Chapter 5

Tribological Behaviour Under Freezing Environment

5.1. Introduction

As discussed in the last chapter, tribological behaviour of C/C and C/C-SiC composites greatly depend on the environment. Most of the investigation on the tribological performance of C/C and C/C-SiC composites are focused on the high temperature environment. At high temperature, weight loss due to mechanical wear and oxidative wear, both contribute to the wear loss [173]. Tribological properties of C/C and C/C-SiC composites depend on interfacial strength and ease of formation of friction film on the surface [20, 50, 179]. The ease of formation of friction film on the surface of the composite depends on the environment, interfacial strength, load, and sliding conditions [151, 170, 180]. Tribological behavior of C/C and C/C-SiC composites have been investigated for different service conditions such as dry, wet, and high-temperature environment because it must fit in different service environments such as high temperature, wetness and salt fog [151]. Aircrafts and high speed cars are also subjected to icing conditions [181, 182]. The engines of aircrafts have been tested for icing/freezing conditions [183]. But tribological behavior of C/C and C/C-SiC composites for their use in aircrafts under freezing conditions has not been investigated yet.

5.2. Materials and Synthesis

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

5.3. Freezing Conditions

To simulate freezing conditions, all prepared samples were kept in the freezer section of the refrigerator for about 180 hours where the temperature was maintained at -6 ^{o}C. Samples were taken out from the freezer section after 180 hours and sliding wear tests were conducted on that samples.

5.4. Sliding wear tests

The details of sliding wear tests are discussed in chapter 3, section 3.3. The ambient temperature of the tests was 32 ± 2 ^{o}C. The maximum final temperature of specimens after sliding wear tests was observed to be ~74 ^{o}C.

5.5. Scanning Electron Microscopy

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

5.6. Results and Discussions

5.6.1. Unidirectional Sliding

5.6.1.1. Friction Response

Fig. 5.1 shows the variation of friction coefficient with normal load. It was observed that C/C composites with parallel orientation of laminates showed decrease in friction coefficient with increase in load. However friction coefficient of C/C composites with normal orientation of laminates first decreased up to 40 N load, then increased for 50 N load and after that again decreased with increase in load.

Friction coefficient of C/C-SiC composites with normal orientation of laminates increased with increase in load up to 50 N load and decreased afterwards whereas friction coefficient of C/C-SiC composites with parallel orientation of laminates increased with increase in load.

Fig. 5.2 shows the variation of friction coefficient with sliding velocity. It can be observed that friction coefficient of C/C composites for both parallel and normal orientation of laminates first increased with increase in sliding velocity and decreased afterwards. However, C/C-SiC normal showed decrease in friction coefficient with increase in sliding velocity and C/C-SiC parallel showed decrease up to 2 m/s sliding velocity and increase afterwards.

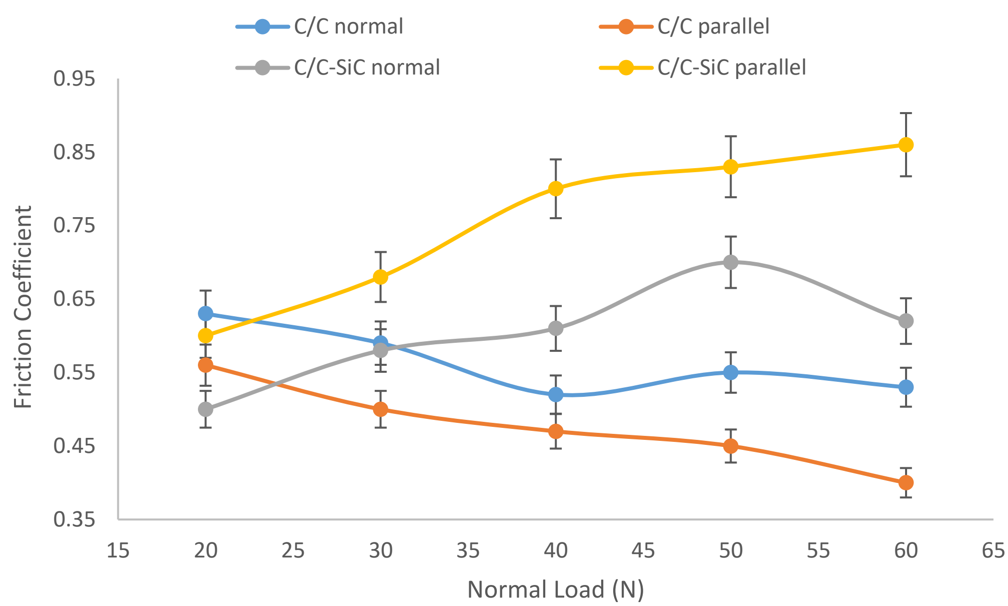


Fig. 5.1. Variation of friction coefficient with normal load for C/C normal, C/C parallel, C/C-SiC normal and C/C-SiC parallel.

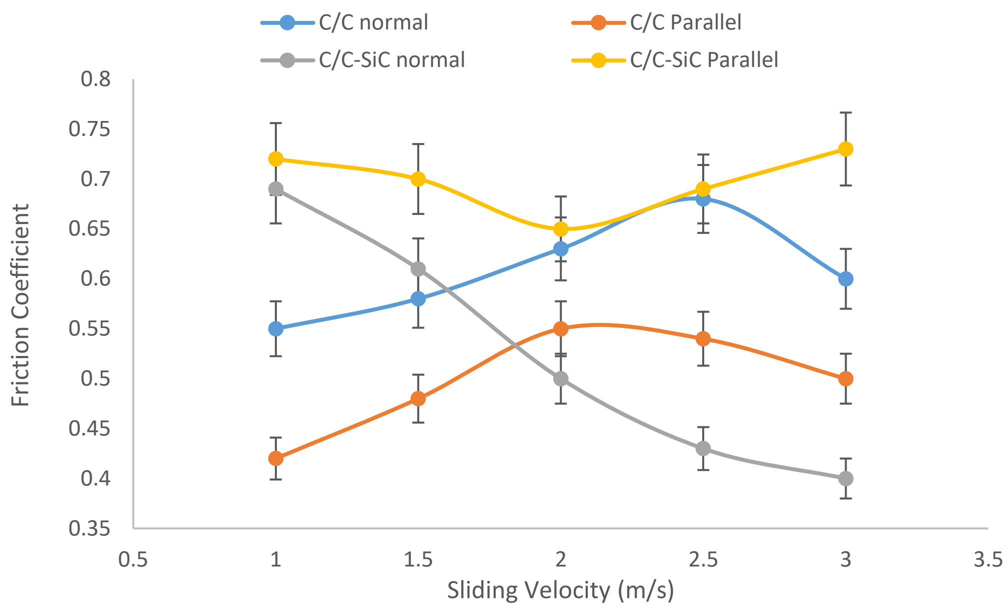


Fig. 5.2. Variation of friction coefficient with sliding velocity for C/C normal, C/C parallel, C/C-SiC normal and C/C-SiC parallel.

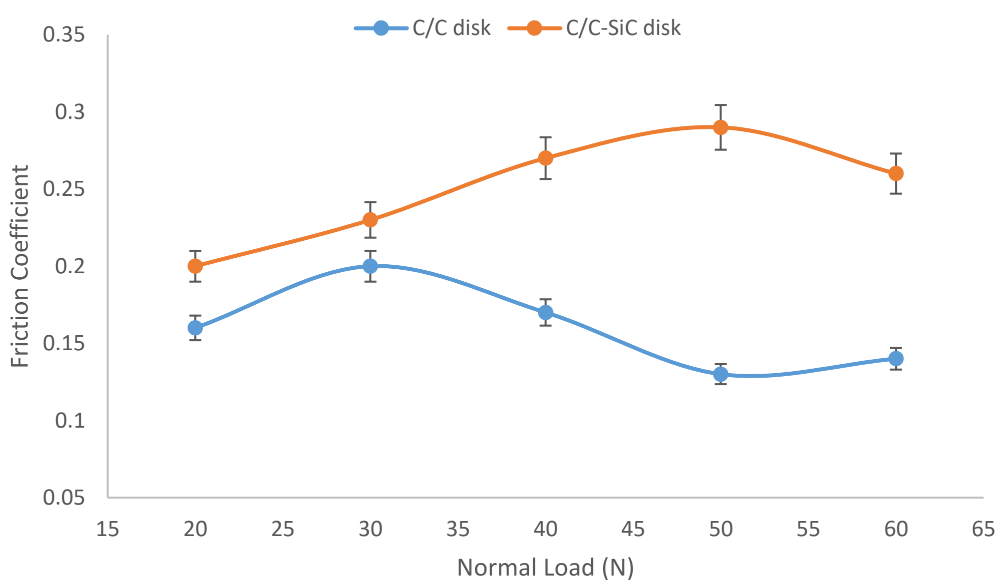


Fig. 5.3. Variation of friction coefficient with normal load in non-conformal hertzian contacts for C/C and C/C-SiC disks.

