Chapter 4

Tribological Behaviour Under Brake Oil Environment

4.1 Introduction

Tribological behaviour of composites (especially ceramic matrix composites) depends greatly on the surrounding environment. As discussed in the chapter 2, C/C composites are very much prone to the environment. Humidity plays an important role in depicting the tribological behavior of C/C composites. It has been proven that the effect of humidity on the tribological behavior of C/C composites depend upon the sliding speed and applied pressure [171]. The adsorbed species on the surface of C/C composites evaporate at high temperature. Thus, the effect of adsorbed species on the tribological performance of C/C composites is low at high energy braking conditions [172]. However, at low energy braking conditions, adsorbed species adhere to the surface of composite and lubricates which greatly affects the tribological performance of composites [168]. Tribological behavior of C/C composites in the dry, wet and acidic environment has generally been investigated for high energy braking conditions [161, 162, 173]. However, its potential use for low energy braking conditions has not been investigated to a greater extent. C/C-SiC composites are also prone to the environment, but the effect of environment is less for C/C-SiC composites as compared to C/C composites due to less porosity and presence of hard silicon carbide phase.

Sometimes a leakage in brake line near the brake disk may lead to spilling of brake oil on the surface of brake disks/pads and get absorbed by it due to which its braking performance degrades. The tribological behavior of C/C and C/C-SiC composites have been investigated in the dry, wet and acidic environment [108, 158, 161, 162, 173, 174]. But their tribological behavior under brake oil has not been investigated yet. To the best of our knowledge, tribological behavior of C/C and C/C – SiC composites in the brake oil environment has not been investigated yet.

Thus in the present chapter, the effect of brake oil on tribological performance on C/C and C/C – SiC composites has been investigated with a variation of laminate orientation, surface conformity and sliding conditions. The results obtained from different surface conformity conditions and laminate orientation have been compared.

4.2 Materials and Synthesis

The details of materials and synthesis are discussed in chapter 3, section 3.2.

4.3 Brake oil absorption

Prior to wear testing, prepared samples were immersed in brake oil for almost 15 hours. The brake oil used was "Servo brake fluid HD" which meet the DOT 3, SAE J1703, FMVSS No. 166, IS 8654 – 2001 specifications. Brake oil was absorbed by C/C and C/C - SiC composites. Samples were weighed before and after immersing in brake oil. Average weight gain per unit surface area was calculated by an increase in weight percent i.e.

$$\%W_g = \frac{W_f - W_i}{W_i} \times 100 \qquad (1)$$

where, $\%W_g$ is increase in weight percent,

W_f is the weight of the sample after taking it out from brake oil,

W_i is the weight of the sample before putting it in brake oil.

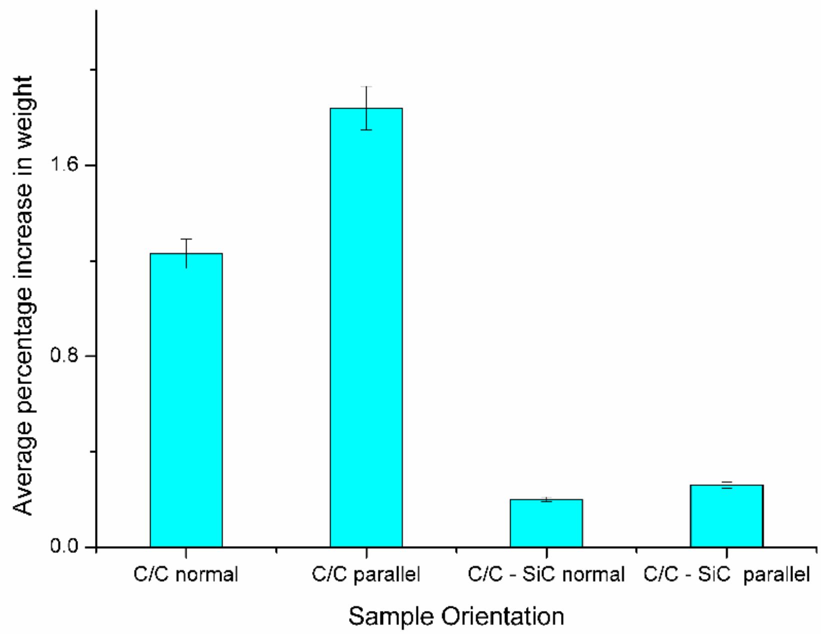


Fig. 4.1. Percentage increase of weight for different orientation of laminates after immersing in brake oil.

It can be observed from Fig. 4.1 that C/C composites absorbed more oil as compared to C/C-SiC composites due to more open porosity of C/C composites. Composites with the parallel orientation of laminates contained more surface pores. Thus, composites with normal orientation of laminates absorbed less oil as compared to composites with the parallel orientation of laminates. The difference in weight gain of C/C-SiC parallel and C/C-SiC normal was not significant.

4.4 Sliding wear tests

The details of sliding wear tests are discussed in chapter 3, section 3.3.

4.5 Scanning Electron Microscopy

The details of scanning electron microscopy are discussed in chapter 3, section 3.4.

4.6 Results and Discussion

4.6.1. Unidirectional Sliding

4.6.1.1. Decay rate of friction coefficient in brake oil condition

The decay rate of friction coefficient in brake oil condition was calculated using Eq. 2 [151] as given by,

$$D\ (\%) = \left(1 - \frac{\mu_{oil}}{\mu_{dry}}\right) \times 100 \tag{2}$$

where, $D\ (\%)$ is the decay rate of friction coefficient,
μ_{oil} is the friction coefficient in brake oil condition,
μ_{dry} is the friction coefficient in dry condition.
The tests in dry condition were performed, and the results are presented in Chapter 3. Fig. 4. 2 shows the average decay rate of friction coefficient in brake oil condition.

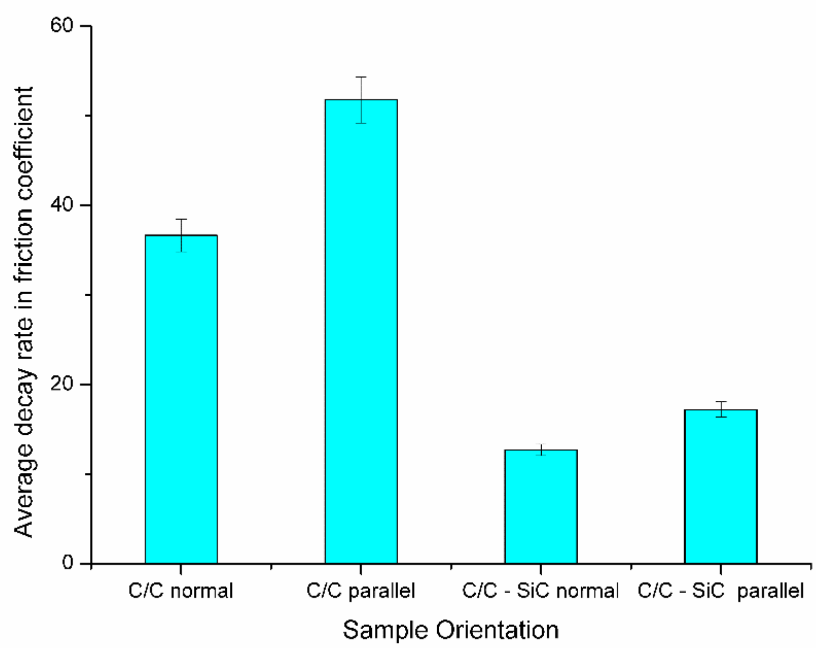


Fig. 4.2. Average decay rate of friction coefficient in brake oil condition.

It can be observed from Fig. 4.2 that C/C parallel showed the highest sensitivity to brake oil while C/C-SiC normal showed least sensitivity. C/C – SiC composites are less sensitive to brake oil environment as compared to C/C composites.

4.6.1.2. Friction Response

Representative plots of friction coefficient versus time for C/C and C/C – SiC composites with normal and parallel orientation of laminates are shown in Fig. 4.3 and 4.4 respectively.

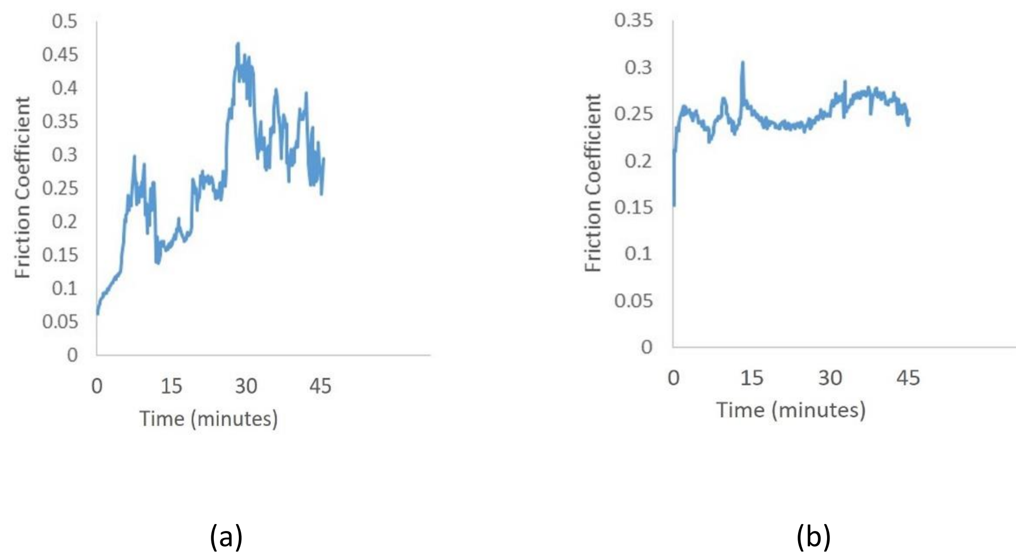
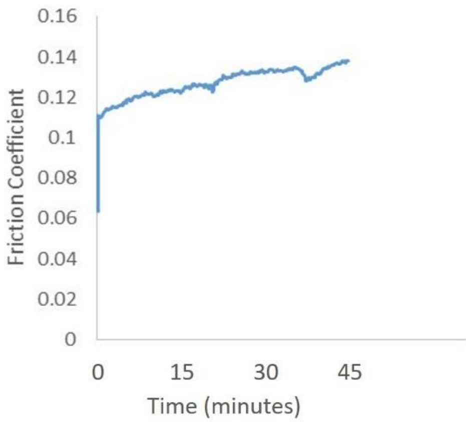
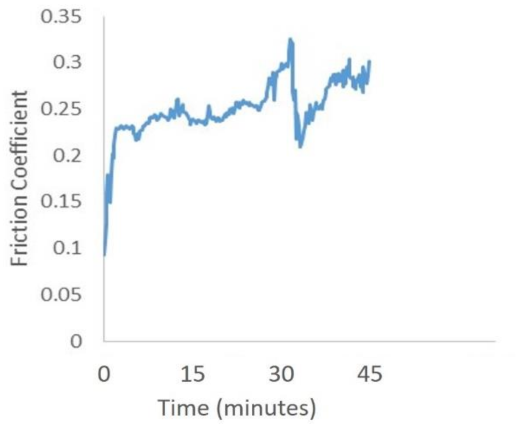


Fig. 4.3. Representative plot for variation of friction coefficient with time plotted for 40 N load and 2 m/s sliding velocity with normal orientation of laminates (a) C/C composites, (b) C/C – SiC composites.



