 (a-d) illustrates the effect of applied load on wear rate at various sliding distances. From the figure it is shown that the wear rate of all composition rises substantially with the increase in applied load from 10 N to 40 N. However, at all loads, the minimum wear rate is found for the T3.0 composite. Similar findings are also reported in earlier literatures by other materials researchers [Rajkumar et al., 2011]. During wear test, the real area of contact is always less than the apparent area of contact as the result of sample surface roughness. As the load rises, the real area of contact increases which rises the plastic deformation of the asperities leading to higher wear rate of the samples [Menezes et al., 2013]. The oxidative layer may also develop on the surface of sample. This is the result of increased temperature at the interface of sample and counter disc because of friction. The oxidative layer decreases the metallic contact between the sample and steel disc and decreases the wear rate. Hence, at lower normal load conditions, the wear rate exhibits less value and the wear mechanism is mild/oxidative. As the applied load increases, oxidation of the surface takes place as a result of the rise in temperature. Therefore, a thick oxidative layer is formed at higher load. This oxidative layer gets broken with continuous sliding and may function as a third object between the surfaces causing the wear rate of composite to increase. So, at higher applied load conditions, the wear mechanism is severe/oxidative-metallic [Chourasiya et al., 2020]. Figure 4.11 (e) illustrates the effect of load on specific wear rate at 3000 m sliding distance. It is seen that specific wear rate decreases with the load. However, as the applied load increases the change in specific wear rate is very less.

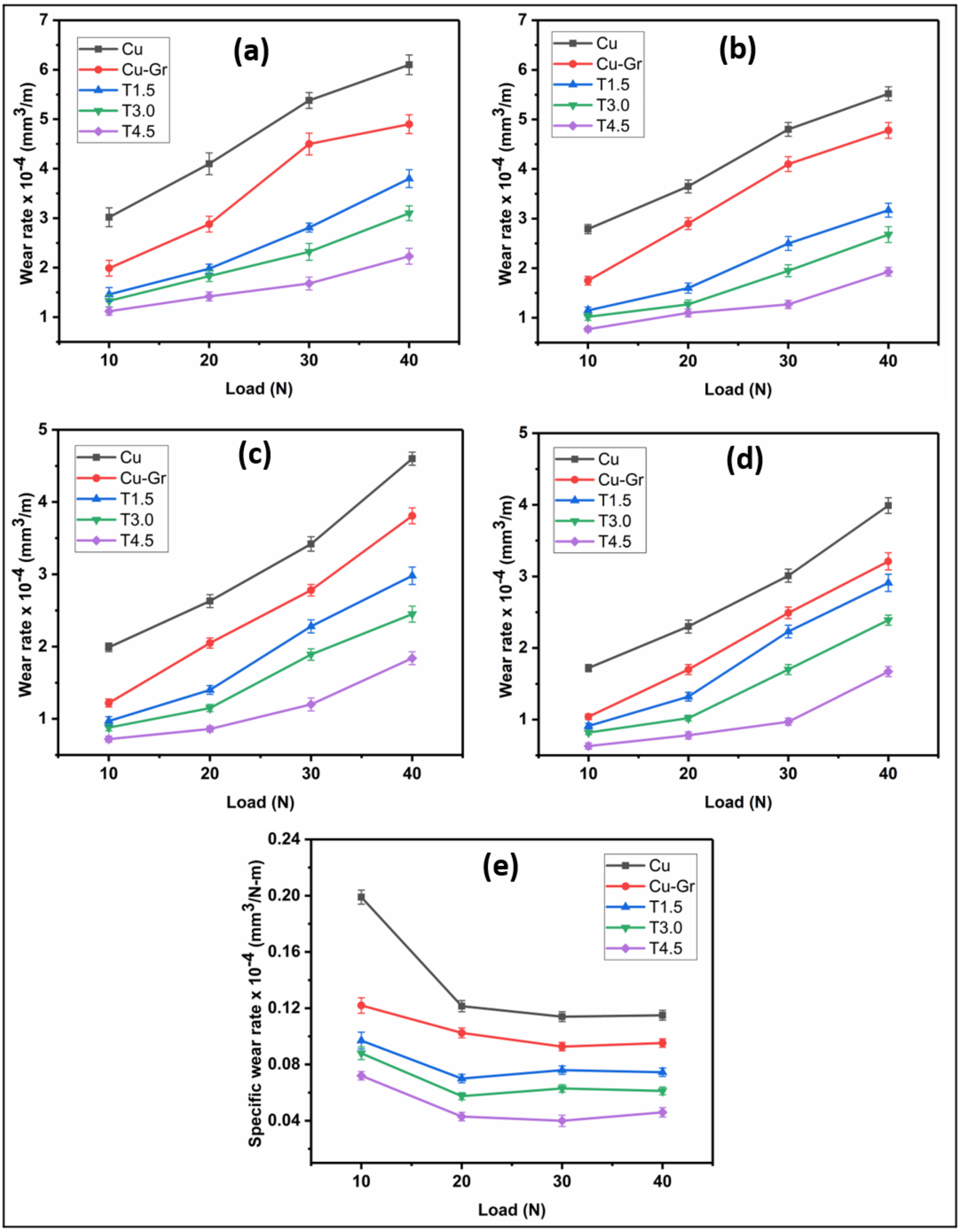

Fig. 4.11 Influence of applied load on wear rate at sliding distance of (a) 1000 m (b) 2000 m (c) 3000 m (d) 4000 m and (e) Specific wear rate at 3000 m sliding distance

Applied load also affects the COF as displayed in Fig 4.12. It is depicted from the figure that COF of Cu and composites increases when load is raised from 10 N to 40 N for all the sliding distances. With increase in the applied load, more plastic deformation takes place which increases the COF. However, in T1.5 to T4.5 composites, additionally, the TiC particles may come out from the sample surface under high load and contribute to an increase in COF value.