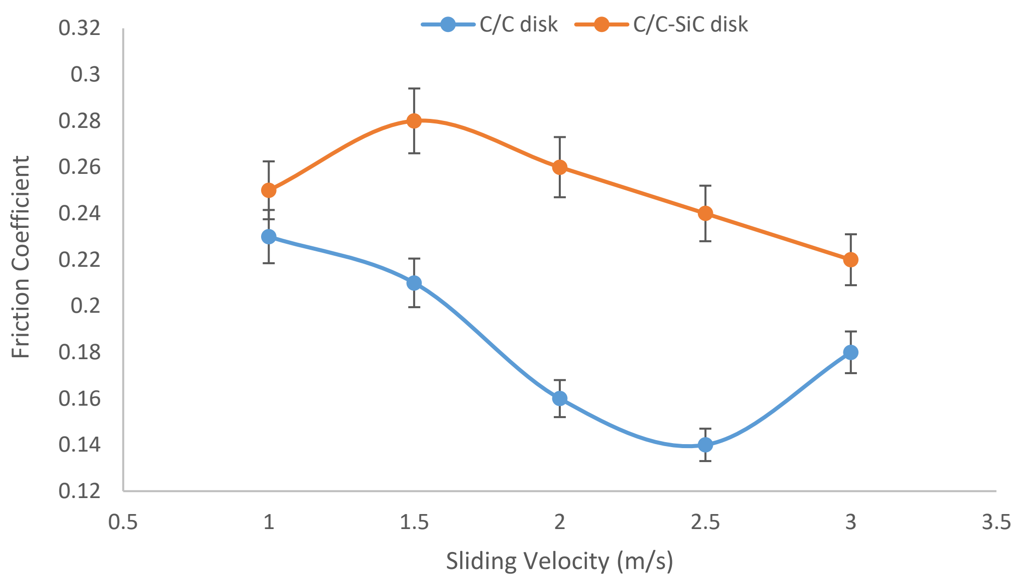


Fig. 5.4. Variation of friction coefficient with sliding velocity in case of non-conformal hertzian contacts for C/C and C/C-SiC disks.

The friction coefficient of C/C composites in case of non-conformal hertzian contacts first increased up to 30 N load and decreased afterwards with increase in load as can be observed in Fig. 5.3. The value of friction coefficient of C/C-SiC plate first increased with load up to 50 N load and decreased at 60 N load. It can also be observed that value of friction coefficient in case of non-conformal hertzian contacts was lower as compared to low conformity contacts.

It can be observed from Fig. 5.4 that in case of non-conformal hertzian contacts, friction coefficient of C/C composites first decreased with sliding velocity and increased after 2.5 m/s sliding velocity. For C/C-SiC plate, friction coefficient first increased with increase in sliding velocity up to 1.5 m/s and decreased afterwards.

5.6.1.2. Wear Behaviour

Fig. 5.5 shows the wear behaviour of C/C and C/C-SiC composites with increase in load. C/C composites showed an initial increase and then decrease in wear loss with increase in load whereas, C/C-SiC composites showed continuous increase in wear loss. The wear loss of C/C-SiC parallel was not significantly affected by increase in load whereas C/C-SiC normal showed great sensitivity towards increase in load.

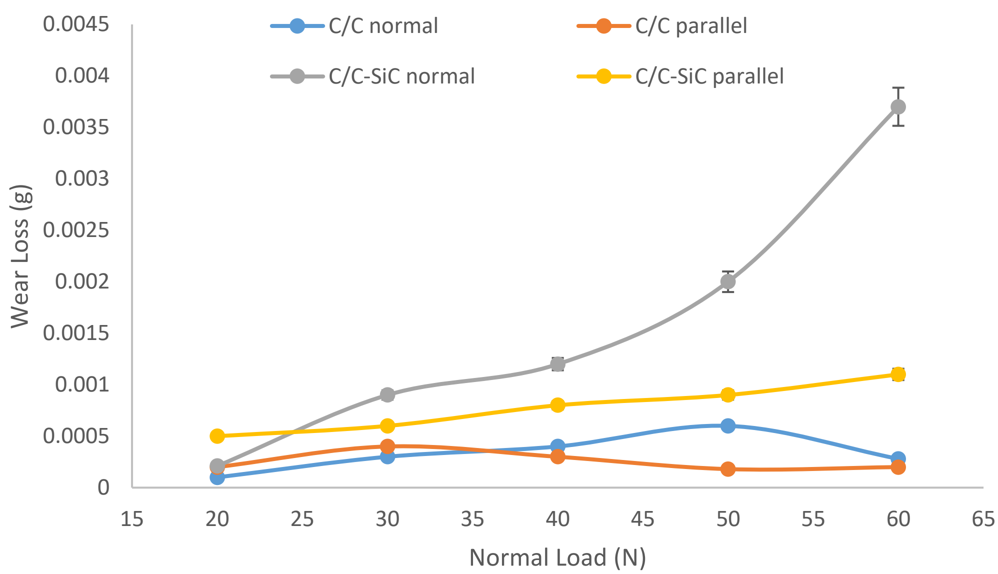


Fig. 5.5. Variation of wear loss with normal load for C/C normal, C/C parallel, C/C-SiC normal and C/C-SiC parallel.

Sliding velocity also affected the wear behaviour of C/C-SiC composites as can be observed in Fig. 5.6. C/C and C/C-SiC composites showed opposite wear behaviour in general i.e. the wear loss of C/C composites generally increased with increase in sliding velocity whereas C/C-SiC composites generally showed decrease in wear loss.

In case of non-conformal hertzian contacts, C/C and C/C-SiC composites showed almost same wear behaviour i.e. initial rise with increase in load and then decrease, and initial dip with increase in sliding velocity and increase afterwards.

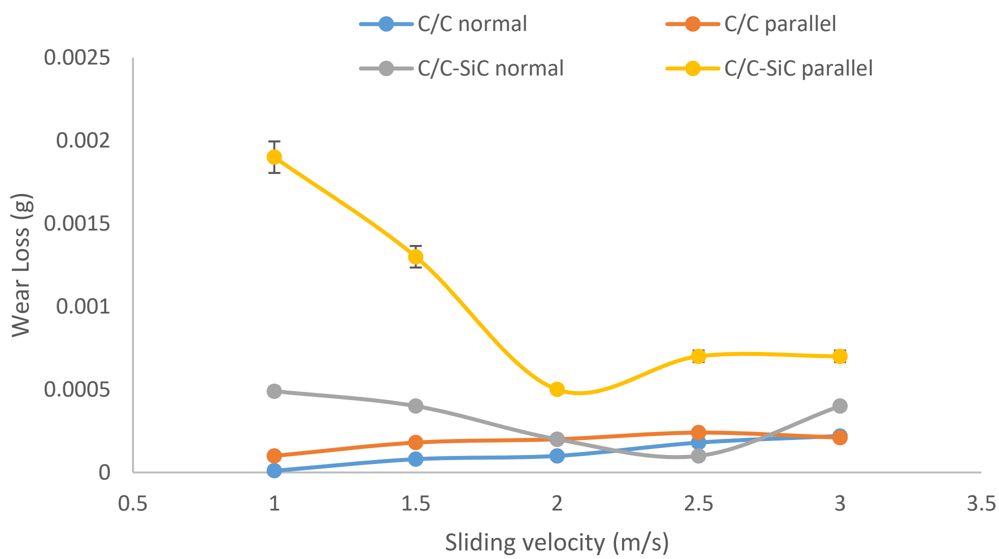


Fig. 5.6. Variation of wear loss with sliding velocity for C/C normal, C/C parallel, C/C-SiC normal and C/C-SiC parallel.

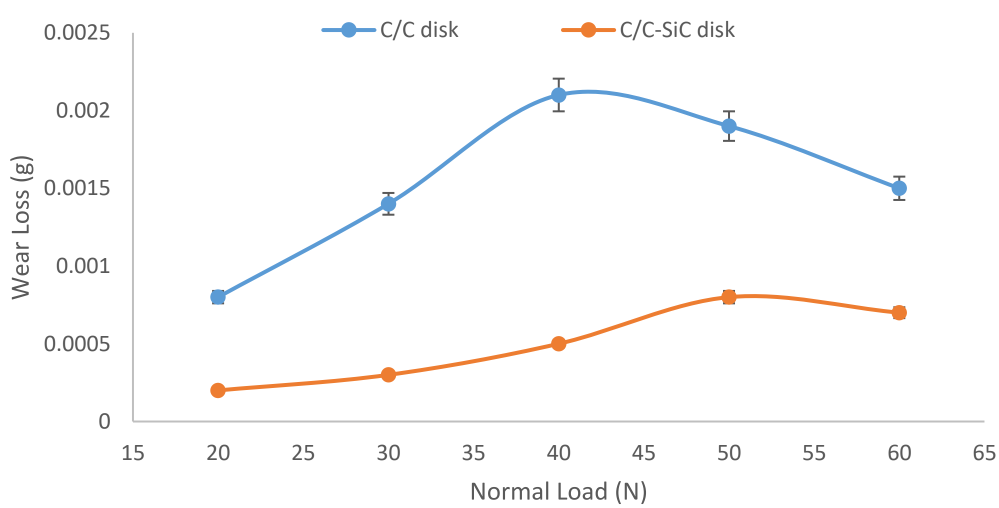


Fig. 5.7. Variation of wear loss with load for non-conformal hertzian contacts for C/C and C/C-SiC disks.