(a)



(b)

Fig. 4.4. Representative plot for variation of friction coefficient with time plotted for 40 N load and 2 m/s sliding velocity with parallel orientation of laminates (a) C/C composites, (b) C/C – SiC composites.

It can be observed from Fig. 4.3 that in case of normal orientation of laminates, C/C composites showed more fluctuations as compared to C/C-SiC composites although C/C composites absorbed more oil. This may be attributed to the fact that wear debris got mixed with oil which didn't adhere on the surface in the presence of oil. In case of parallel orientation of laminates (Fig. 4.4), C/C composites showed less fluctuations as compared to C/C-SiC composites.

Fig. 4. 5 shows the variation of mean friction coefficient with the load in brake oil condition. It can be observed from Fig. 4. 5 that C/C parallel exhibited the lowest friction coefficient in brake oil condition at all tested loads whereas C/C – SiC parallel showed the highest friction coefficient at higher loads. The variation in the friction coefficient of C/C parallel was very less with the increase in load. The friction coefficient of C/C normal first increased with an

increase in load and after a certain point, it showed a decreasing trend. The friction coefficient of C/C–SiC normal was highest at low loads.

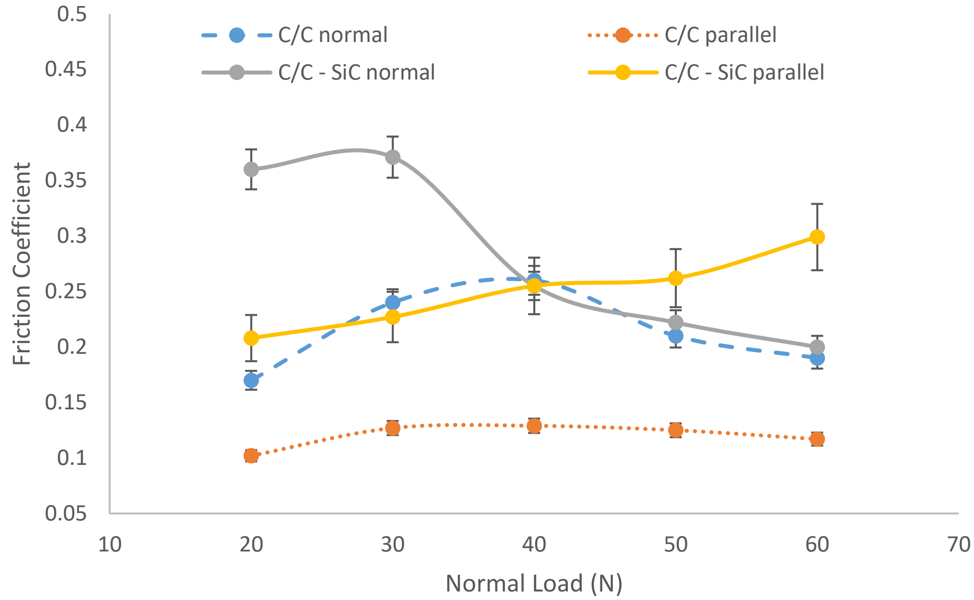


Fig. 4.5. Variation of friction coefficient with normal load at 2 m/s sliding velocity for C/C normal, C/C parallel, C/C-SiC normal, and C/C-SiC parallel.

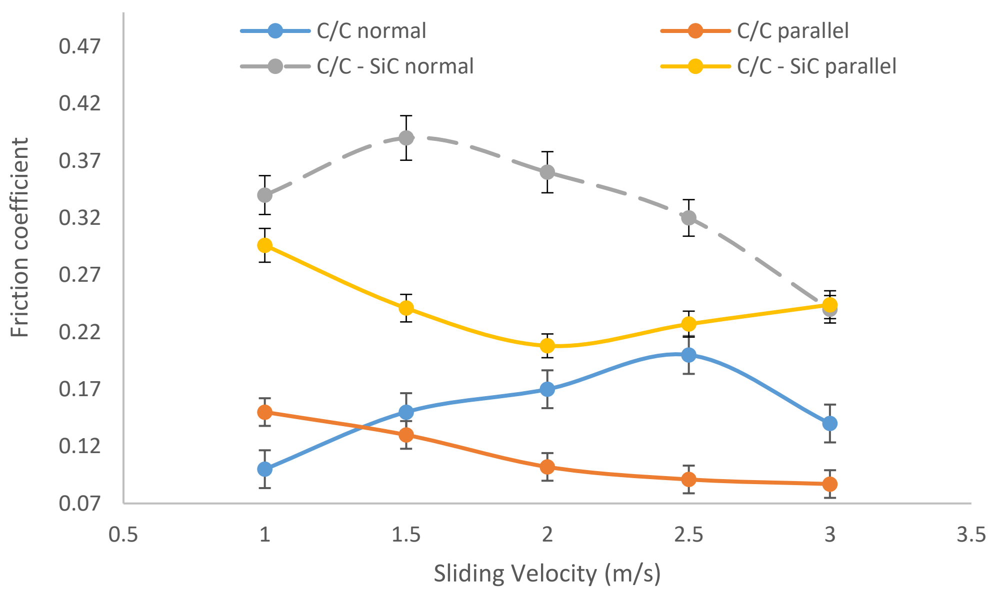


Fig. 4.6. Variation of friction coefficient with sliding velocity at 20 N load for C/C normal, C/C parallel, C/C-SiC normal, and C/C-SiC parallel.

Fig. 4.6 shows the variation of friction coefficient with sliding velocity. It can be observed from Fig. 4.6 that C/C composites exhibited less friction coefficient as compared to C/C-SiC composites. The friction coefficient of C/C parallel decreased with an increase in sliding velocity, and for C/C-SiC parallel, friction coefficient first increased and then decreased.

It can be observed from Fig. 4.7 that friction coefficient of C/C disk (ball on disk configuration) was less than C/C – SiC disk (ball on disk configuration) at all tested loads. The friction coefficient of both composites increased with increase in load.

Fig. 4.8 shows the variation of the friction coefficient of C/C disk and C/C – SiC disk with sliding velocity. It can be observed from Fig. 4.8 that the friction coefficient of C/C disk increased with an increase in sliding velocity. After 2 m/s sliding velocity, the increase in friction coefficient was very sharp.

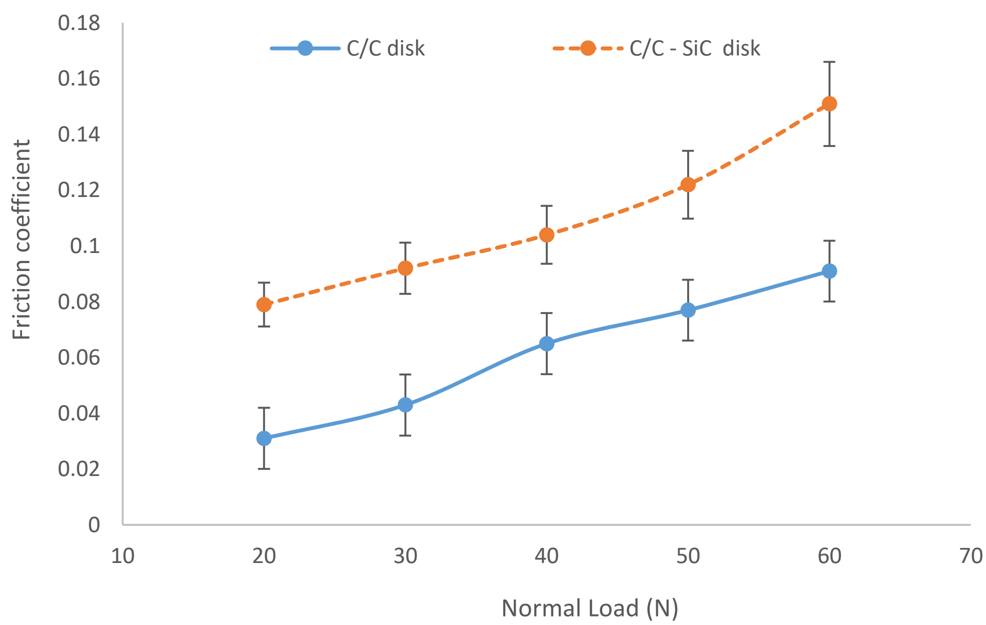


Fig. 4.7. Variation of friction coefficient with normal load at 2 m/s sliding velocity in non-conformal Hertzian contacts for C/C and C/C-SiC disks.

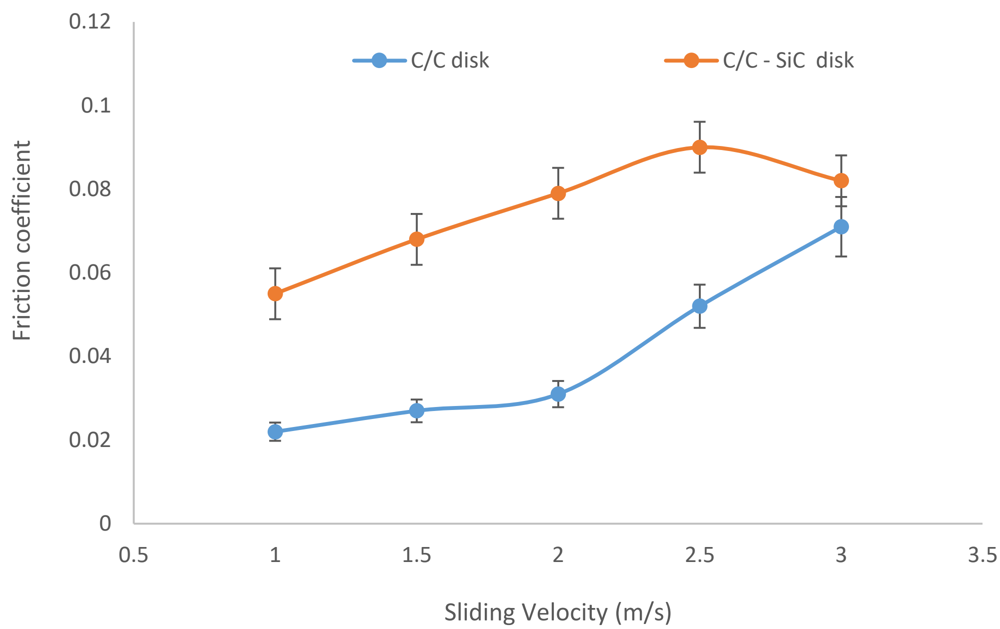


Fig. 4.8. Variation of friction coefficient with sliding velocity at 20 N load in non-conformal Hertzian contacts for C/C and C/C-SiC disks.