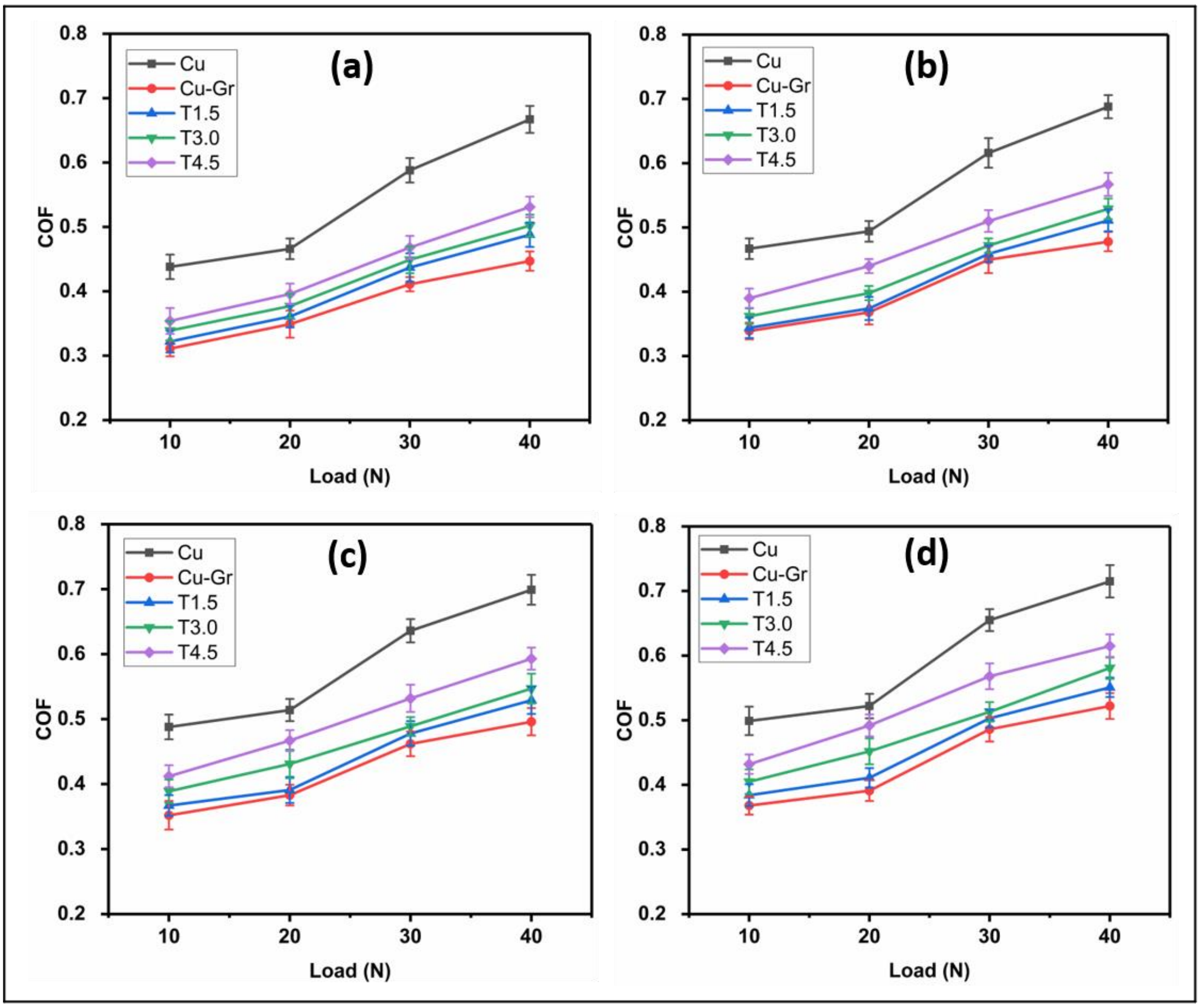

Fig. 4.12 Influence of applied load on COF at sliding distance of (a) 1000 m (b) 2000 m (c) 3000 m (d) 4000 m

Worn surfaces of T3.0 composites under different loads are illustrated in Figs. 4.13(a-d) it is revealed that at low load of 10 N some amount of delamination occurs. However, oxide layer formation is also observed at 30 N load due to rise in temperature owing to the frictional heating as revealed in Fig. 4.13(c). Further the onset of a severe wear regime occurs at 40 N applied load due to the larger contact area between mating surfaces. The elevated load results in increased frictional heat and softening the matrix phase and may result in the excessive plastic deformation at 40 N load. This also enhances the penetration of hard asperities onto the disc surface, contributing to a higher wear rate.