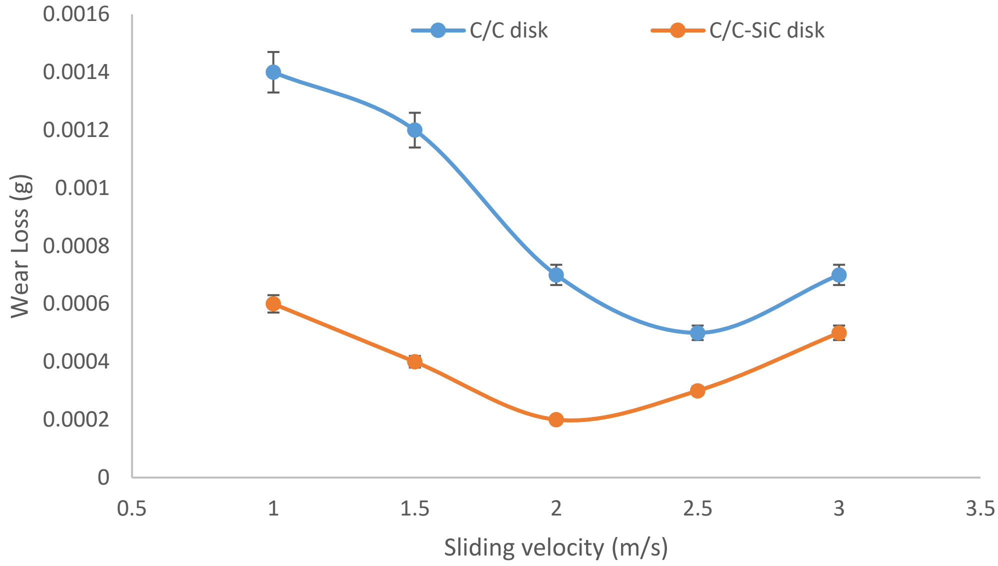
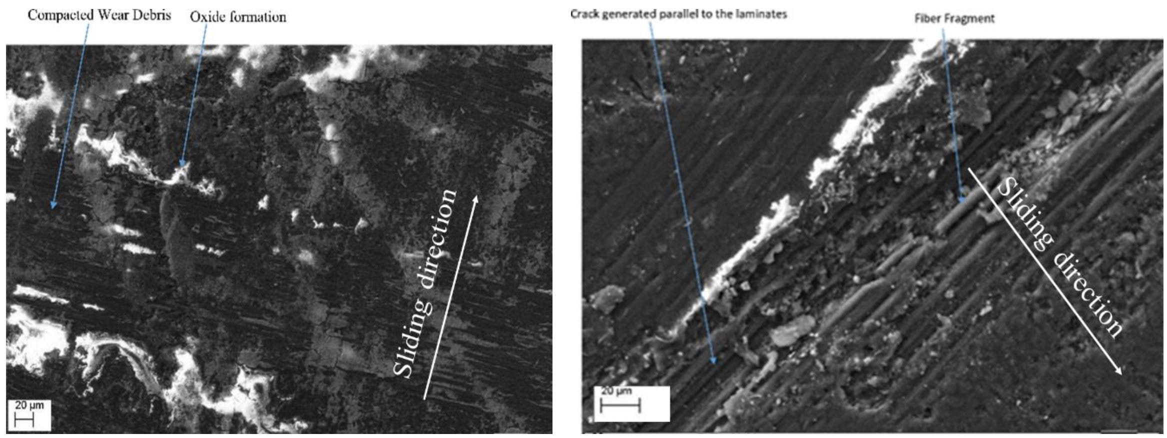


Fig. 5.8. Variation of wear loss with sliding velocity for non-conformal hertzian contacts for C/C and C/C-SiC disks.

5.6.1.3. Discussion

Friction coefficient of composites having normal orientation of laminates first decreased with increase in load up to 40 N load. At low loads, C/C composites were likely to form small flaky debris. The increase in load improved the deformation of carbon matrix and compaction of wear debris was enhanced. This led to formation of friction film on the surface of composite and decreased friction coefficient. Fig. 5.9(a) shows C/C normal tested at 40 N load. Compacted wear debris can be observed on the surface of composite. Some oxides were also observed on the surface of composite due to rise in temperature. As the load was increased further, the frictional shear forces increased which enhanced the fibre breakage and debonding as discussed in section 3.3.3. The morphology of wear debris changed from small flaky to large debris due to generation of fibre fragments as can be observed from Fig. 5.9(b).



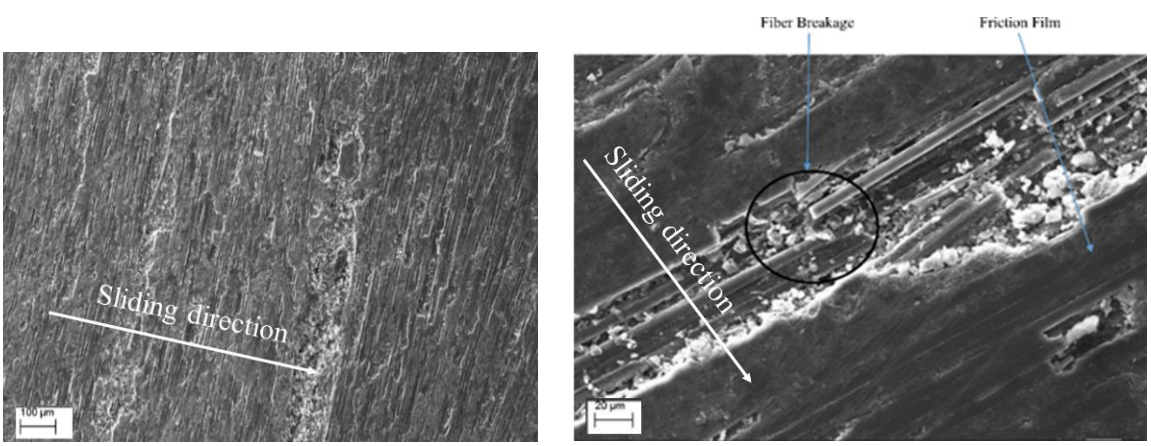
(a) (b)

Fig. 5.9. SEM images showing (a) Compacted wear debris and oxide layer in C/C normal tested at 40 N load, and (b) Cracks parallel to the laminates and fibre fragments in C/C normal tested at 50 N load.

Fibre fragments rolled in between the contacting surfaces before being ejecting out. Thus they led to damage of friction film [19]. Increase in load also led to increase in braking energy. Thus temperature of contacting surfaces increased which damaged the inner structure and led to generation of cracks which developed parallel to the laminates as can be observed in Fig 5.9(b).

The damage of friction film resulted in incomplete friction film on the surface of composite. The combined effect of incomplete friction film and oxides formation due to rise in temperature led to increase in friction coefficient when the load was increased from 40 N to 50 N. As the load was increased further, the increase in temperature led to graphitization at local positions which increased the flow of carbon matrix and wear debris [30]. Thus a smooth and completed friction film was formed on the surface which decreased friction coefficient.

Worn surface morphology depends upon the orientation of fibres with respect to the sliding surface [31]. The formation of type I (particulate) and type II (film) debris and delamination step depend on the orientation of fibres in unidirectional composites [31, 32]. This statement also held well in case of laminated composites. Friction coefficient of C/C composites with parallel orientation of laminates decreased with increase in load. The open porosity in case of parallel orientation of laminates was more as compared to normal orientation of laminates as can be seen in Fig. 5.10(a). Thus the formed wear debris filled the surface of composite and formed a smooth surface. This led to decrease in friction coefficient. The thermal conductivity of C/C composites is less with normal orientation of laminates as compared to parallel orientation of laminates [28]. The temperature rise of contacting surfaces was less for parallel orientation of laminates as compared to normal orientation of laminates.