The friction coefficient of C/C-SiC disk increased up to 2.5 m/s sliding velocity and decreased afterward. C/C – SiC disk exhibited higher friction coefficient as compared to C/C disk.

4.6.1.3. Wear Behaviour

Fig. 4.9 shows the variation of wear loss with the load in brake oil condition. It can be observed from Fig. 4.9 that C/C normal showed the lowest wear loss at high loads whereas C/C parallel showed highest wear loss at high loads.

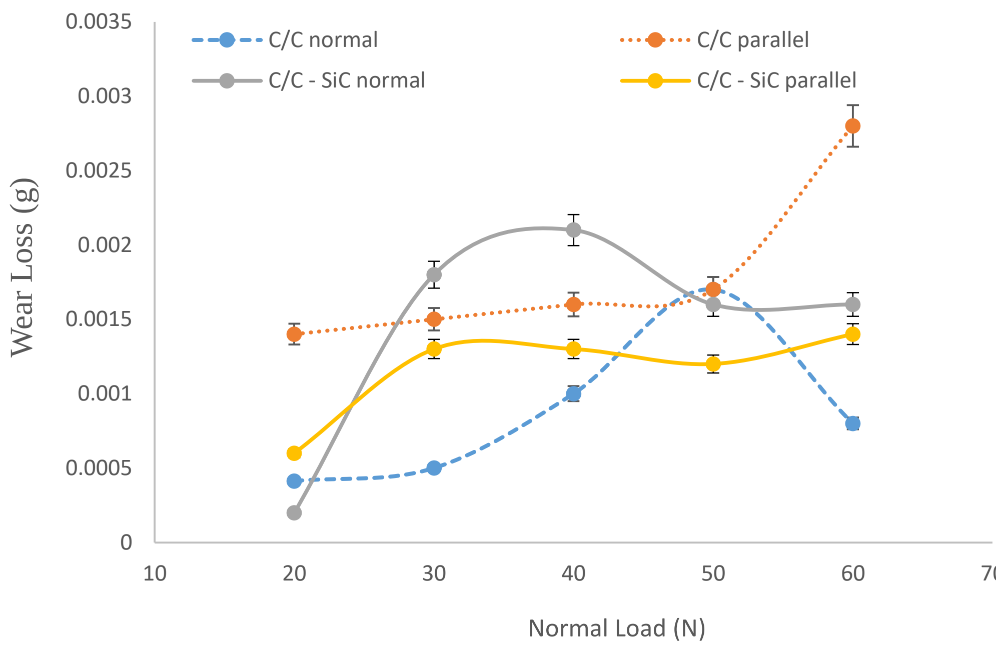


Fig. 4.9. Variation of wear loss with normal load at 2 m/s sliding velocity for C/C normal, C/C parallel, C/C-SiC normal, and C/C-SiC parallel.

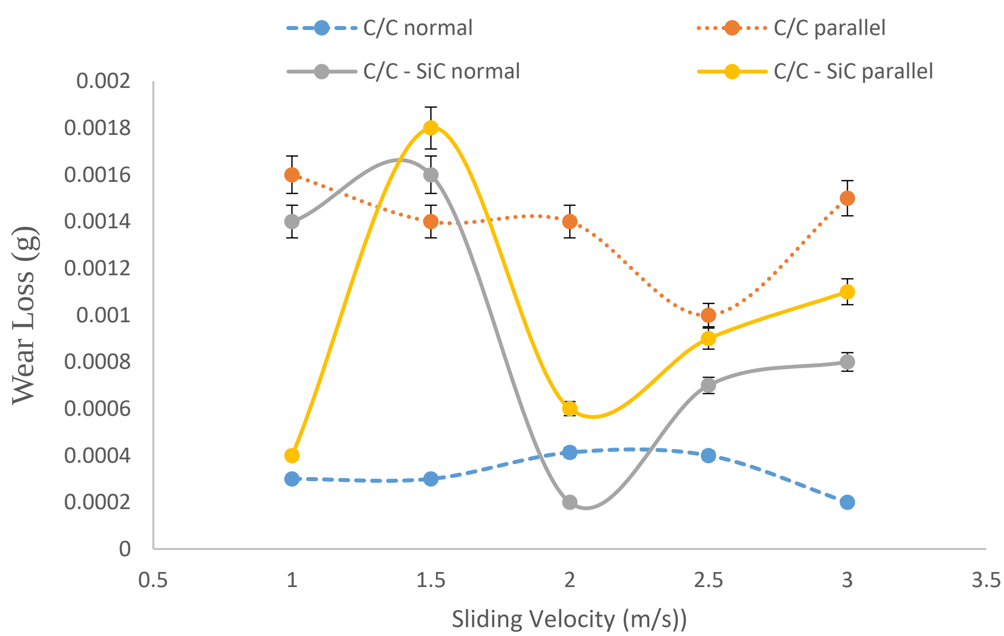


Fig. 4.10. Variation of wear loss with sliding velocity at 20 N load for C/C normal, C/C parallel, C/C-SiC normal, and C/C-SiC parallel.

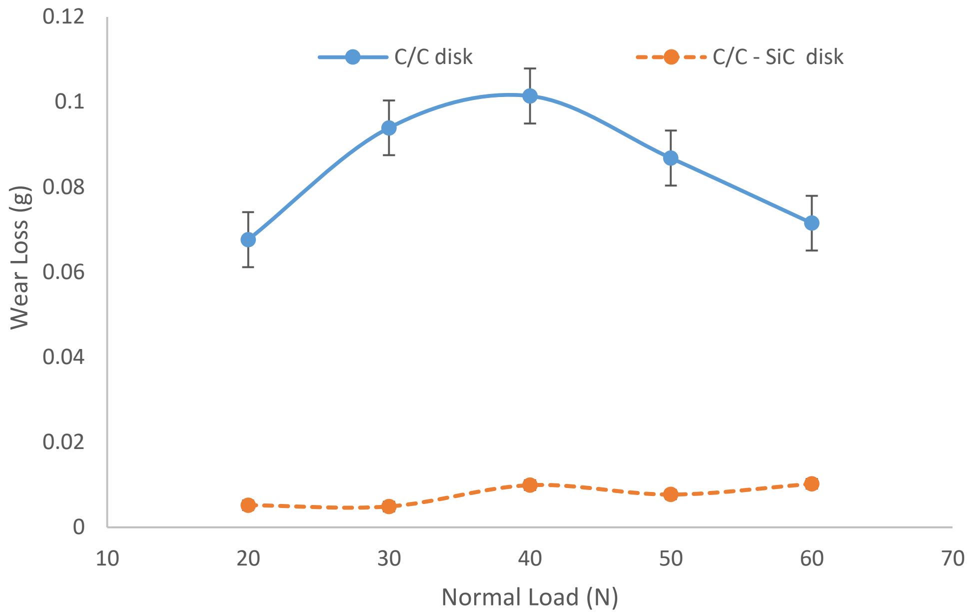


Fig. 4.11. Variation of wear loss with normal load at 2 m/s sliding velocity in non-conformal Hertzian contacts for C/C and C/C-SiC disks.

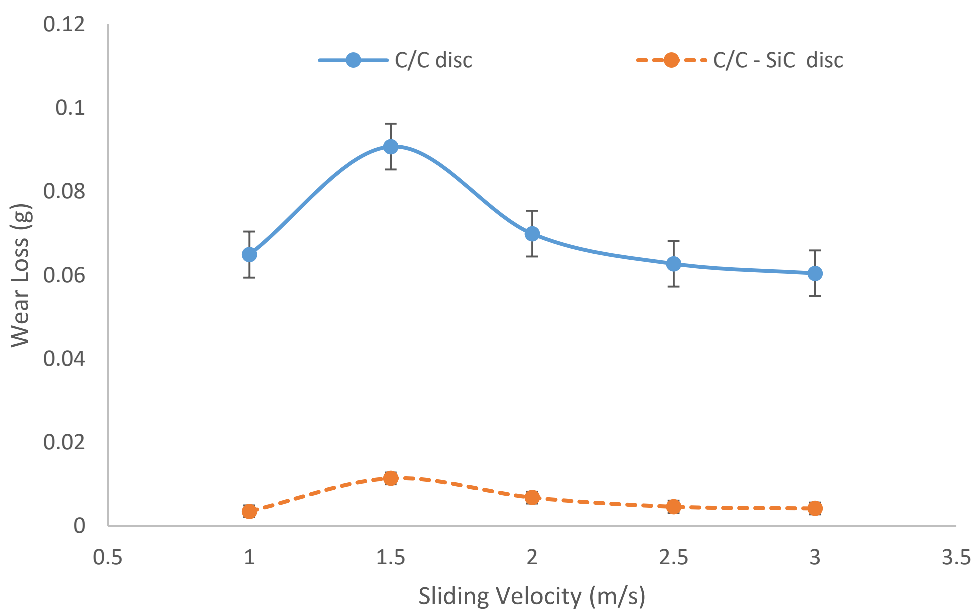


Fig. 4.12. Variation of wear loss with sliding velocity at 20 N load in non-conformal Hertzian contacts for C/C and C/C-SiC disks.

Fig. 4.10 shows the variation of wear loss with sliding velocity at 20 N load. It can be observed from the figure that C/C parallel showed highest wear loss at high loads and C/C normal showed the lowest wear loss at high loads.