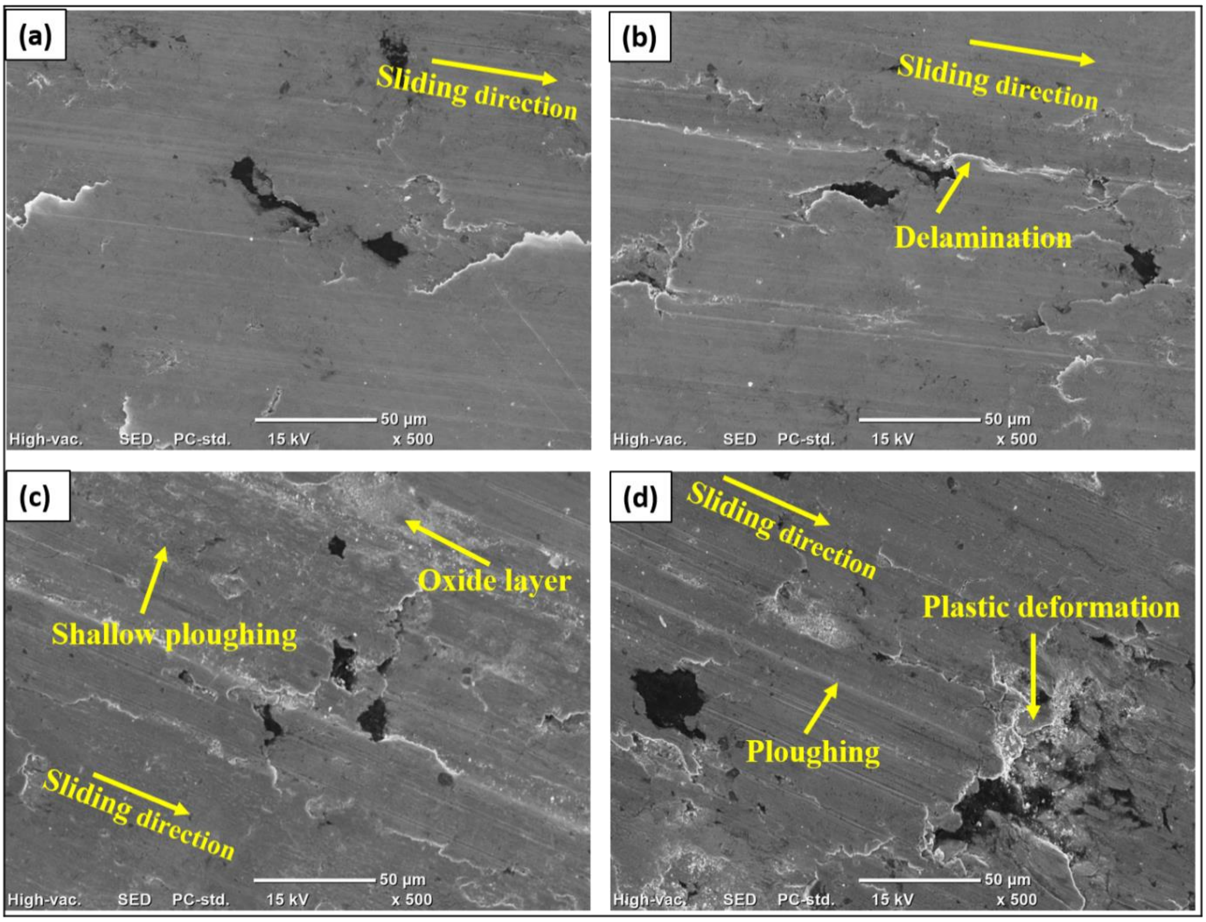

Fig. 4.13 SEM images of worn surface of T3.0 composite at 3000 m of sliding distance and applied load of (a) 10 N (b) 20 N (c) 30 N (d) 40 N

Figure 4.14 (a-d) shows 3D AFM images of worn surfaces of T3.0 composite at various loads ranging from 10 N to 40 N. The images highlight a direct relationship between the applied load and the average peak and valley height, showing an increase from 300 nm to 1.4 µm as the load progresses from 10 N to 40 N. This observed increase in surface roughness aligns with the above obtained wear rate results.