(a) (b)

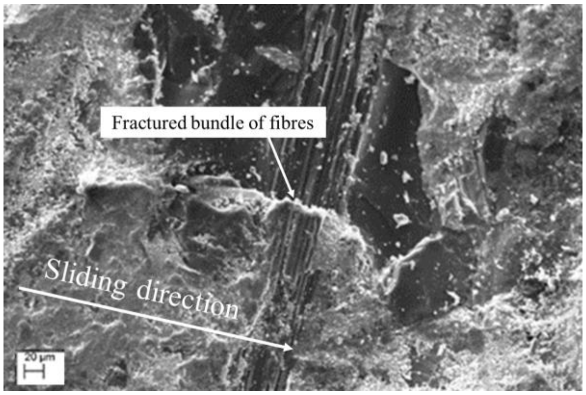
Fig. 5.10. SEM images showing C/C parallel tested at (a) 20 N load, and (b) 40 N load.

Due to less temperature rise in case of parallel orientation of laminates, less oxidation occurred which led to decrease in friction coefficient [33]. Fibre breakage was also observed at higher loads. But fibre breakage in the form of fragments was not observed as can be seen in Fig. 5.10(b).

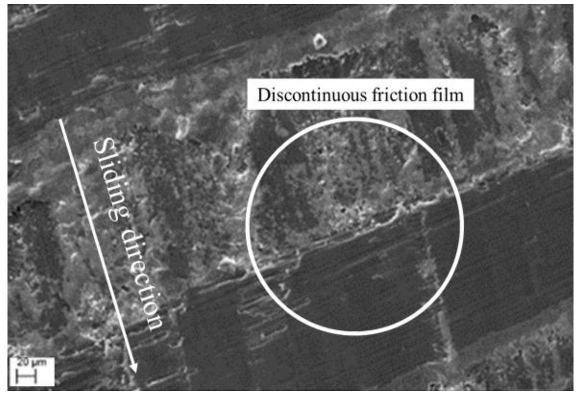
A thin friction film can also be observed from Fig. 5.10(b). As generation of fibre fragments in case of parallel laminates was very less, the friction film was not disrupted easily and friction coefficient further decreased with increase in load.

Friction coefficient of C/C composites with normal orientation of laminates was higher than with parallel orientation of laminates at all tested loads and sliding velocities when treated in freezing environment. This was attributed to the formation of type I debris due to fibre microfracture and less surface porosity in case of composites with normal orientation of laminates [31]. Type I debris damaged the friction film. Composites with parallel orientation of laminates formed the smooth surface as the time progressed.

C/C-SiC normal showed increase in friction coefficient up to 50 N load due to deeper penetration of asperities. Further, the formation of continuous friction film was difficult in case of C/C-SiC composites due to presence of hard SiC particles which can be observed in Fig. 5.11(a). Some fractured fibre bundles can also be observed. The breaking of fibre bundles consumed more energy which increased friction coefficient. At high load, increase in braking force led to increase in temperature which ease the formation of friction film. But hard SiC particles abraded the formed friction film which resulted in discontinuous friction film as can be observed in Fig. 5.11(b).



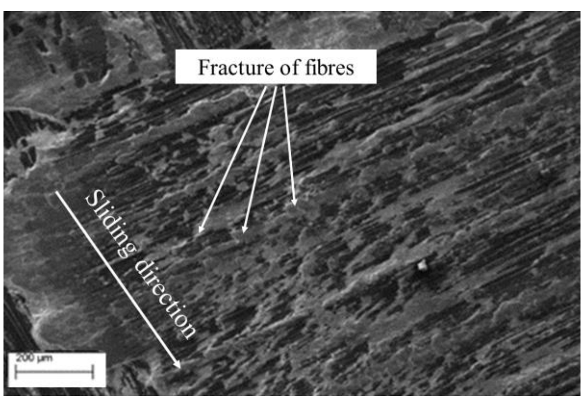
(a)



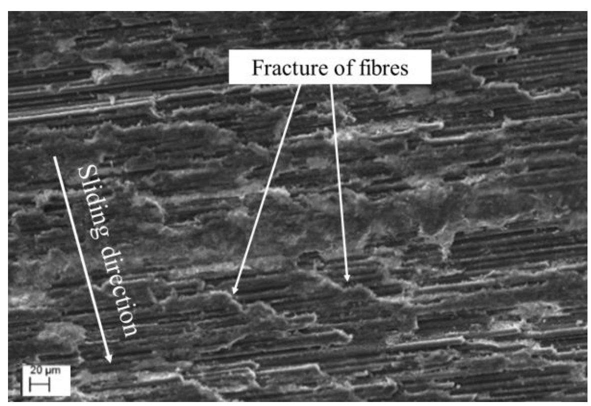
(b)

Fig. 5.11. SEM images showing C/C-SiC normal tested at (a) 40 N load, and (b) 50 N load.

C/C-SiC parallel showed increase in friction coefficient with increase in load. C/C-SiC parallel contained more proportion of fibres in the contact surface. The fibres were micro fractured as the asperities of the counterface penetrated which can be observed in Fig. 5.12(a) and Fig. 5.12(b). The fracture of fibres required more energy which increased friction coefficient with increase in load.



(a)



(b)

Fig. 5.12. SEM images showing C/C-SiC parallel tested at (a) 40 N load, and (b) 50 N load.

Friction coefficient of C/C composites with normal orientation of laminates first increased up to 2.5 m/s sliding velocity and decreased after that. C/C and C/C-SiC composites contains many structural defects such as dislocations and pores [34]. Due to these structural defects, oxygen atoms are chemically absorbed and forms C-O and C=O bands. The BET surface area of carbon fibres increases as the temperature decreases [35]. C/C composites kept in freezing environment led to increase in BET surface area which led to increase in absorption of oxygen atoms. Thus water molecules get physically adsorbed outside of the oxygen atoms. Adsorbed water molecules lubricated the contacting surface. Thus friction coefficient at low sliding velocity was lower. Increase in sliding velocity increased braking energy which led to increase in temperature and, desorption of water molecules took place. Thus friction coefficient increased as the sliding velocity was increased up to 2.5 m/s sliding velocity. As the velocity was increased further, increase in temperature increased the plasticity of wear debris which formed a friction film on the surface which reduced friction coefficient. It can be observed from Fig. 5.13(a) and Fig. 5.13(b) that the surface of composite tested at 3 m/s sliding velocity was smoother as compared to that tested at 2 m/s sliding velocity.

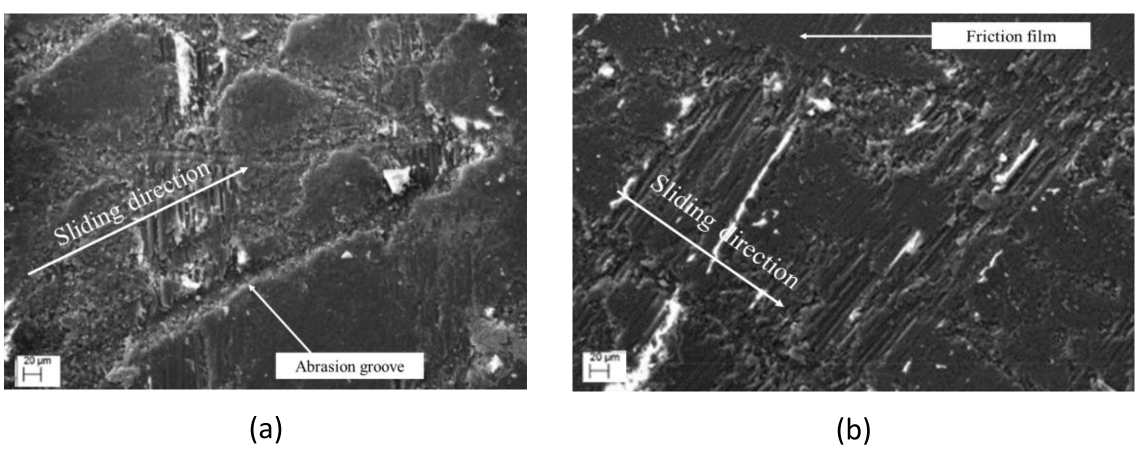
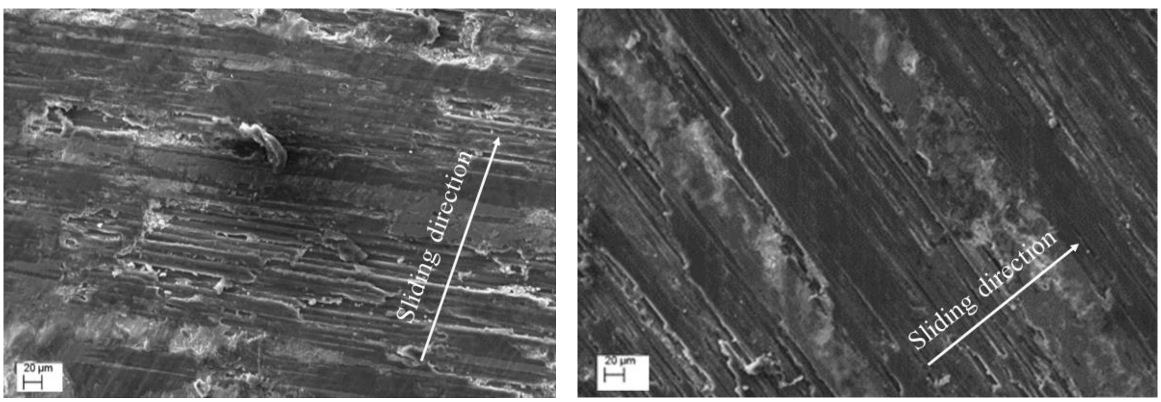


Fig. 5.13. SEM images showing C/C normal tested at (a) 2 m/s sliding velocity, and (b) 3 m/s sliding velocity.