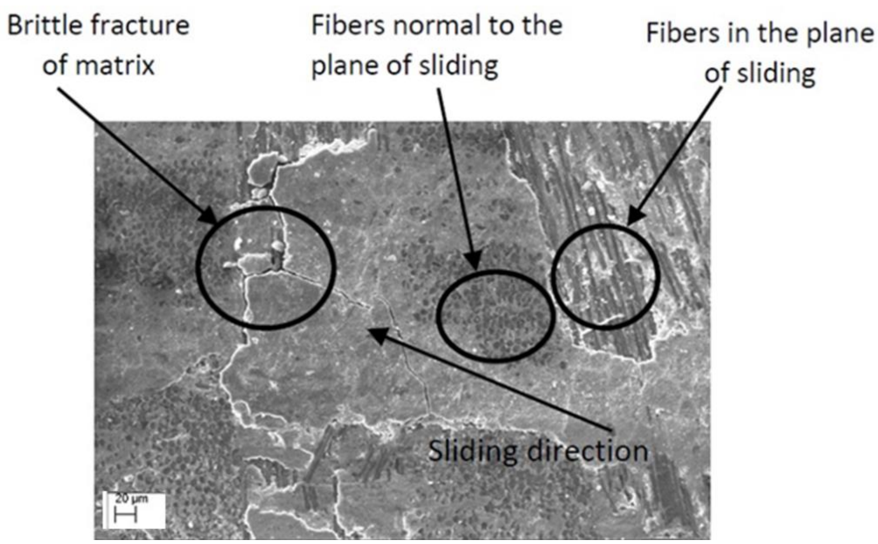
Fig. 4.11 shows the variation of wear loss with normal load at 2 m/s sliding velocity. It can be observed from Fig. 4.11 that wear loss of C/C composite was more as compared to C/C-SiC composite for non-conformal Hertzian contacts.

Fig. 4.12 shows the variation of wear loss with sliding velocity at 20 N load. It can be observed from Fig. 4.12 that wear loss first increased and then decreased with an increase in sliding velocity.

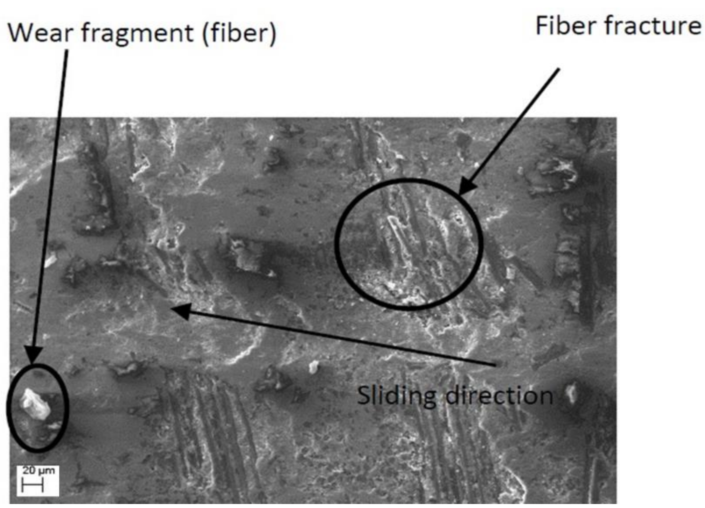
4.6.1.4. Discussion

The friction coefficient of C/C and C/C-SiC composites reduced after treating it with brake oil as can be observed in Fig. 4.2. However, the reduction was more in case of C/C composites as compared to C/C-SiC composites. This was attributed to the fact that C/C composites are more porous as compared to C/C-SiC composites due to which C/C composites absorbed more brake oil. C/C parallel absorbed more oil as compared C/C normal due to more surface porosity in the plane of lamina as compared to the normal direction.

As the load was increased in the case of C/C normal, friction coefficient first increased and decreased afterward. As the load was increased, more and more asperities came in contact and increased the real contact area which increased friction coefficient. However, due to the brittle nature of the carbon matrix, it got fractured and generated wear debris, as shown schematically in Figs. 3.2 (b) and (c). Brittle fracture of carbon matrix can be observed in Fig. 4.13(a).



(a)



(b)

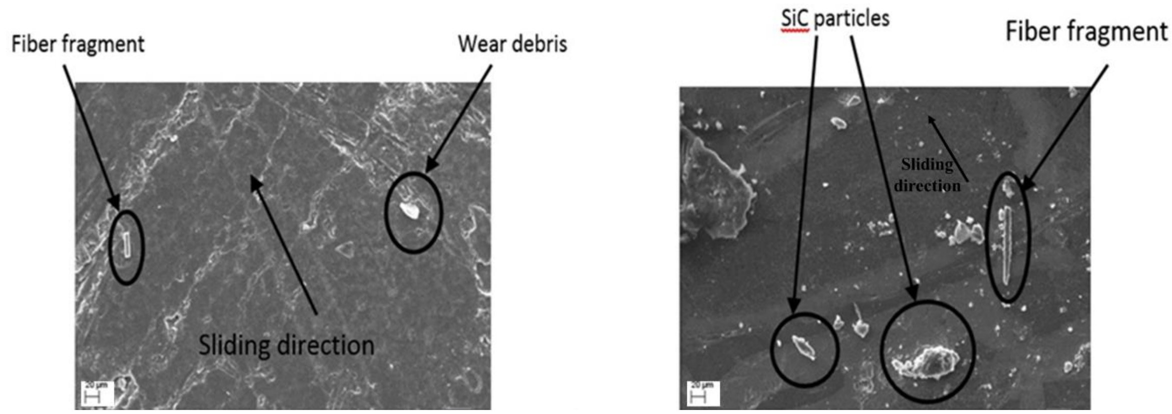
Fig. 4.13. SEM images showing (a) brittle fracture of matrix in C/C normal tested at 30 N load and 2 m/s velocity, and (b) fibre fracture in C/C normal tested at 50 N load and 2 m/s velocity.

Due to the incorporation of oil, generated wear debris got mixed with oil and did not stick to the counterface to form a smooth friction film due to which friction coefficient got increased.

As the load was increased further, fiber fracture in the form of fragments took place as can be observed in Fig. 4.13(b). Due to an increase in load, the excess oil between the composite and the counterface got squeezed out, and compaction of wear debris took place [175]. This led to the formation of friction film and decreased the friction coefficient.

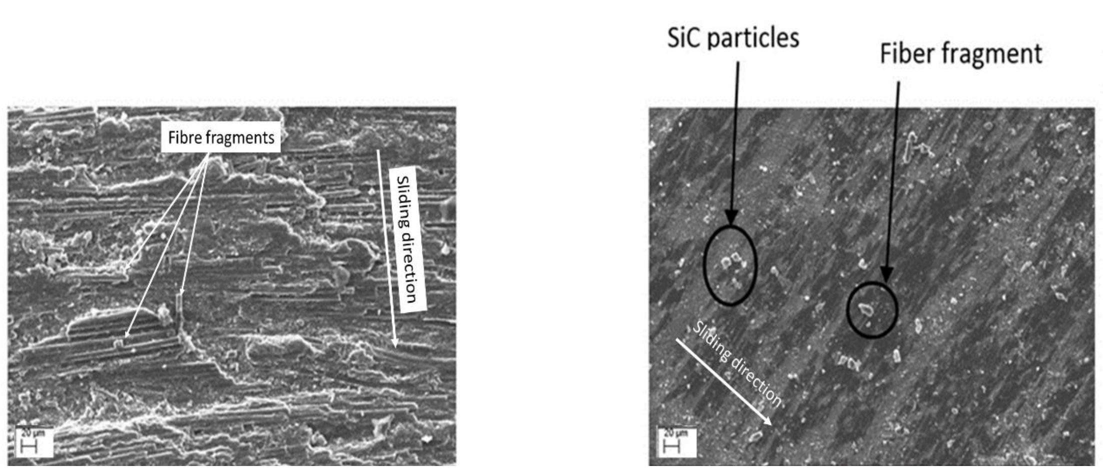
C/C parallel showed very less sensitivity to an increase in load. This was attributed to the fact that C/C parallel absorbed more brake oil. As the load was increased, the oil from the pores lubricated the counterface very well. However, the ability of formation of friction film in oil environment reduces, but the generation of friction film still took place at high loads which reduced friction coefficient [176]. Fig. 4.14(a) shows the SEM image of C/C parallel tested at 40 N load and 2 m/s sliding velocity.

The decay rate of C/C-SiC normal and C/C-SiC parallel was less. Both of these composites absorbed less oil due to less open porosity. C/C-SiC normal showed a decrease in friction coefficient with the increase in load. This was due to pulverization of wear debris at high loads which formed friction film (as shown in Fig. 3.3 (b)) and reduced friction coefficient [125]. However, the wear debris also contained SiC particles which are very hard to be pulverized at low energy conditions. Thus SiC particles acted as third body particles. Fig. 4.14(b) shows C/C-SiC normal tested at 40 N load and 2 m/s sliding velocity. In the case of C/C-SiC parallel, most of the oil was adsorbed on the surface and very less was penetrated. Thus at low loads, oil lubricated the surface well and squeezing out of oil was very less. However, at high loads squeezing of oil occurred which in turn increased the friction coefficient.



(a) (b)

Fig. 4.14. SEM images showing (a) fibre fragment in wear debris of C/C parallel tested at 40 N load and 2 m/s sliding velocity, and (b) SiC particles in C/C- SiC normal tested at 40 N load and 2 m/s sliding velocity.



(a) (b)

Fig. 4.15. SEM images showing (a) C/C disk, and (b) C/C-SiC disk tested at 50 N load and 2 m/s sliding velocity.

It can be observed from Fig. 4.7 that the friction coefficient of C/C composite was lower than C/C-SiC composite in non-conformal Hertzian contacts. The contact area between ball and disk increased with the time of sliding. As the load was increased, the contact area increased faster which increased the value of friction coefficient. It can be observed from Fig. 4.15(a) that fiber breakage in C/C disk has occurred in non-conformal Hertzian contacts. However, oil between disk and ball was not able to affect the friction behavior to a significant extent but, wear debris (especially fiber fragments) got mixed with oil near the contact area and stuck to the ball which increased friction coefficient at high loads.

In the case of C/C-SiC parallel, SiC particles played an important role in increasing the friction coefficient due to its hardness. Fig. 4.15(b) shows the worn surface of C/C-SiC disk tested at 40 N load and 2 m/s sliding velocity. SiC particles abraded the steel ball, and some of the material of ball was transferred to the composite surface which was confirmed by the presence of Fe and Cr in EDX spectrum of the worn surface of C/C-SiC disk as shown in Fig. 4.16.