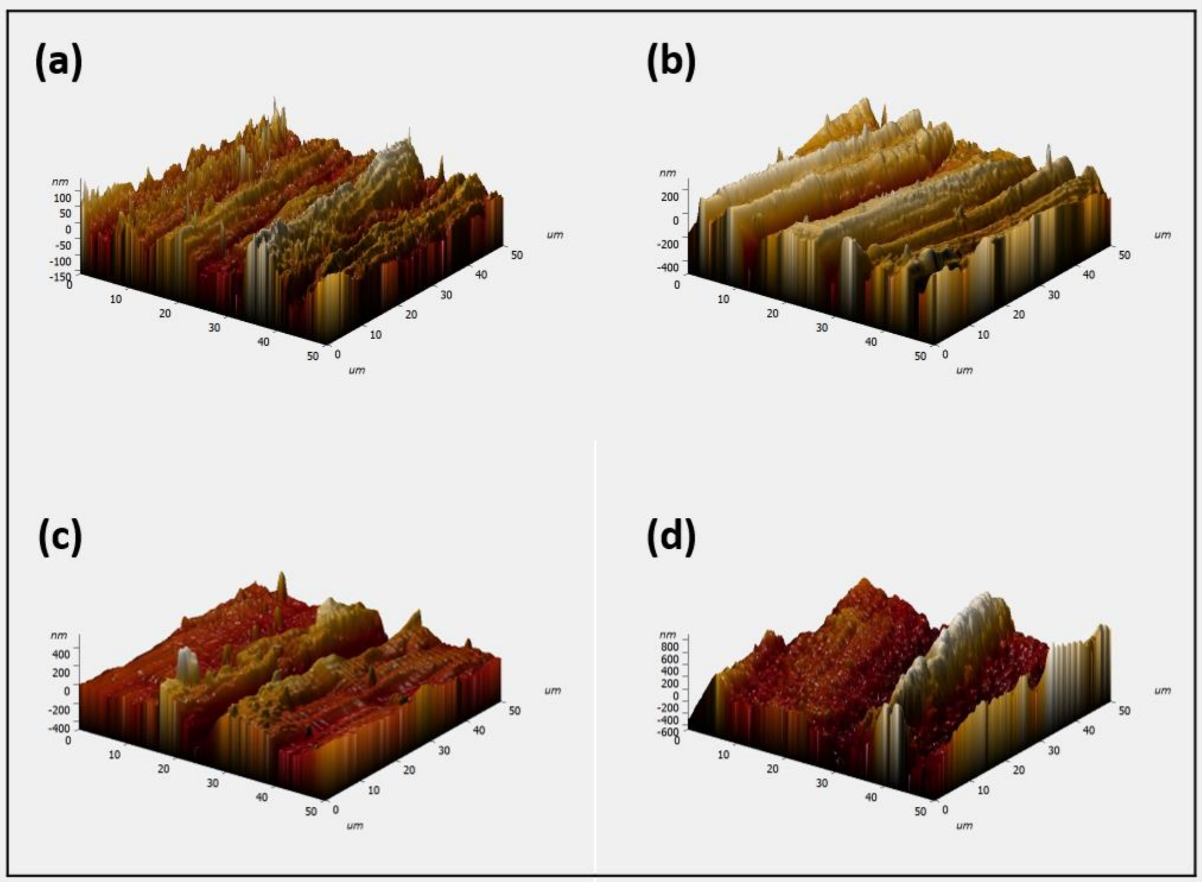

Fig. 4.14 AFM image of T3.0 composite at 3000 m of sliding distance and applied load of (a) 10 N (b) 20 N (c) 30 N (d) 40 N

4.2.4 Influence of TiC content

Figures 4.15 and 4.16 illustrates the influence of TiC amount on wear rate and COF at varying sliding distances. Fig. 4.15 shows that the wear rate in composites is much lower than pure Cu and minimum wear rate is observed for the T4.5 composite with 4.5 wt.% TiC particles. It is found that the wear rate decreases when graphite is added in the Cu matrix and also with an increase in TiC content. The hardness of the composite having 5 wt.% graphite (Cu-Gr composite) is lower than Cu but the wear rate drastically reduces since graphite has self-lubricating properties [P. Ravindran et al., 2013]. Although for composites, a decrease in hardness leads to higher wear rate [M. Kestursatya et al., 2003]. But here, a uniform lubricating graphite film forms between the mating surfaces which isolates the pin sample from the hard-counter surface. This film improves the wear resistance of composite by retarding the severe adhesion of ductile Cu to the counter surface.

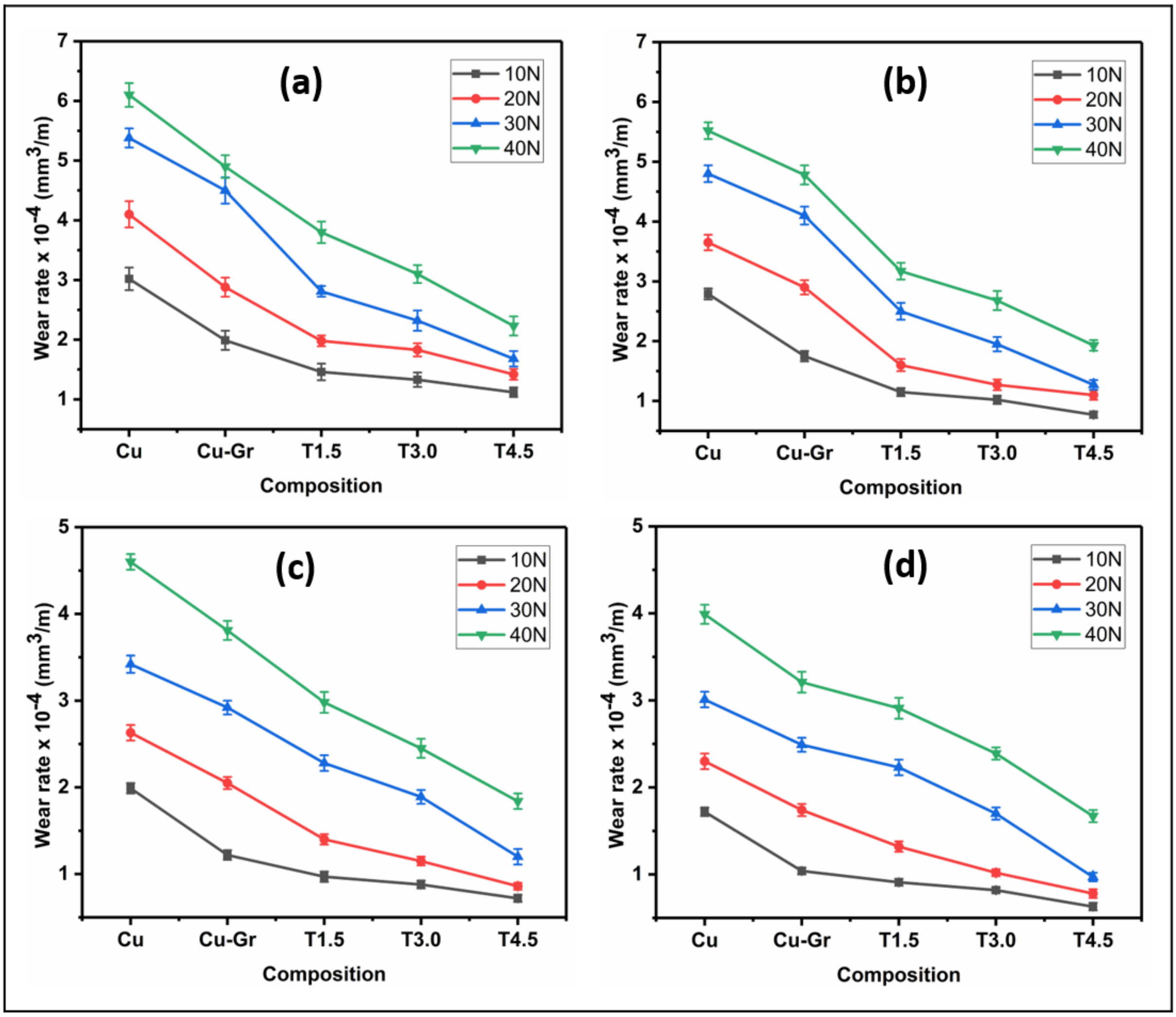

Fig. 4.15 Influence of Gr and TiC content on wear rate at constant sliding velocity of 1.5 m/s and different sliding distance of (a) 1000 m (b) 2000 m (c) 3000 m (d) 4000 m