Friction coefficient of C/C-SiC normal decreased with increase in sliding velocity. The increase in sliding velocity resulted in increase in temperature which in turn increased the plasticization of carbon matrix and fractured carbon fibres. Increased plasticization led to increase in tendency of formation of friction film due to which friction coefficient decreased with increase in sliding velocity. The extent of friction film can be observed in Fig. 5.14(a) and Fig. 5.14(b) for 2 m/s and 2.5 m/s sliding velocity respectively.



(a) (b)

Fig. 5.14. SEM images showing C/C-SiC normal tested at (a) 2 m/s sliding velocity, and (b) 2.5 m/s sliding velocity.

Friction coefficient of C/C composites with parallel orientation of laminates also followed the same trend as followed by normal orientation of laminates. But the friction coefficient was lower than that of normal orientation of laminates. This can be attributed to the more proportion of fibres in the interacting surface in case of parallel orientation of laminates as compared to normal orientation of laminates. Thus overall BET surface area was more. Surface porosity also led to increase in effective BET surface area. Surface pores also acted as sites for debris entrapment. Thus friction coefficient of C/C composites with parallel orientation of laminates was less as compared to normal orientation of laminates. Fig. 5.15 shows C/C parallel tested at 1.5 m/s sliding velocity. It can be observed from Fig. 5.15 that fibres in case of parallel orientation of laminates were exposed more to the atmosphere as compared to composites with normal orientation of laminates.

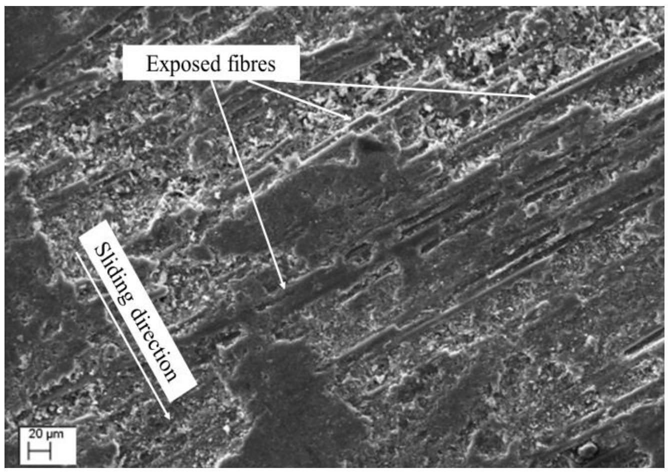
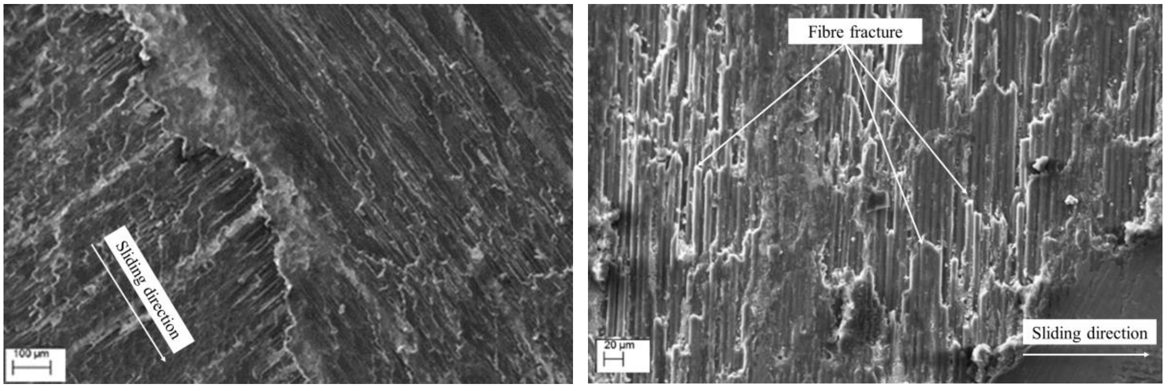


Fig. 5.15. SEM image showing C/C parallel tested at 1.5 m/s sliding velocity.

Friction coefficient of C/C-SiC parallel firstly decreased with increase in sliding velocity up to 2 m/s sliding velocity and increased thereafter. The first decrease may be attributed to the adsorbed water molecules. Further, there was not prominent fibre fracture up to 2 m/s sliding velocity as can be observed in Fig. 5.16(a). As the sliding velocity was increased beyond 2 m/s sliding velocity, increased energy resulted in increased temperature which led to desorption of water molecules and degraded the carbon fibre. Thus there was prominent fibre fracture at 2 m/s sliding velocity as can be observed in Fig. 5.16(b).

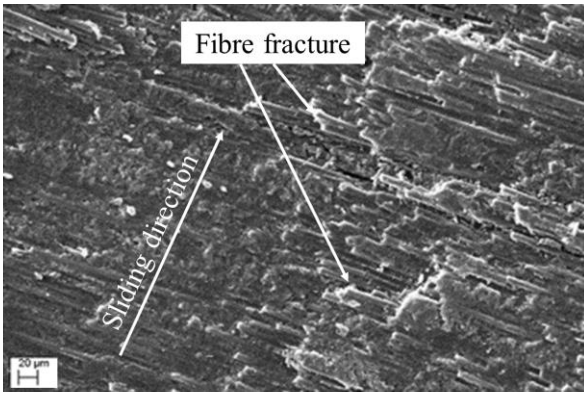


(a) (b)

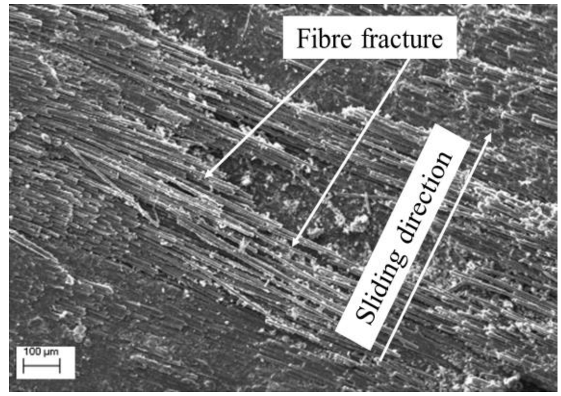
Fig. 5.16. SEM images showing C/C-SiC parallel tested at (a) 2 m/s sliding velocity, and (b) 2.5 m/s sliding velocity.

The stresses in case of non-conformal hertzian contacts were localized and very high. Friction coefficient of C/C plate increased up to 30 N load and decreased after that. The first low value of friction coefficient was attributed to adsorbed water molecules on the surface. As load was increased to 30 N, desorption of water molecules led to increase in friction coefficient. Debris in the form of fibre fragments was observed. When the load was increased beyond 30 N, stresses were sufficient to raise the temperature to a level where fibre fragments formed friction film easily. This decreased the friction coefficient.

Fibre fracture can be observed from Fig. 5.17(a). It was observed that the formed film was not so smooth at 40 N load. Increase in load beyond 40 N led to formation of smooth friction film. The friction behaviour of C/C-SiC composites with increase in load was almost same as C/C composites in case of non-conformal hertzian contacts.



(a)



(b)

Fig. 5.17. SEM images showing C/C composite in non-conformal hertzian contacts tested at (a) 40 N load and 2 m/s sliding velocity, and (b) 20 N load and 3 m/s sliding velocity.

Friction coefficient of C/C composites in case of non-conformal hertzian contacts decreased with increase in velocity up to 1.5 m/s sliding velocity and increased beyond that. The decrease was attributed to easy formation of friction film as the sliding velocity was increased. When the sliding velocity increased beyond 2.5 m/s, the increased breaking energy changed the morphology of wear debris from small fibre fragments to larger ones. As C/C composites wore out more readily in non-conformal hertzian condition, it made a groove on the surface of composite in which ball slid. The groove prevented the ejection of large fibre fragments and it rolled in between the interacting surfaces. Fibre fragments led to degradation of formed film which in turn led to increase in friction coefficient at higher velocities. Fibre fracture in case of C/C disc (i.e. non-conformal hertzian contacts) at 3 m/s sliding velocity can be observed in Fig. 5.17(b).