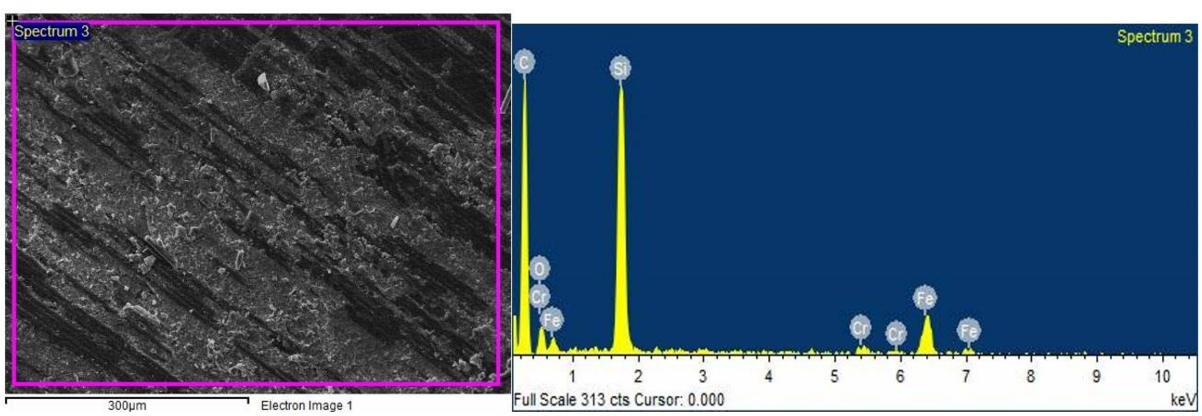
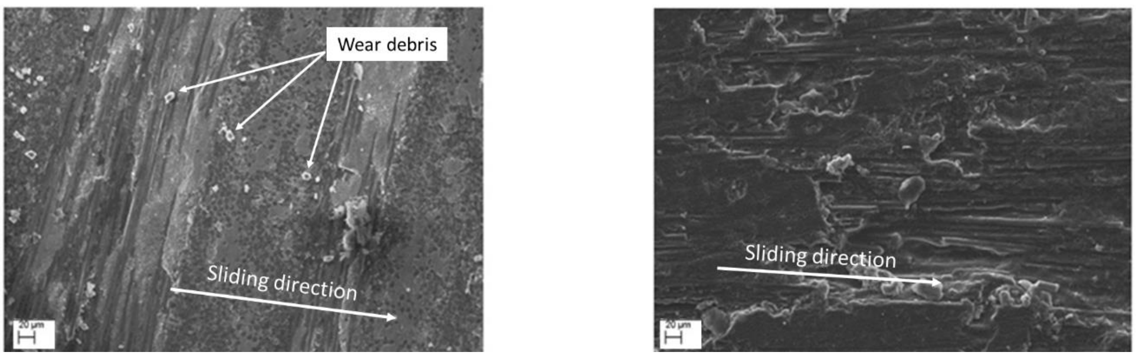


Fig. 4.16. EDX spectrum of C/C-SiC disk tested at 30 N load and 2 m/s velocity.

The friction coefficient of C/C normal first increased with an increase in sliding velocity and decreased afterward. At low sliding velocity, the formation of friction film was delayed due to low velocity [177] and the presence of oil. Thus friction coefficient first increased with sliding velocity. However as the velocity was increased beyond 2.5 m/s, friction film formed early which decreased the friction coefficient. Fig. 4.17(a) shows C/C normal tested at 2.5 m/s sliding velocity and 20 N load. Wear debris can be observed in Fig. 4.17(a).

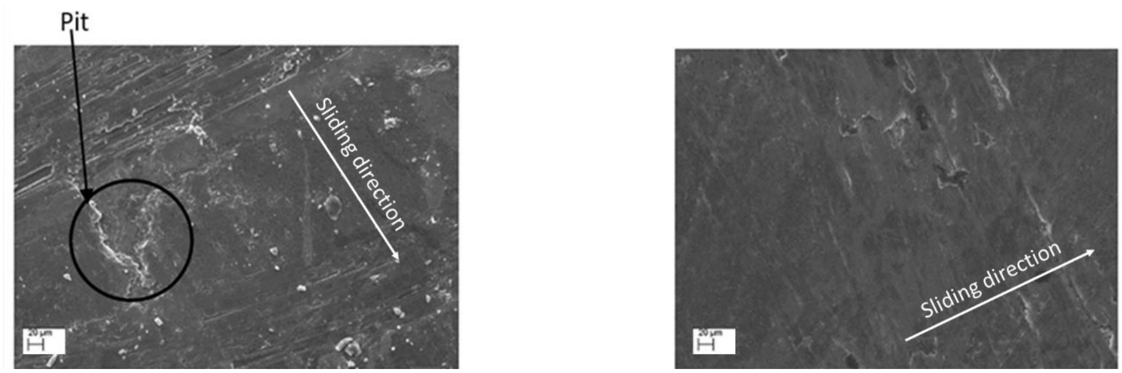


(a) (b)

Fig. 4.17. SEM images showing C/C composites tested at 2.5 m/s velocity and 20 N load (a) C/C normal, and (b) C/C parallel.

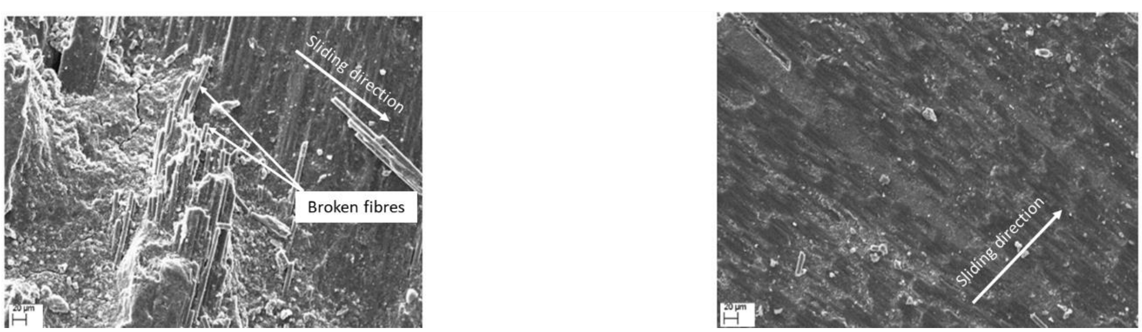
The friction coefficient of C/C parallel decreased with an increase in sliding velocity. This was attributed to the fact that as sliding velocity increased, it created a partial negative pressure at the surface of the composite due to high speed. Thus oil from the subsurface rush to the surface which lubricated the surface partially as surface porosity of C/C parallel was high. This decreased friction coefficient. However as sliding velocity was increased further, the early formation of friction film also contributed to a decrease in friction coefficient. Fig. 4.17(b) shows C/C parallel tested at 2.5 m/s sliding velocity and 20 N load.

Due to the presence of hard SiC particles, C/C – SiC composites exhibited higher friction coefficient as compared to C/C composites at all tested velocities in both orientations. Fig. 4.18(a) shows that there was the presence of pits in the worn surface of C/C-SiC normal. Small particles like wear debris can also be observed. Fig. 4.18(b) shows that worn surface of C/C-SiC parallel was relatively smooth as compared to C/C-SiC normal.



(a) (b)

Fig. 4.18. SEM images showing C/C-SiC composites tested at 2.5 m/s sliding velocity and 20 N load (a) C/C-SiC normal, (b) C/C-SiC parallel.



(a) (b)

Fig. 4.19. SEM images showing (a) C/C disk tested at 3 m/s sliding velocity and 20 N load, and (b) C/C-SiC disk tested at 2.5 m/s sliding velocity and 20 N load.

The friction coefficient of C/C-SiC composites was higher than C/C composites in localized stress conditions (non-conformal Hertzian contacts) at all tested velocities. At high sliding velocity, broken fibers can be observed in C/C disk as shown in Fig. 4.19(a). The breaking of fibers required more energy which in turn increased the friction coefficient. However, the presence of SiC phase was responsible for higher friction coefficient in C/C – SiC composites. Broken fibers observed was very less in C/C – SiC disk as shown in Fig. 4.19(b). Wear loss of C/C normal first increased with an increase in load and decreased afterward which was due to an increase in abrasion as more asperities came in contact at high load. However as the load was increased further, compaction of wear debris took place due to squeezing out of excess oil. Thus friction film was formed on the surface which decreased the friction coefficient. C/C parallel showed an increase in wear loss with the increase in load due to softening of the matrix by brake oil as asperities penetrated easily in the soft matrix. C/C parallel absorbed more oil as compared to other composites.

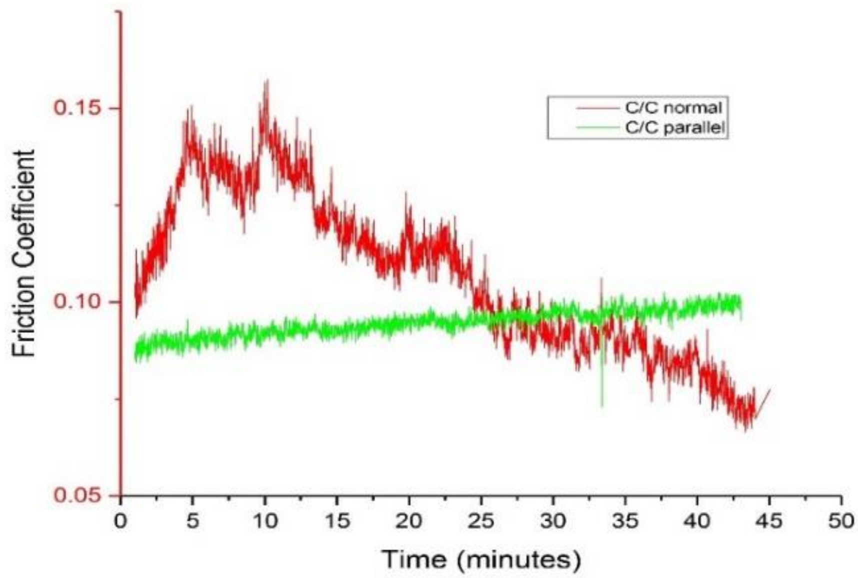
Wear loss of C/C- SiC normal first increased with an increase in load and decreased afterward. The increase was due to an increase in abrasive wear with an increase in load. However as the load was increased further, SiC got detached from the composite surface and got mixed with oil. This mixture filled the space between composite and counterface. As SiC particles are very hard, it prevented the direct contact of composite and counterface thus, in turn, decreased wear loss. The same mechanism happened with C/C-SiC parallel. However C/C-SiC parallel showed less wear loss (as compared to C/C normal) due to more absorbance of oil and presence of hard SiC phase.