The wear performance of TiC reinforced composites (T1.5 to T4.5) increases with the weight percent of TiC because of the hard TiC particles which are present in the composite. In the initial stage of sliding the Cu matrix comes in contact with metallic counter surface and Cu gets abraded. Then, the fresh TiC gets exposed to the counter surface and thereby carrying the load and providing hindrance to further surface deformation of the matrix material which in turn reduces the wear rate. These hard TiC particles retard the gradual wear of copper matrix and reduce the wear rate of the composite.

The variation of COF value with respect to the reinforcements is shown in Figure 4.16. For Cu-Gr composite (5 wt.% graphite) it is found that the COF value decreases substantially.

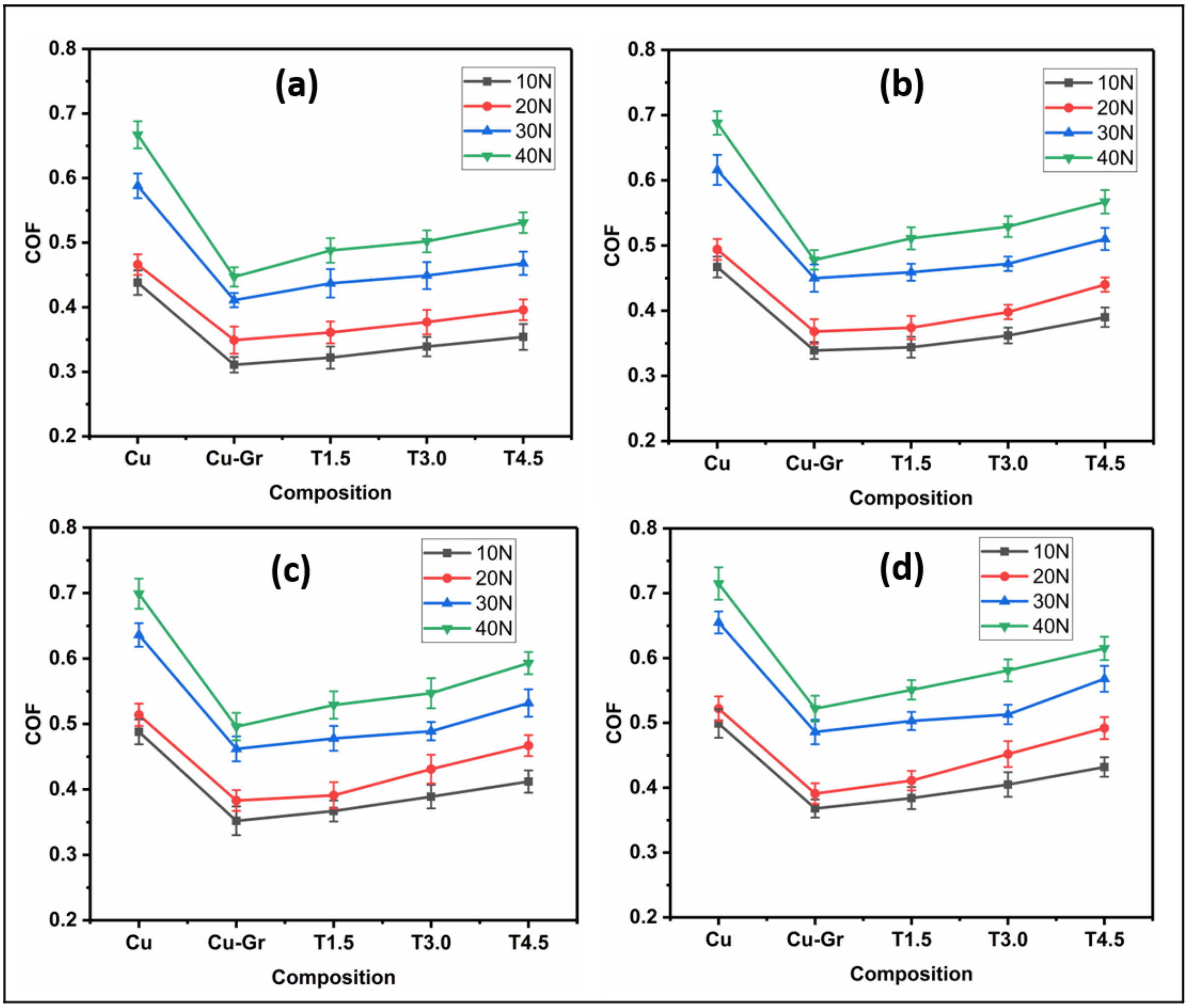

Fig. 4.16 Influence of Gr and TiC content on COF at constant sliding velocity of 1.5 m/s and different sliding distance of (a) 1000 m (b) 2000 m (c) 3000 m (d) 4000 m

This drastic reduction is due to the self-lubrication feature of graphite. The graphite particles get smeared at the contacting surfaces when force is applied. The smeared graphite forms a transition layer and reduces the direct exposure of the counter surface with the composite pins. It results in a substantial reduction in the coefficient of friction. However, for TiC reinforced composites, the COF showed the trends which was contrary to wear rate. It is found that there is an enhancement in COF value as wt.% of TiC increased when compared to Cu-Gr composite. During sliding, TiC particles get protruded from the softer matrix, and these hard particles rub against the counter surface. The TiC particles come out and lead to a slight increment in the coefficient of friction. The protruded TiC particles get in between the two contacting surfaces which causes ploughing action on the surface of composites. The same effect is also found in the literature involving hard silicon carbide particles in soft matrix [R.K. Uyyuru et al., 2003]. However, the steady increase in the coefficient of friction is attributed to the growing contribution of TiC particles as the composites undergo wear.