Friction coefficient of C/C-SiC plate showed opposite behaviour as shown by C/C plate. As the sliding velocity was increased, increase in temperature led to easy penetration of asperities in the counterface which increased friction coefficient up to 1.5 m/s sliding velocity. When the sliding velocity was increased beyond 1.5 m/s, increase in temperature was aided by formation of friction film and rolling of SiC particles in between the contact surfaces which decreased friction coefficient.

Friction coefficient in case of non-conformal hertzian contacts was less as compared to low conformity contacts. This was attributed to mechanism of film formation and debris type as it changed with surface conformity. The temperature rise in case of non-conformal hertzian contacts was more due to very high and localized stresses. This enhanced the formation of friction film.

The wear loss of C/C composites with normal orientation of laminates increased up to 50 N load and decreased after that. It was observed that cracks were generated parallel to the laminates when the composites were loaded with normal orientation of laminates. As the load was increased, the shear forces between contacting surfaces increased which tend to bend the composite laminates. Thus cracks were generated parallel to the laminates. The development of cracks depend on the applied load. Thus cracks led to generation of more wear debris which led to increase in wear loss. A smooth and completed friction film was formed when the load was increased beyond 50 N which resulted in decrease in wear loss.
C/C-SiC composites (whether parallel or normal) showed increase in wear loss with increase in load due to increase in abrasion because asperities penetrated deeper as the load was increased. Some fibre bundles were fractured due to abrasion in case of C/C-SiC normal as can be observed in Fig. 5.11(a). Although friction film was formed at higher loads but it was abraded by SiC particles due to which formation of friction film did not significantly affected

the wear loss. Fibre micro fracture in case of C/C-SiC parallel can be observed in Fig. 5.12(a) and Fig. 5.12(b).

Due to thermal mismatch between fibre and matrix, cracks were developed as composites were kept in freezing environment. This effect was predominant in case of parallel orientation of laminates as parallel laminated composites contained more proportion of fibres at contacting surface. Due to development of cracks in case of C/C composites, carbon matrix loosened and its emergence as wear debris was easy when the load was applied. Thus the wear loss in case of C/C parallel was more as compared to C/C normal at 20 N and 30 N. Fig. 5.18(a) shows C/C parallel tested at 30 N load. Cracks due to thermal mismatch can be observed. Wear loss in case of parallel orientation of laminates increased up to 30 N load due to desorption of water molecules and loosening of carbon matrix. However as the load was increased from 30 N to 50 N, wear loss decreased due to formation of smooth surface due to filling up of porous sites on the surface and formation of friction film. However as the load beyond 50 N, early formation of friction film took place. After the formation of friction film, debris generation was less. Due to repeated stress and increase in temperature, friction film delamination occurred (as illustrated in Fig. 3.3 (b)) and it required more debris to be compacted to form continuous friction film. This led to increase in wear loss at 60 N load. Fig. 5.18(b) shows C/C parallel tested at 60 N load. Delamination pits can be observed in Fig. 5.18(b).

(a) (b)

Fig. 5.18. SEM images showing (a) Cracks due to thermal mismatch in C/C parallel tested at 30 N, and (b) Delamination pits in C/C parallel tested at 60 N.

Wear loss of C/C composites with normal orientation of laminates increased with increase in sliding velocity. The first lower value was attributed to the adsorption of water molecules which lubricated the surface. Increase in sliding velocity led to increase in braking energy and increased the temperature of surface. Increase in temperature led to desorption of water molecules and decreased the lubrication effect and therefore increased the wear loss. The synergism between ease of formation of friction film at higher sliding velocities and its disruption described the slope of wear loss with sliding velocity.

Wear loss of C/C composites with parallel orientation of laminates increased up to 2.5 m/s sliding velocity and decreased at 3 m/s. The increase in plasticity of wear debris at higher sliding velocity led to decrease in wear loss at 3 m/s sliding velocity. Wear loss of composites with parallel orientation of laminates was more as compared to normal orientation of laminates except at 3 m/s. Hardness of carbon fibres along its axis is more as compared to transverse direction. Thus resistance to abrasion in case of parallel orientation of laminates was less as compared to normal orientation of laminates. Thus wear loss of C/C parallel was higher than that of C/C normal. At higher sliding velocities, the formation of smooth surface due to filling up of surface pores and compaction of wear debris was relatively easy in case of parallel orientation of laminates. Thus wear loss of C/C parallel at 3 m/s sliding velocity was lower as compared to C/C normal.

C/C-SiC normal showed decrease in wear loss with increase in sliding velocity up to 2.5 m/s sliding velocity and increased thereafter. The decrease in wear loss was attributed to ease of formation of friction film with increase in sliding velocity. However, increase in temperature due to increase in sliding velocity also led to fibre fracture and pull out during sliding which increased wear loss at high sliding speed. Almost same trend was shown by C/C-SiC parallel.

Generation of wear debris in the form of fibre fragments at loads up to 40 N and formation of friction film beyond 40 N described the wear loss behaviour of C/C composites with load in non-conformal hertzian contacts. The ease of formation of friction film with increase in sliding velocity up to 2.5 m/s and change of wear debris morphology from small to large ones at 3 m/s depicted the wear loss behaviour of C/C composites with sliding velocity in non-conformal hertzian contacts. C/C and C/C-SiC exhibited almost same wear behaviour in non-conformal hertzian contacts.

5.6.2. Reciprocating Sliding

5.6.2.1. Friction Response

It can be observed from Fig. 5.19 that in case of reciprocating sliding conditions, friction coefficient of C/C normal firstly increased with increase in normal load up to 60 N and decreased thereafter. The friction behaviour of C/C parallel was almost same as that of C/C normal. C/C-SiC composites also showed first rise in friction coefficient with increase in load and decrease afterwards.

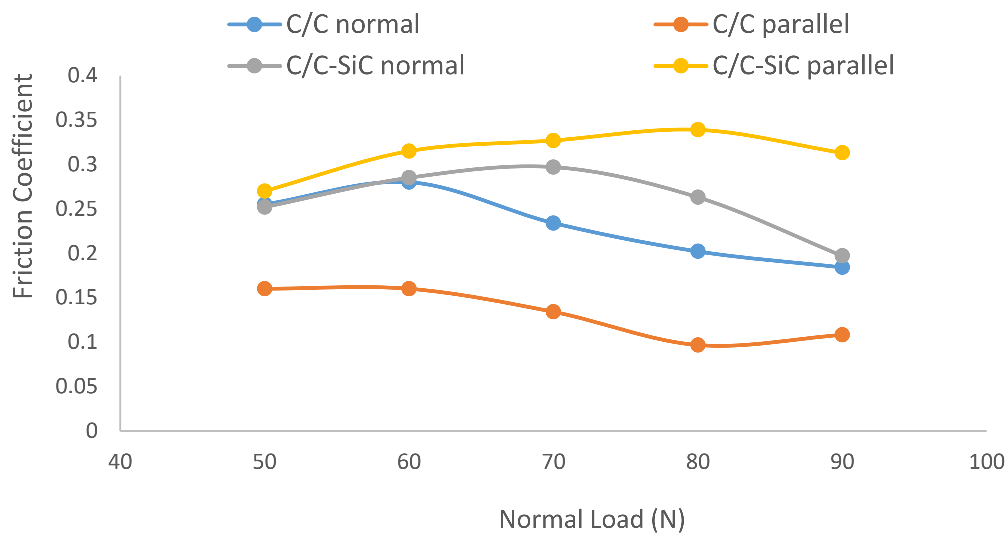


Fig. 5.19. Variation of friction coefficient with normal load in low conformity contacts for C/C normal, C/C parallel, C/C-SiC normal and C/C-SiC parallel.

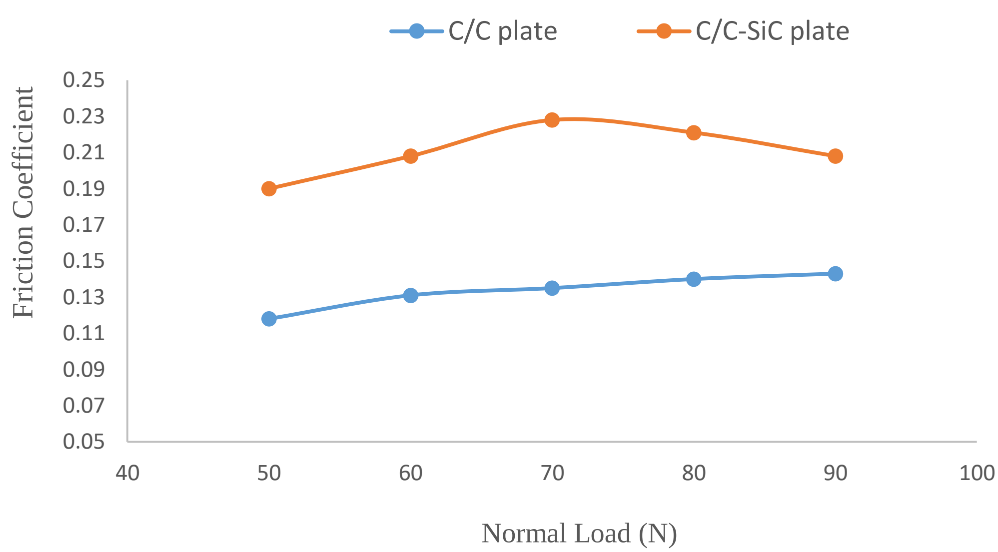


Fig. 5.20. Variation of friction coefficient with normal load in non-conformal Hertzian conformity contacts for C/C and C/C-SiC plate.