Wear loss of C/C parallel was higher as compared to C/C normal at all tested velocities. This was due to the softening of the matrix by oil. C/C- SiC parallel showed higher wear loss as compared to C/C – SiC normal at all tested sliding velocities except at 1 m/s sliding velocity. Wear loss of both C/C and C/C-SiC disks first increased with an increase in load and decreased with further increase in load. The increase was due to an increase in abrasion action as the load was increased. However, the decrease was due to the generation of fiber fragments in case of C/C disk and SiC particles in C/C-SiC disk at high loads. Same happened with C/C disk and C/C-SiC disk when tested at different velocities as an early generation, or delayed generation of wear debris at different velocities dictated the wear behavior.

4.6.2. Reciprocating Sliding

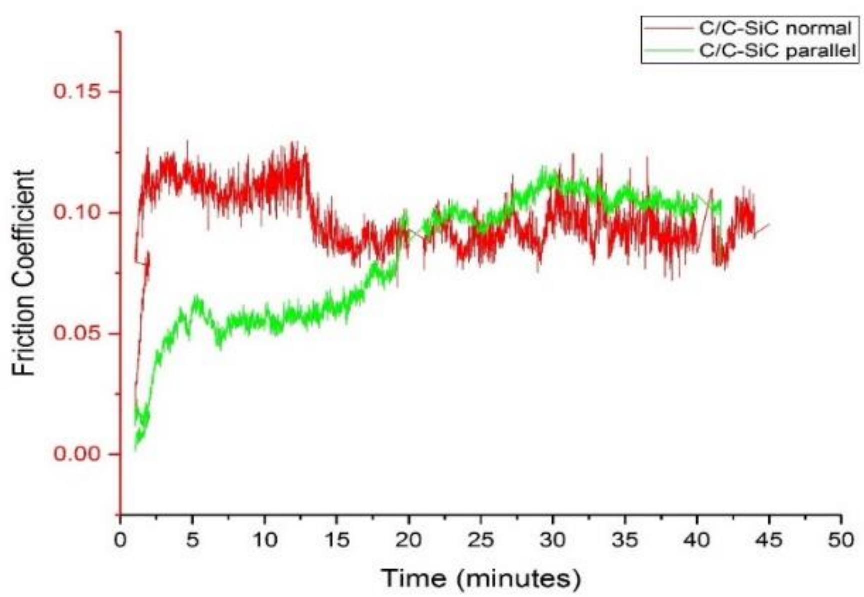
4.6.2.1 Friction response

Fig. 4.20(a) shows the variation of friction coefficient with time in the case of C/C composites. It was observed that the friction coefficient of C/C normal first increased with time and after some time, it decreased whereas C/C parallel showed almost stable behavior. The fluctuations in friction coefficient in case of C/C normal was more as compared to C/C parallel.



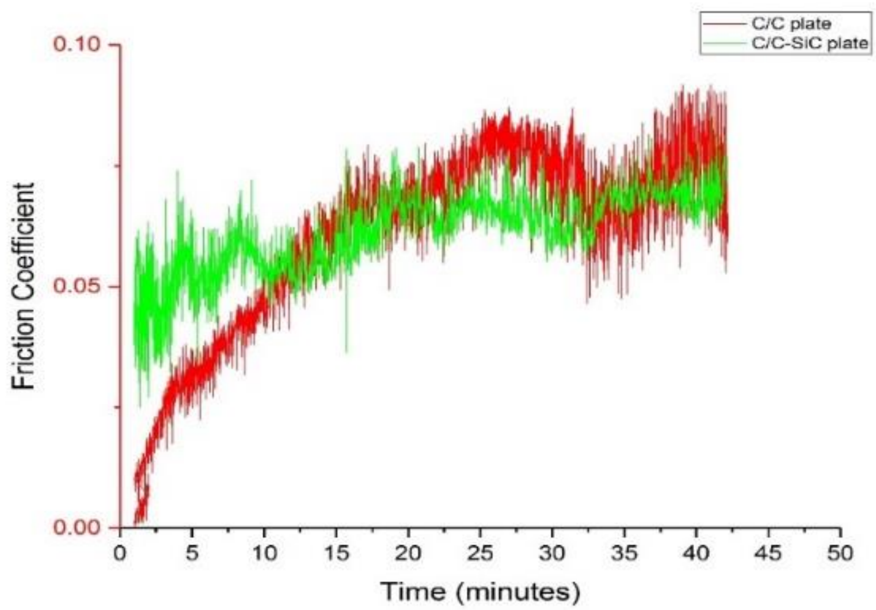
C/C normal
C/C parallel
Friction Coefficient
0.15
0.10
0.05
0
5
10
15
20
25
30
35
40
45
50
Time (minutes)

(a)



C/C-SiC normal
C/C-SiC parallel
Friction Coefficient
0.15
0.10
0.05
0.00
0
5
10
15
20
25
30
35
40
45
50
Time (minutes)

(b)



(c)

Fig. 4.20. Representative plot for variation of friction coefficient with time at 70 N load in (a) C/C composites and (b) C/C – SiC composites tested in low conformity contacts and, (c) C/C and C/C-SiC composites tested in non-conformal hertzian contacts.

Fig. 4.20(b) shows the variation of friction coefficient with time in case of C/C-SiC composites. It was observed that the rise in friction coefficient was sharp for first few cycles in case of C/C-SiC normal. However friction coefficient for both orientation of laminates acquired almost same values when the number of cycles increased.

It can be observed from Fig. 4.20(c) that fluctuations in friction coefficient in case of non-conformal hertzian contacts was more as compared to low conformity contacts. Friction coefficient of C/C composites increased sharply with time whereas friction coefficient of C/C-SiC composites didn't vary much with time in non-conformal hertzian contacts.

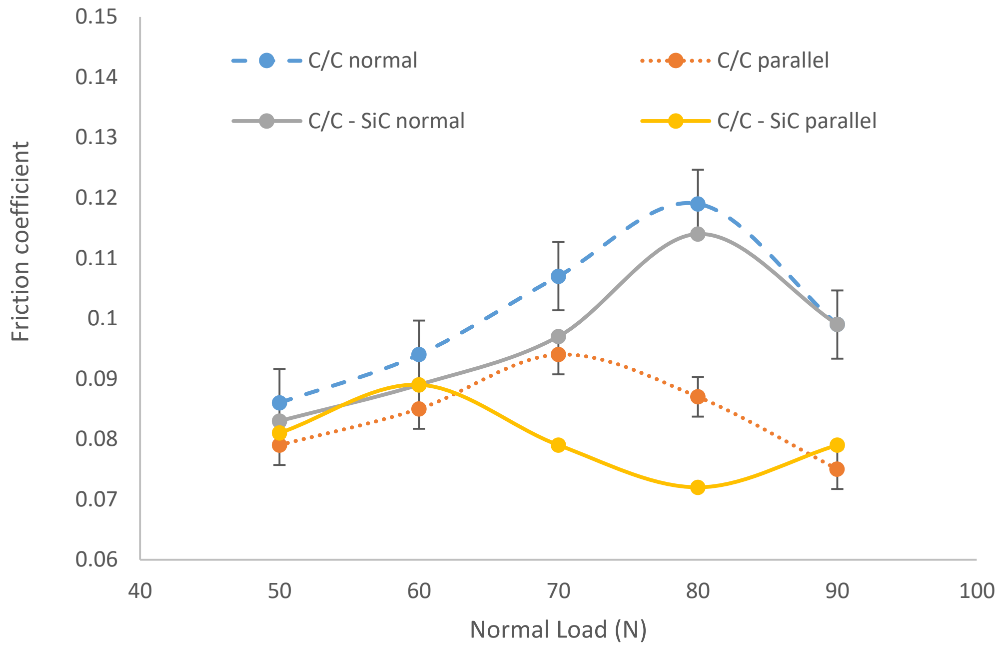


Fig. 4.21. Variation of friction coefficient with normal load in low conformity contacts for C/C normal, C/C parallel, C/C-SiC normal and C/C-SiC parallel composites.

It can be observed from Fig. 4.21 that at low loads, the friction coefficients of C/C and C/C-SiC composites are almost same for parallel as well as normal orientation of laminates. As the load was increased, friction coefficient of C/C normal, C/C parallel and C/C-SiC normal first increased and after that decreased. However in case of C/C-SiC parallel, friction coefficient first increased with increase in load, then decreased and again increased after that. It can be observed from Fig. 4.22 that friction coefficient of C/C-SiC composites was more as compared to C/C composites in non-conformal hertzian contacts. C/C-SiC composites showed increase in friction coefficient with increase in load. However, friction coefficient of C/C composites first increased with increase in load and decreased after that.

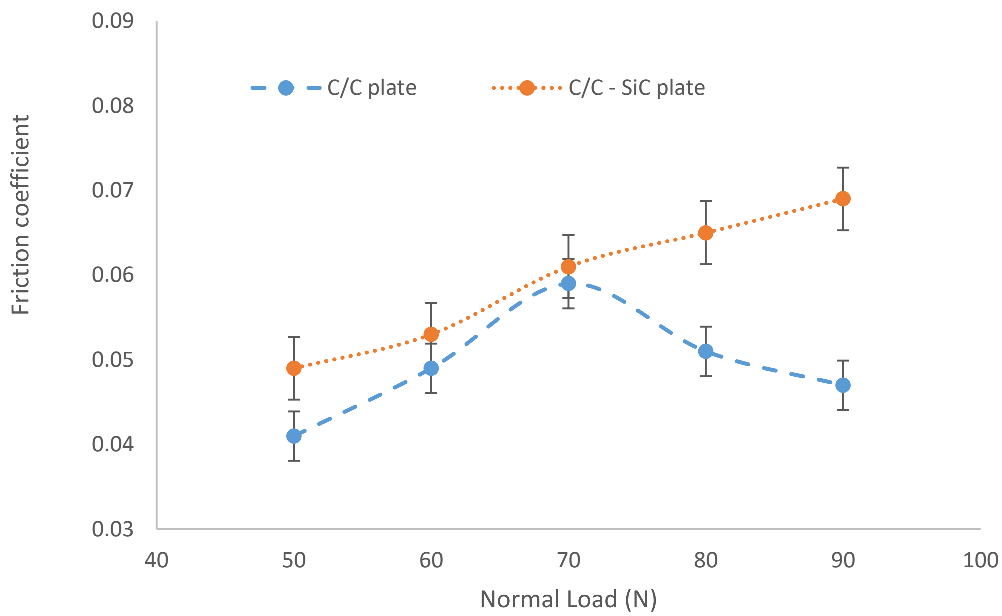


Fig. 4.22. Variation of friction coefficient with load in non-conformal hertzian contacts for C/C and C/C-SiC plate.