Figure 4.17 illustrates the wear coefficient of different composition at a constant sliding distance of 3000 m. Using Archard's wear equation, the wear coefficient is also determined. It was found that wear coefficient of Cu and composites decreases with increasing load.

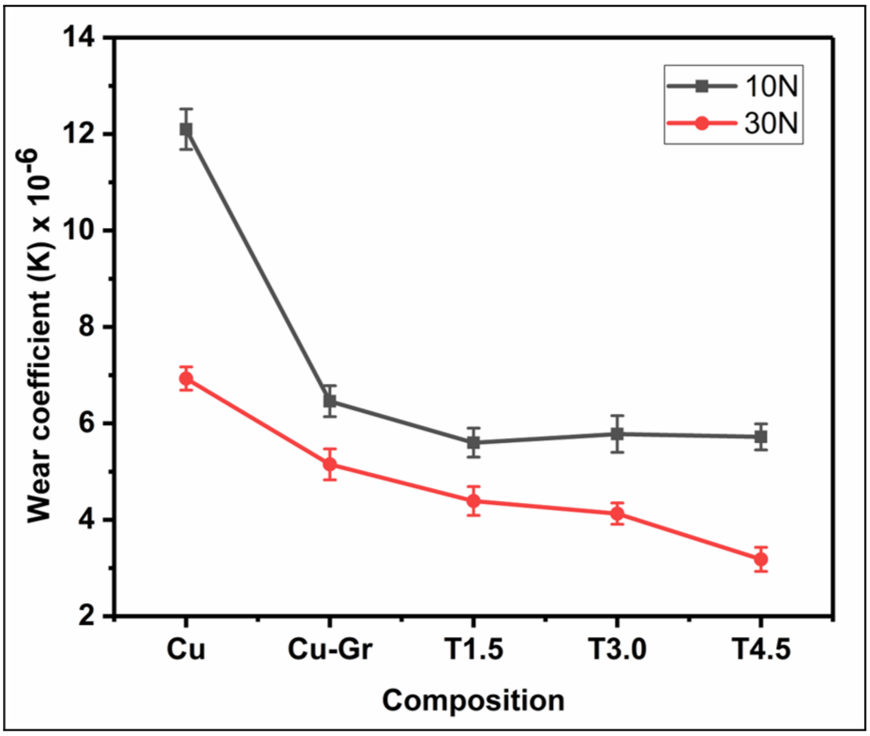

Fig. 4.17 Influence of Gr and TiC content on wear coefficient at constant sliding distance of 3000 m

We note that elevating the TiC content results in a reduction of the wear coefficient, reaching its lowest point at 4.5 wt.% of TiC particles. This suggests that enhancing the TiC content improves the wear-resistant characteristics of the composites. This finding is valuable for tailoring the composite composition to meet specific application requirements, particularly those involving wear concerns.

Figures 4.18 (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 30 N and sliding distance of 3000 m. It is observed from Figure 4.18(a-e) that the worn surface of pure Cu shows delamination with deep grooves. The severe adhesion of ductile copper matrix with the mating surface takes place resulting in high amount of delamination throughout the sample and causing delamination wear. However, with addition of graphite in the Cu matrix (Cu-Gr composite), the delamination effect is significantly reduced. The graphite particles embedded in the matrix restrict sticking of matrix to the counter surface by forming a lubricating film, however some ploughing marks are also observed. These results also in agreement with the observed results of wear in both the samples.

The worn surface of T1.5 composite as in Fig 4.18 (c) consists of small-size wear debris and less delamination and for the T4.5 composite in Fig. 4.18 (e), the worn surface is smooth ploughing with fine cracks. It indicates that as the TiC content in the composites is increasing in the composite, there is a transition in the mode of wear from delamination to mixed mode (having delamination and abrasive wear). The minimum surface features are observed in the composite having 4.5 wt.% of TiC particles. The wear debris may get accumulated and causes cracking on the surface of the composite [S. Das et al., 2019]. These results also agreed with the observed wear results of T1.5 to T4.5 samples.