Friction coefficient of C/C composite increased with increase in load in case of non-conformal hertzian contacts (Fig. 5.20) whereas in case of C/C-SiC composites, friction coefficient firstly increased with increase in load up to 70 N and decreased thereafter.

5.6.2.2. Wear Behaviour

C/C and C/C-SiC composites showed increase in wear loss with increase in load for low conformity contacts as can be observed in Fig. 5.21. The wear loss in case of non-conformal hertzian contacts firstly increased with increase in load and decreased thereafter for both C/C and C/C-SiC composites Fig. 5.22.

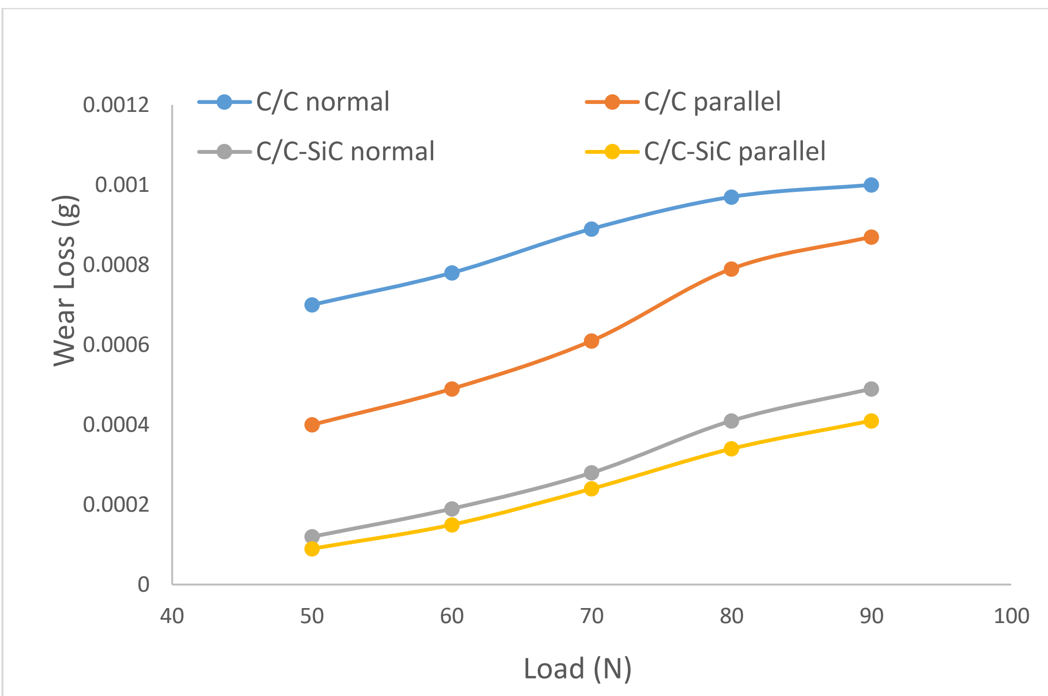


Fig. 5.21. Variation of friction coefficient with load in low conformity contacts for C/C normal, C/C parallel, C/C-SiC normal and C/C-SiC parallel composites.

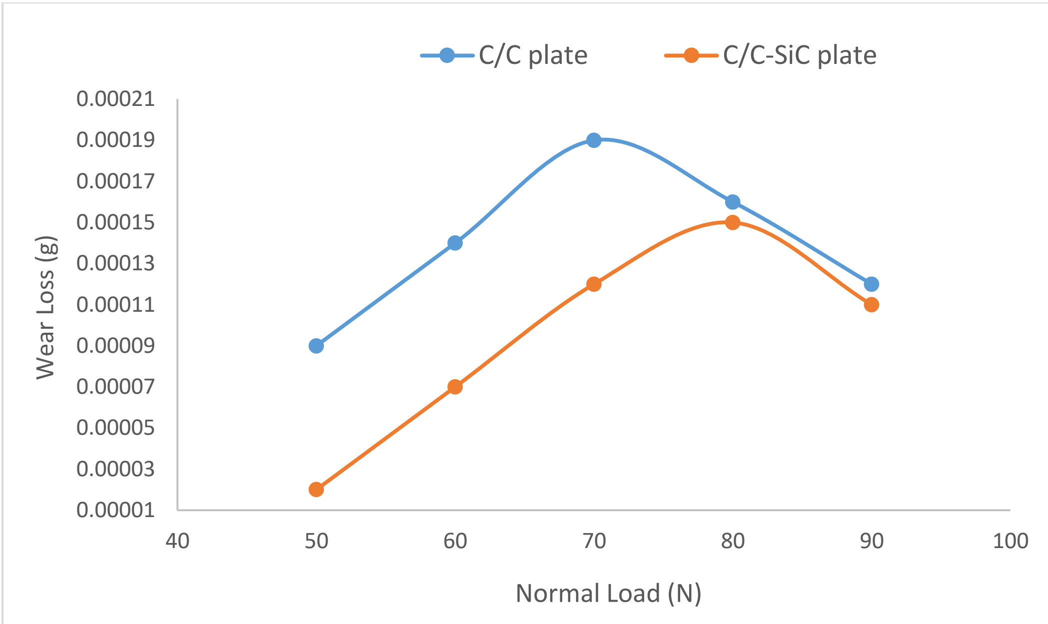
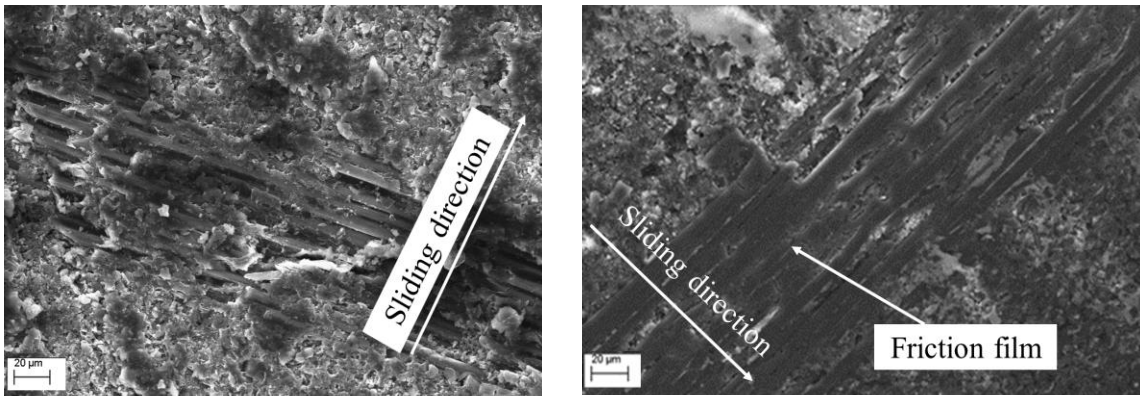


Fig. 5.22. Variation of friction coefficient with load in non-conformal Hertzian conformity contacts for C/C and C/C-SiC plates.

5.6.2.3. Discussion

In case of reciprocating motion, sliding occurs in a very confined region. So the wear debris is not usually ejected out from the contact surfaces. Friction coefficient of C/C normal increased with increase in load up to 60 N. This may be attributed to the deeper penetration of asperities. Repeated flexion in opposite direction resulted in the generation of bending stresses due to which cracks initiated and have a tendency to propagate parallel to the lamina. The loosened matrix material due to initiation of cracks rolled in between the contact surfaces. At higher loads, easy pulverization and shearing of wear debris formed a friction film on the surface which led to decrease in friction coefficient. Fig. 5.23(a) and Fig. 5.23(b) show C/C normal tested at 60 N and 70 N load respectively. It can be seen that friction film was observed at 70 load but there were negligible signs of friction film at 60 N load. When

C/C normal was tested in dry conditions at 60 N load, friction film started to form but in case of freezing conditions, first signs of friction film were observed at 70 N load.