4.6.2.2. Wear behaviour

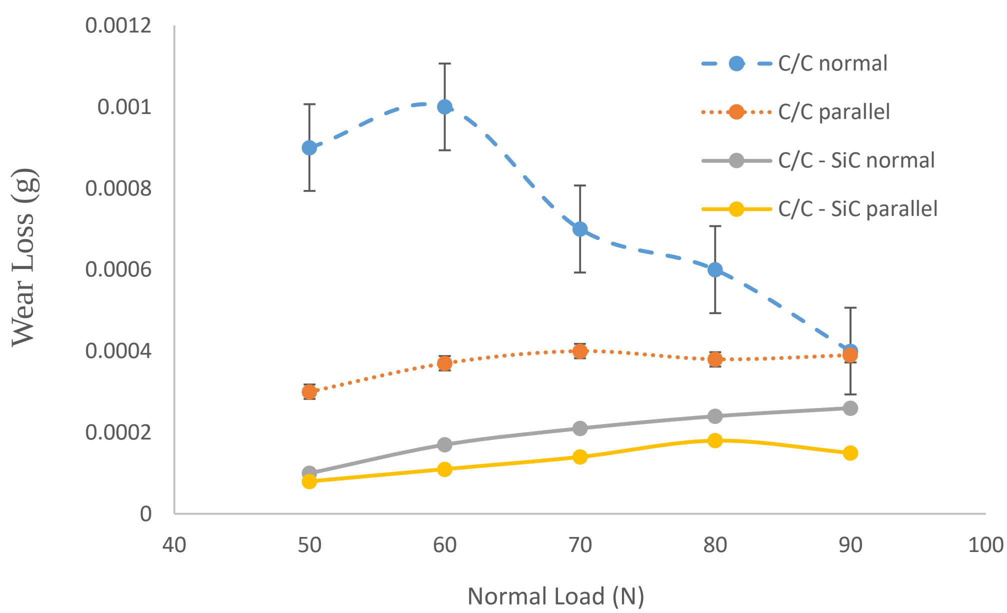


Fig. 4.23. Variation of wear loss with normal load in low conformity contacts for C/C normal, C/C parallel, C/C-SiC normal and C/C-SiC parallel composites.

It can be observed from Fig. 4.23 that C/C normal showed highest wear loss. Wear loss of C/C parallel and C/C-SiC normal increased with increase in load while wear loss of C/C normal first increased with increase in load and decreased after that.

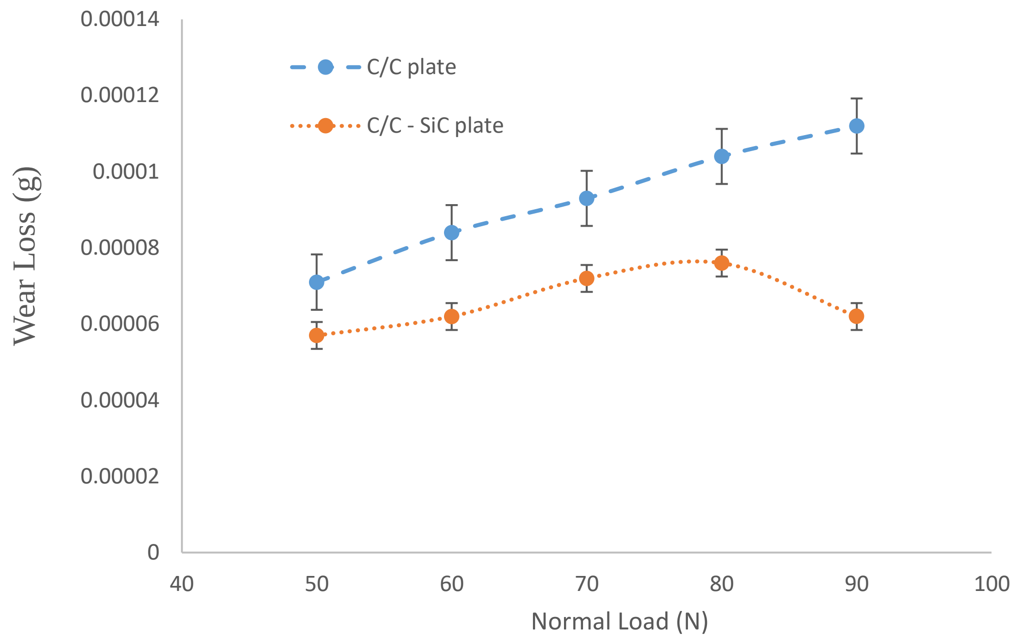


Fig. 4.24. Variation of wear loss with normal load in non-conformal hertzian contacts for C/C and C/C-SiC plate.

It can be observed from Fig. 4.24 that in case of non-conformal hertzian contacts, wear loss of C/C composites increased with increase in load while wear loss of C/C-SiC composites first increased with increase in load and decreased after that.

4.6.2.3. Discussion

Friction film formation, disruption, adhesion and abrasion of contact conjunctions depicts the tribological behavior of C/C and C/C – SiC composites in dry environment [178] but friction film formation was less in the presence of brake oil because brake oil got mixed with wear debris and prevented adhesion of wear debris on the surface. Thus, tribological response of C/C and C/C-SiC composites was different in brake oil environment.

Fluctuations in friction coefficient for composites having normal orientation of laminates was more as compared to composites having parallel orientation of laminates. This was due to more surface porosity and more absorption of oil in case of parallel orientation of laminates. Sliding occur in a very confined region under reciprocating conditions. Thus some of wear debris filled the pores on the surface and some of it made a film of low shear resistance on the surface of composite with parallel orientation of laminates. The escapement of wear debris from in between the contacting surfaces by any kind of force (e.g. centrifugal force in case of unidirectional pin on disk sliding), was very less. In case of composites having normal orientation of laminates, surface porosity as well as absorption of brake oil was less. Although the generated wear debris made a film of low shear resistance on the surface of composite, but due to presence of oil, the film didn't show strong adhesion to the surface of composite. Thus the formed film was easily drawn away by counter surface in the subsequent cycle. Due to this, composites with normal orientation of laminates showed more fluctuations in friction coefficient.

Composites with normal orientation of laminates showed higher friction coefficient as compared to composites with parallel orientation of laminates in first few cycles. As the number of sliding cycles increased, the proportion of wear debris increased in wear debris and oil mixture. Some of the wear debris and oil mixture squeezed out with time, from in between the contact surfaces. Thus the chances of formation of friction film increased after some cycles in case of composites having normal orientation of laminates as they absorbed less oil. However in case of composites having parallel orientation of laminates, squeezing out of oil led to interaction of fibers of composite and asperities of counter surface. Fiber provided more resistance to sliding as breakage of fibers occurred which required more braking energy. This increased the friction coefficient after few cycles in composites having parallel orientation of laminates.

In case of non-conformal hertzian contacts, friction behavior of C/C-SiC composites was more stable as compared to C/C composites. Friction coefficient of C/C composites increased with time but friction coefficient of C/C-SiC composites didn't vary much with time. In case of non-conformal hertzian contacts (i.e. ball on plate arrangement), the stresses induced were high and localized as compared to low conformity contacts (pin on plate arrangement). Thus the oil in between the contacting surfaces was very less due to generation of high contact stresses and the mixture of wear debris and oil stuck to the ball near the contact area. High stresses pulverized the wear debris and formed friction film. However generation of cyclic compressive stresses of opposite sign led to disruption of friction film [16] which increased friction coefficient of C/C composites as the number of cycles increased in non-conformal hertzian contacts.

Friction coefficient of composites with normal orientation of laminates was more as compared to composites with parallel orientation of laminates in brake oil environment. This was attributed to absorption of more brake oil in case of composites having parallel orientation of laminates. Friction coefficient of C/C composites first increased with increase in load and decreased after that whether it was loaded with normal orientation of laminates or parallel orientation of laminates. C/C-SiC normal also showed the same trend. The increase was attributed to the more asperity interaction and squeezing out of excess oil from in between the contacting surfaces [175]. Fig. 4.25(a) shows C/C normal tested at 80 N. Wear debris in the form of fibers fragments and particles from carbon matrix can be observed. The asperities from the counter surface led to grain abrasion and fiber breakage occurred due to grain abrasion at high loads. The size of fiber fragments in wear debris was not same. The grain abrasion increased with increase in load which in turn increased the friction coefficient. However as the load was increased further, pulverization of debris took place. Due to squeezing out of excess oil, the pulverized wear debris was able to form a friction film on the surface. This decreased the friction coefficient at high loads.

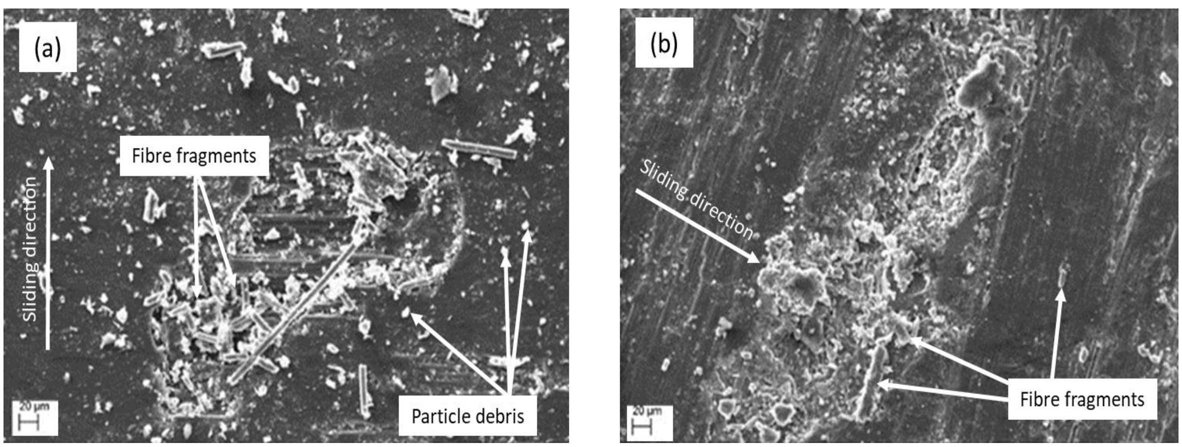


Fig. 4.25. SEM images showing composites tested at 80 N load (a) C/C normal, and (b) C/C-SiC normal.

Fig. 4.25(b) shows C/C-SiC normal tested at 80 N load. Wear debris in the form of SiC particles and fiber fragments can be observed. SiC particles are hard to pulverize. Thus, as the load was increased, these SiC particles penetrated the counter surface and increased the friction coefficient through grain abrasion (as shown in Fig. 3.3 (c)). However as the load was increased further, the SiC particles erupted from the matrix in the form of wear debris as a result of repeated flexion in opposite directions. The sliding area is confined in reciprocating sliding. Thus SiC acted as third body and prevented the directed contact of the interacting surfaces which in turn decreased friction coefficient.