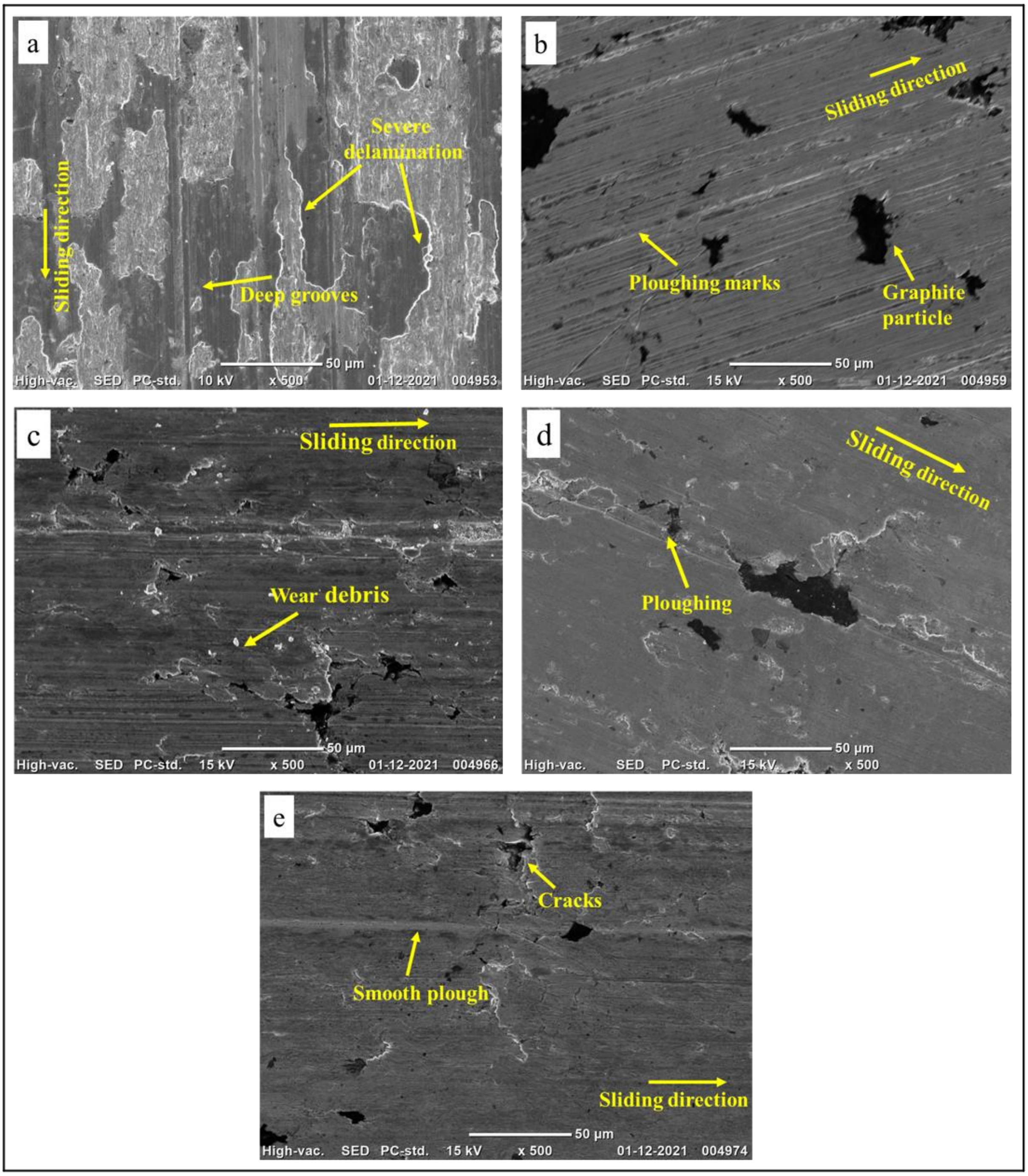

Fig. 4.18 SEM images of worn surface at 30 N load and 3000 m of sliding distance for (a) Cu and composites (b) Cu-Gr, (c) T1.5, (d) T3.0 and (e) T4.5

Figure 4.19(a-e) displays the AFM micrographs of pure Cu, Cu-Gr and TiC composites with different amount of TiC particles. The worn surfaces exhibit distinct peaks and valleys of varying heights. It is noted that the Cu worn surface has a higher maximum average peak value of 3 µm compared to the composites.

Although, the average peak to valley height decreases from 3.0 µm to 600 nm with the incorporation of reinforcement particles. Minimum value of is for T3.0 composite having 4.5 wt.% TiC particles. Decreased peak values on the surface implies less wear of material [N. Jafari et al., 2014]. This result is also in line with obtained wear results.