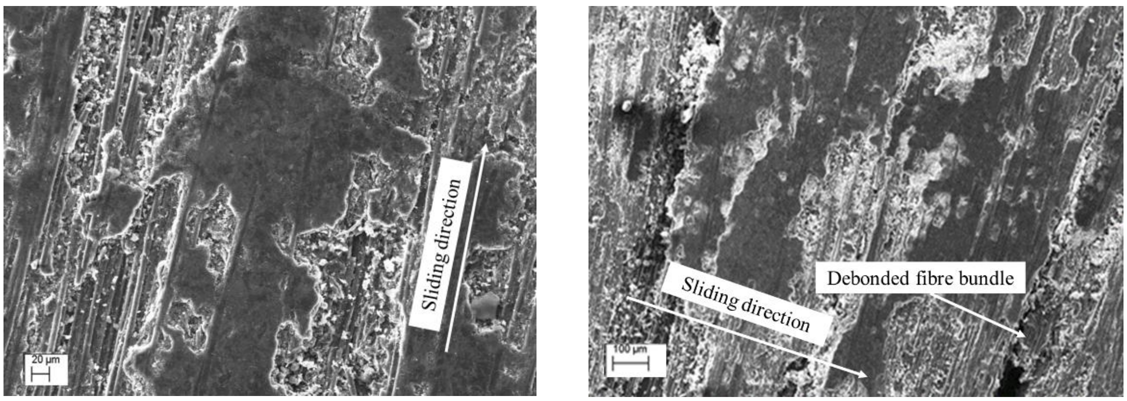


(a) (b)

Fig. 5.23. SEM images showing C/C normal tested at (a) 60 N load, and (b) 70 N load.

As stated earlier in this chapter, C-O and C=O were formed due to freezing environment outside which water molecules were physically adsorbed. These water molecules prevented the adhesion of wear debris on the surface at low loads and thus friction film was formed only at higher loads.

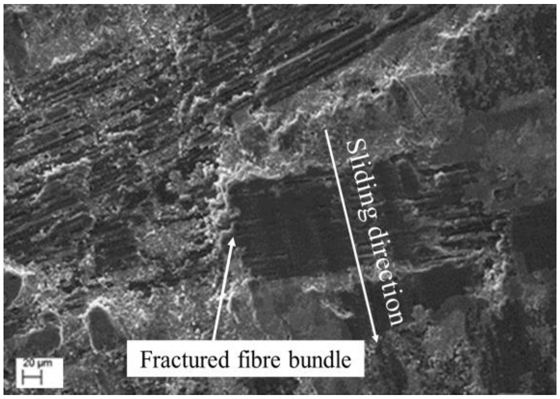
Friction coefficient of C/C composites in parallel orientation of laminates was lower as compared to normal orientation of laminates. This can be attributed to more surface porosity of C/C parallel as compared to C/C normal. The macro pores were filled by wear debris which resulted in smoother surface as compared to C/C normal and hence low value of friction coefficient. Fig. 5.24(a) shows the surface of C/C parallel tested at 60 N load. As the load was increased, some portion of the fibre bundles were debonded from the surface because cracks generated at high loads as can be observed in Fig. 5.24(b). The generated wear debris (fibre fragments and particles) pulverized at high load and formed a friction film which reduced friction coefficient at high loads.



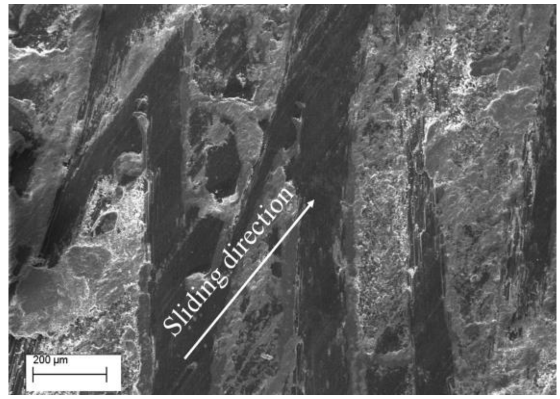
(a) (b)

Fig. 5.24. SEM images showing C/C parallel tested at (a) 60 N load, and (b) 70 N load.

C/C-SiC normal showed rise in friction coefficient with increase in load up to 70 N and decreased afterwards. When C/C-SiC normal composites were tested in dry condition, cracks due to repeated flexion were observed and are absent in freezing conditions. The reason is not very clear. This may be due to presence of oxide layer in case of freezing conditions which reduced the shearing forces and hence bending stresses. Increase in friction coefficient up to 70 N load may be attributed to the deeper asperities penetration. Fracture of fibre bundle due to abrasion at 70 N load can be observed in Fig. 5.25(a). As the load was increased further, hard SiC were casted out from the surface and rolled in between the contact surface which decreased the friction coefficient. The surface of C/C-SiC normal tested at 80 N load is shown in Fig. 5.25(b).



(a)



(b)

Fig. 5.25. SEM images showing C/C-SiC normal tested at (a) 70 N load, and (b) 80 N load.

Very less abrasion marks due to two body abrasion were observed. C/C-SiC parallel also showed the same behaviour as that shown by C/C-SiC normal. Fibre rupture was observed at 80 N load (Fig. 5.26). Fibre fragments and loose SiC particles filled the surface macropores and resulted in increase in smoothness of surface which decreased friction coefficient at 90 N load.

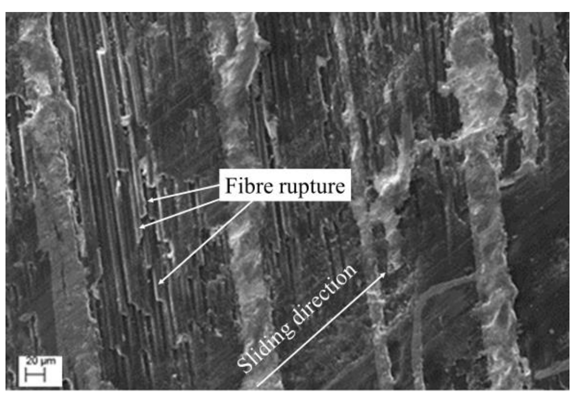


Fig. 5.26. SEM image showing C/C-SiC parallel at 70 N load.

It was observed that variation in friction coefficient with load was not significant in case of freezing conditions as compared to dry conditions.

C/C composites showed increase in friction coefficient with increase in load in case of non-conformal hertzian contacts, whereas C/C-SiC composites showed increase up to 70 N load and decrease afterwards due to rolling of SiC particles in between the surfaces.

Wear loss of C/C and C/C-SiC composites increased with increase in load in low conformity contacts. The main wear mechanisms were abrasive wear and matrix loosening due to repeated flexion in opposite directions. Wear loss of C/C composites increased with increase in load up to 70 N load in case of non-conformal hertzian contacts. This may attributed to the generation of high and localized stresses which made the asperities penetrate deeper with increase in load. However as the load was increased further beyond 70 N, formation of friction film took place which decreased wear loss although friction film was also disrupted due to high stresses. Similarly in case of C/C-SiC plate, the decrease in wear loss at high loads was attributed to the rolling of SiC partcles in between the contact surfaces which prevented the direct contact of the surfaces and reduced two body abrasion.

5.6.3. Conclusion

5.6.3.1. Unidirectional Sliding

The important conclusions obtained from the tribological investigation of C/C and C/C-SiC composites in freezing environment for unidirectional sliding are as follows:-

1. In case of C/C composites, friction coefficient with normal orientation of laminates was higher as compared to parallel orientation of laminates at all tested loads and sliding velocities. However, C/C-SiC composite showed opposite i.e. friction

coefficient with normal orientation of laminates was lower as compared to parallel orientation of laminates.

2. C/C composites showed decrease in friction coefficient whereas C/C-SiC composites increase in friction coefficient with increase in load for low conformity contacts. This may be attributed to the presence of SiC in C/C-SiC composites which increased abrasion at high loads.
3. An oxide layer was observed on the surface of composites which was absent in dry and brake oil environment.
4. At higher loads and sliding velocities, C/C composites with normal orientation of laminates and C/C-SiC composites with parallel orientation of laminates exhibited higher friction coefficient as compared to their parallel and normal counterpart respectively.
5. For non-conformal hertzian contacts, C/C-SiC composites exhibit higher friction coefficient as compared to C/C composites.
6. When normal load increases beyond 40 N, wear loss of C/C-SiC composites with normal orientation of laminates increases rapidly.

5.6.3.2. Reciprocating sliding

The important conclusions obtained from the tribological investigation of C/C and C/C-SiC composites in freezing environment for reciprocating sliding are as follows:-

1. In case of C/C-SiC composites, composites with parallel orientation of laminates exhibited higher friction coefficient whereas opposite occurred for C/C composites in low conformity contacts.

2. Cracks due to repeated flexion were not significantly visible whereas these type of cracks were visible in dry and brake oil environment,
3. C/C and C/C-SiC composites with parallel orientation of laminates exhibited lower wear loss as compared to normal orientation of laminates in low conformity contacts although the difference was very less for C/C-SiC composites.
4. There was a large difference in the values of friction coefficient of C/C and C/C-SiC composites in non-conformal hertzian contacts.