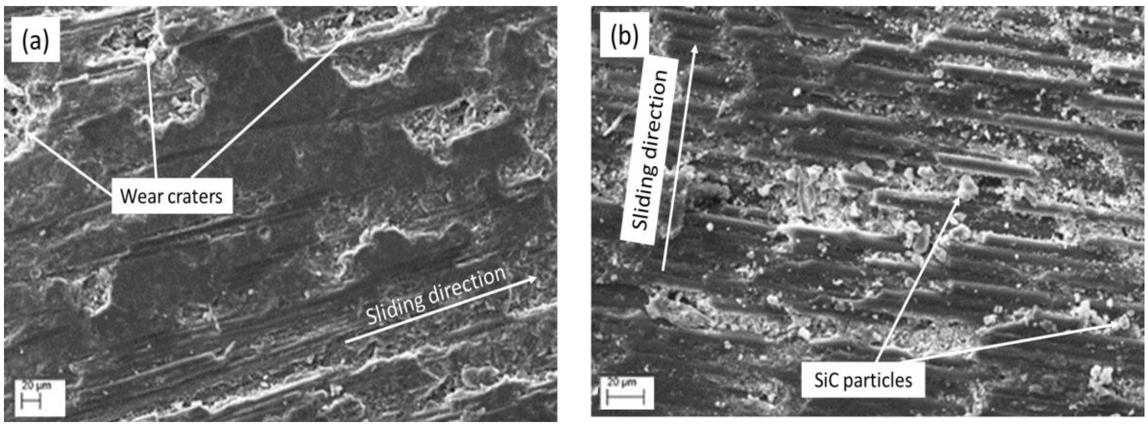


Fig. 4.26. SEM images showing (a) C/C parallel tested at 70 N load, (b) C/C-SiC parallel tested at 90 N load.

Fig. 4.26(a) shows C/C parallel tested at 70 N load. Some wear craters were observed. Treating composite with brake oil led to softening of matrix. However softening was predominant in case of parallel orientation of laminates due to more absorption of oil. Thus matrix material was ejected easily and made the surface more rough which increased the friction coefficient. The chance of adhesion of wear debris on the surface was less due to presence of brake oil. As the load was increased further, squeezing out of excess brake oil and formation of smooth surface by filling up craters with wear debris led to decrease in friction coefficient.

Fig. 4.26(b) shows C/C-SiC parallel tested at 90 N load. SiC particles in the form of wear debris can be observed. Fiber breakage can also be observed which was due to grain abrasion of C/C-SiC parallel at high loads. In case of C/C-SiC parallel, the absorption of brake oil was less as compared to C/C parallel. Thus brake oil didn't much lubricated the surface. Penetration of hard SiC particles in the counter surface led to first rise in friction coefficient value. As the load was increased, SiC particles in wear debris acted as third body and decreased the friction coefficient. As the load was increased further, the applied pressure was sufficient for the embedment of SiC particles in the counter surface which in turn increased friction coefficient through grain abrasion of C/C-SiC parallel.

It was observed that generally C/C composites showed high friction coefficient value as compared to C/C-SiC composites in reciprocating sliding under brake oil environment which is opposite to the results obtained in unidirectional sliding under dry conditions [13, 16]. This was due to sliding in a confined region because of small stroke length in case of reciprocating sliding. In case of unidirectional sliding, mutual overlap coefficient (MOC) is less and the wear debris is gradually eliminated from the contact area. However in case of reciprocating sliding, MOC is high and wear debris get entrapped in the contact area. The entrapment of SiC particles in the contact area led to decrease in friction coefficient of C/C-SiC composites because SiC particles are not easy to cut even at high loads and acted as third body. Whereas, in case of C/C composites, the entrapment of carbon wear debris led to formation of friction film which was easily disrupted due to repeated flexion in opposite direction in case of reciprocating sliding.

For non-conformal hertzian contacts, friction coefficient of C/C-SiC composites was higher as compared to C/C composites. Stresses were very high and localized in low conformity contacts. Generation of high stresses led to disruption of friction film formed on the surface of C/C composites which increased the friction coefficient as the load was increased. However as the load was increased further, a negative pressure was generated at the surface of composite due to reciprocating sliding. As oil was entrapped in the pores of C/C composites due to its open surface porosity, it rushed to the surface due to negative pressure which lubricated the surface. This in turn decreased the friction coefficient at high loads. Fig. 4.27(a) shows the worn surface of C/C composites tested at 80 N load under non-conformal hertzian contacts. Wear debris observed was very less. The wear debris generated got mixed with oil and stuck to the ball near the contact area.

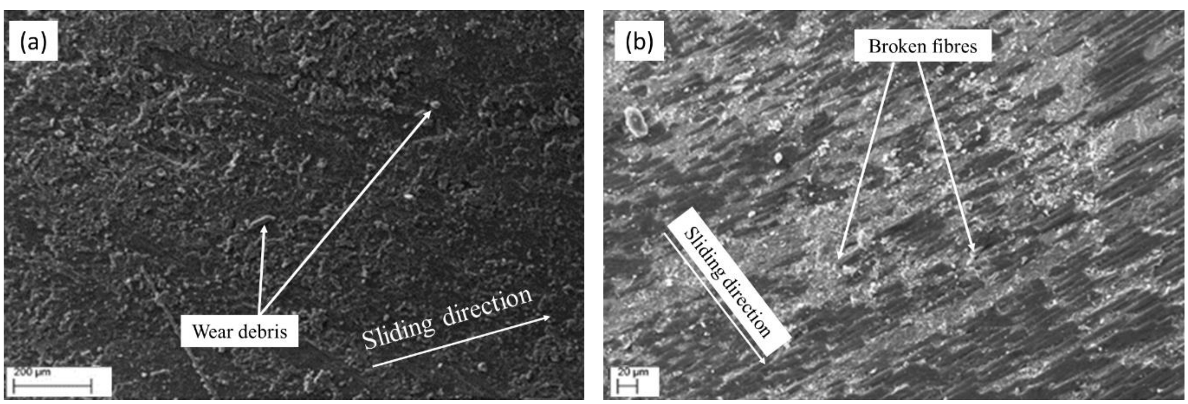


Fig. 4.27. SEM images showing composites tested in non-conformal hertzian contacts (a) C/C plate tested at 80 N load, and (b) C/C-SiC plate tested at 70 N load.

In case of C/C-SiC composites tested in non-conformal hertzian contacts, the wear debris generated (SiC particles) embedded in the counter surface, however the contact area was small. The embedded SiC particles in the counter surface abraded the composites. Resistance to sliding was also provided by fibers as broken fibers can be observed in Fig. 4.27(b). Higher the load, deeper the penetration of SiC particles and more resistance to sliding was provided as deeper penetration covered more fiber filaments. This increased the friction coefficient as the load was increased. Friction coefficient in case of non-conformal hertzian contacts was low as compared to low conformity contacts.

It was observed that wear loss in case of C/C parallel, C/C-SiC normal and C/C-SiC parallel generally increased with increase in load. But the increase was not much significant. However in case of C/C normal, wear loss first increased and then decreased significantly. The increase in wear loss of C/C composites was attributed to increase in abrasive wear with load and decrease in wear loss was attributed to formation of friction film at high loads. The possibility of friction film in case of C/C parallel was less due to more absorption of oil. Thus wear loss increased with increase in load. However increase was not much significant because brake oil lubricated the surface. The hardness of C/C-SiC composites is more as compared to C/C composites. Thus wear loss of C/C composites was more as compared to C/C-SiC composites. In non-conformal hertzian contact conditions also, C/C composites showed high wear loss as compared to C/C- SiC composites.

Friction coefficient and wear loss decreased to a greater extent in brake oil. The dispersion of wear debris in the brake oil prevented adhesion on the surface of composite as well counter surface. But presence of oil on the surface and subsurface led to lubrication of surface which decreased the friction coefficient. Further, adhesion and formation of friction film was prevented by brake oil which reduced the wear loss.

4.7. Conclusion

4.7.1. Unidirectional Sliding

The important conclusions obtained from the present investigation on the unidirectional sliding behaviour of brake oil treated C/C and C/C-SiC composites in unidirectional sliding are as follows:-

1. C/C composites gained more weight in brake oil as compared to C/C-SiC composites which was due to more surface porosity of C/C composites.
2. C/C-SiC composites showed less sensitivity to brake oil as compared to C/C composites. A maximum of almost 52% decay rate was observed in the friction coefficient of C/C composites and almost 17% in the case of C/C-SiC composites.
3. Generation of friction film in brake oil treated composites was a bit difficult as wear debris got mixed with brake oil and stuck to the surface of counterface which shows less adhesion with the counterface. However, at high loads, oil squeezed out, and the chance of formation of friction film increased.
4. The synergism between friction film formation, lubricating action by oil, mixing of debris with oil and type of debris (fiber fragments or through matrix) depicted the tribological behavior of C/C and C/C-SiC composites.
5. C/C-SiC composites loaded in the parallel orientation of laminates showed the highest friction coefficient at high loads whereas C/C composites showed the lowest friction coefficient when loaded in the parallel orientation. This was due to more absorption of brake oil by C/C composites.
6. In the case of non-conformal Hertzian contacts, sticking of wear debris (mixed with oil) near the contact area dictated the tribological behavior.
7. There was almost 5 to 10 folds decrease in friction coefficient in case of non-conformal Hertzian contacts as compared to partial conformity contacts.

4.7.2. Reciprocating Sliding

The important conclusions obtained from the present investigation on the unidirectional sliding behaviour of brake oil treated C/C and C/C-SiC composites in unidirectional sliding are as follows:-

1. Composites with parallel orientation of laminates showed less fluctuations in friction coefficient due to more absorption of oil and low adhesion of wear debris to the counter surface in the presence of oil. The formation of friction film was difficult to observe in brake oil conditions due to dispersion of wear debris in oil
2. Presence of brake oil reduced friction coefficient by 70% – 80% and wear loss by 75% – 90% as compared to dry environment.
3. Friction coefficient of C/C composites was generally more than that of C/C-SiC composites in low conformity conditions due to presence of hard SiC particles which prevented direct contact of interacting surfaces, and confined region sliding which prevented escapement of SiC particles.
4. Friction coefficient of composites with parallel orientation of laminates was generally less due to more surface porosity and absorption of oil as compared to composites having normal orientation of laminates.
5. Friction coefficient decreased by 1.5 to 3 times and wear loss by 5 to 10 times in non-conformal hertzian contacts as compared to low conformity contacts, due to less asperity interaction and high and localized stress regions at same load level.