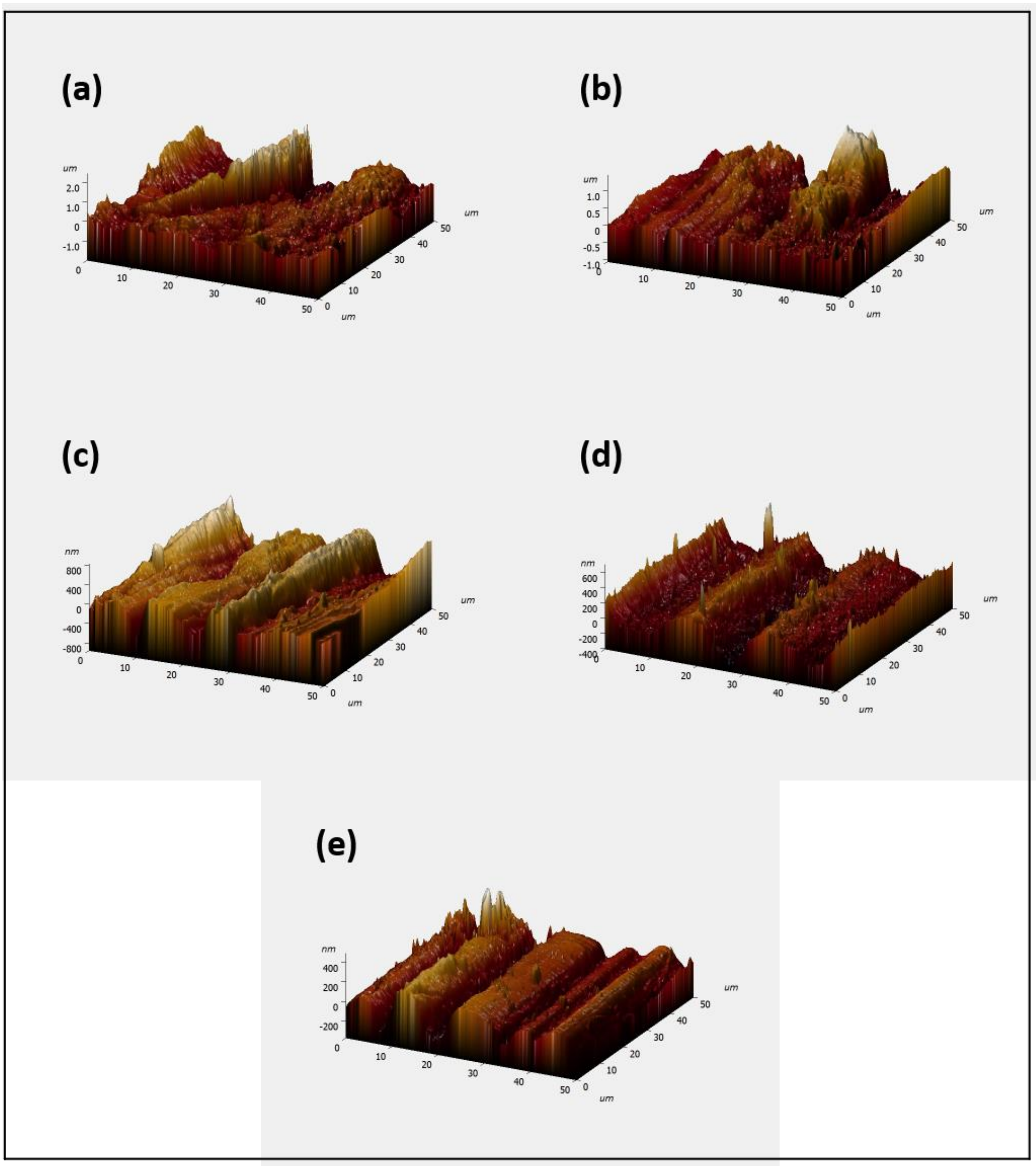

Fig. 4.19 AFM images of worn surface at 30 N load and 3000 m of sliding distance for (a) Cu and composites (b) Cu-Gr, (c) T1.5, (d) T3.0 and (e) T4.5

4.2.4.1 Topographical parameters of worn surface

The surface topographical parameters were also calculated for the different AFM micrographs of different compositions and their values are provided in Table 4.1. These parameters which have a major impact on tribological properties, are measured by analysing the surface texture scans of worn surfaces [D Raoufi et al., 2007] The topographical parameters include an average surface roughness (S_a), root mean square roughness (S_q), area peak to valley height (S_t), skewness of the plane (S_{sk}) and kurtosis of the plane (S_{ku}) [D.K. Prajapati et al., 2019]. The S_a (the average roughness obtained from AFM) value represents the average height estimated over an entire area and is commonly used in assessing the roughness of worn surfaces. It helps in identifying changes in the overall profile height pattern and ensuring compliance with the accepted fabrication methods. S_t (the area peak-to-valley height) value provides the entire roughness of the sample's surface and is given by the vertical span between the highest and lowest points in the selected region. S_q (root mean square roughness) is a metric for dispersion of surface heights that is employed to determine the skew and kurtosis parameters. S_q is regarded to be more accurate than average roughness for substantial variations from the mean plane. Skewness (S_{sk}) parameter is used for evaluating the symmetrical divergence of worn surface from the mean plane and is thought to be more sensitive to sudden high peaks or deep valleys. S_{sk} provides insights into the load bearing capability. A negative skew value is suggestive of a more favourable bearing surface. Using Kurtosis (S_{ku}) value, the distribution of spikes below and above the mean plane is measured for worn surfaces. It is primarily future to control the stress fractures. A surface is considered "spikey" when its kurtosis value exceeds three (>3) and "bumpy" when it is less than three (<3). Surfaces showing perfect randomness have a kurtosis value equal to three (= 3) [B.R. Kumar et al., 2012].

Table 4.1 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	360.012	488.211	4410.011	0.527	4.499
Cu-Gr	233.321	318.154	2550.141	0.236	4.836
T1.5	198.356	254.751	1798.893	0.219	3.190
T3.0	110.013	130.088	1128.141	0.071	2.554
T4.5	81.556	104.142	884.271	-0.264	3.545

According to the data in Table 4.1, the average roughness, represented by S_a value, decreases from 360.012 nm to 81.556 nm as the reinforcement content increases. The S_a values are less than the S_q values for respective compositions. Also, the S_t value keeps on decreasing from pure copper (Cu) to T3.0 composite. It is observed that a negative skewness value means deep valleys are dominating over the selected region while positive skewness denote peaks are dominant. 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 achieving to zero as TiC content is raised indicating improvement in load bearing capability and it is negative for T4.5 composite (S_{sk} value is −0.264). The kurtosis value S_{ku} is close to 3 for composites (T1.5 to T4.5) 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. As for pure copper Cu and Cu-Gr composite the S_{ku} value are 4.499 and 4.836, respectively that are more than 3, as a result their distribution will have a large number of high peaks and deep valleys with spikes over the surface. Cu sample has both high S_{ku} value and a high St value indicating rougher surface than other samples. These parameters analysis imply that minimum wear is observed for T4.5 composite with a smoother surface topography.

4.3 CONCLUSIONS

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

- The wear rate and COF of Cu matrix is reduced with addition of graphite particles owing to formation of graphitic film.
- The wear rate is also reduced with the incorporation of TiC particles due to increased hardness, but the COF shows the enhancement.
- The wear rate shows an increasing trend with increase of applied load, sliding velocity and sliding distance for all the compositions.
- The T4.5 composite containing of 4.5 wt.% of TiC particles depicts approximately 65 % and 59% less wear rate in comparison to pure Cu and Cu-Gr composite at 30 N load and 3000 m sliding distance.
- The EDS elemental mapping of worn surfaces indicates that TiC particles mechanically interlocks the graphite at the interface and prevent its removal and reduce the wear rate.
- Analysis of worn surfaces through SEM and AFM align with the observed tribological results.
- The parameters of AFM revealed highest roughness for pure Cu sample whereas, the 4.5 wt.% TiC reinforced Cu-Gr composite exhibited superior load-bearing capacity and lowest roughness values.