Chapter 6

Reciprocating Sliding Tribology in Self and Complementary Mated Pair

6.1. Introduction

Tribological behavior of a composite material depends upon counterface material. Fibrous composites exhibit different tribological behavior against uniphase material or multi-constituent material. The friction and wear mechanism of laminated composite sliding against laminated composites is different from laminated composite sliding against uniphase material or particulate composite. Most of the researchers have investigated the tribological behavior of both composites with self-mated pair and parallel orientation of laminates. The effect of complementary mated pairs (C/C with C/C-SiC counterface) have been investigated with parallel orientation of laminates in unidirectional sliding for fully conformal surfaces.

6.2. Materials and Synthesis

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

6.3. Reciprocating wear testing

For self-mated pairs, pins of C/C and C/C-SiC composites were slid against C/C and C/C-SiC composite plates respectively. For complementary mated pairs, C/C pin was slid against C/C-SiC composite plate and C/C-SiC pin against C/C composite plates. To carry out tests for normal orientation of laminates, composite pins having normal orientation of laminates with respect to sliding plane were slid against composite plate having parallel orientation of laminates with respect to sliding plane. Similarly for parallel orientation of laminates, composite pins having parallel orientation of laminates with respect to sliding plane were slid against composite plate having parallel orientation of laminates with respect to sliding plane.

Firstly, C/C normal was slid against C/C plate for self-mated pair wear tests. Then C/C parallel was slid against C/C plate. Same self-mated wear tests were carried out for C/C-SiC composites for different orientation of laminates. For complementary wear tests, C/C normal and C/C parallel were slid against C/C-SiC plate and similarly C/C-SiC normal and C/C-SiC parallel were slid against C/C plate.

Wear tests were performed on reciprocating sliding wear test rig (TE 200ST, Magnum Engineers, Bangalore, India). Each test was performed at 5 Hz frequency and for 13500 cycles. Stroke length was kept 3 mm. Friction coefficient and wear loss were investigated. To investigate wear loss, samples (both pin and plate) were weighed before and after the test using weighing machine (Model No.- RA310, Roy Electronics, Varanasi, India). The effect of load on reciprocating wear behavior was also investigated. The load was varied ranging 50N (0.78 MPa normal pressure), 60N (0.94 MPa), 70N (1.10 MPa), 80N (1.26 MPa) and 90N (1.415 MPa). Due to insufficient thickness of samples, a pin holder was used to carry out reciprocating wear tests with parallel orientation of laminates. Relative humidity at the time of testing was 71 +/- 3% and temperature of ambient was 32 +/- 2 ^{o}C.

6.4. Scanning electron microscopy

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

6.5. Results

6.5.1. Variation of friction coefficient and wear loss with load in case of normal/parallel orientation combination of laminates

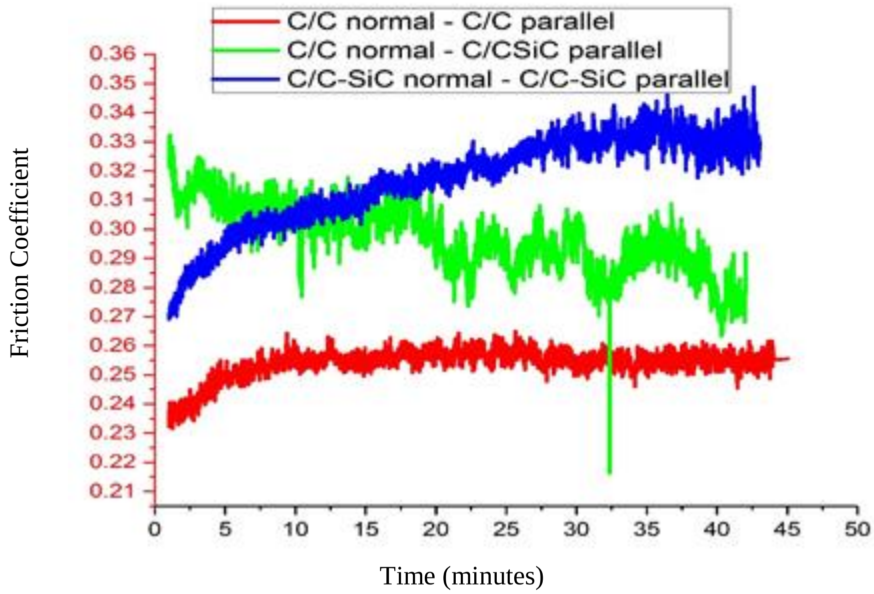


Fig. 6.1. Variation of friction coefficient with time in case of normal/parallel combination of laminated composites (at 80N load).

Fig. 6.1 shows the variation of friction coefficient with time when normal/parallel self-mated and complementary mated combination was tested. It was observed that friction coefficient of C/C-SiC normal-C/C-SiC parallel self-mated pair increased with time whereas friction coefficient of C/C normal-C/C-SiC parallel complementary mated pair decreased with time. The self-mated C/C-SiC pair showed higher friction coefficient value as compared to C/C self-mated and C/C and C/C-SiC complementary mated pair. The friction coefficient of C/C self-mated pair was almost stable and lower than that of C/C-SiC self-mated and C/C and C/C-SiC complementary mated pair.

Fig. 6.2 shows the variation of friction coefficient with load when the composite pin was loaded with normal orientation of laminates and composite plate was loaded with parallel orientation of laminates. It can be observed from Fig. 6.2 that in case of normal/parallel combination of laminates, C/C-SiC self-mated pair exhibited highest friction coefficient and C/C self-mated pair exhibit lowest friction coefficient at high loads. Friction coefficient of C/C and C/C-SiC complementary pair lied between friction coefficient of C/C and C/C-SiC self-mated pair. Friction coefficient first decreased with increase in load and after that increased for both complementary and self-mated pair.

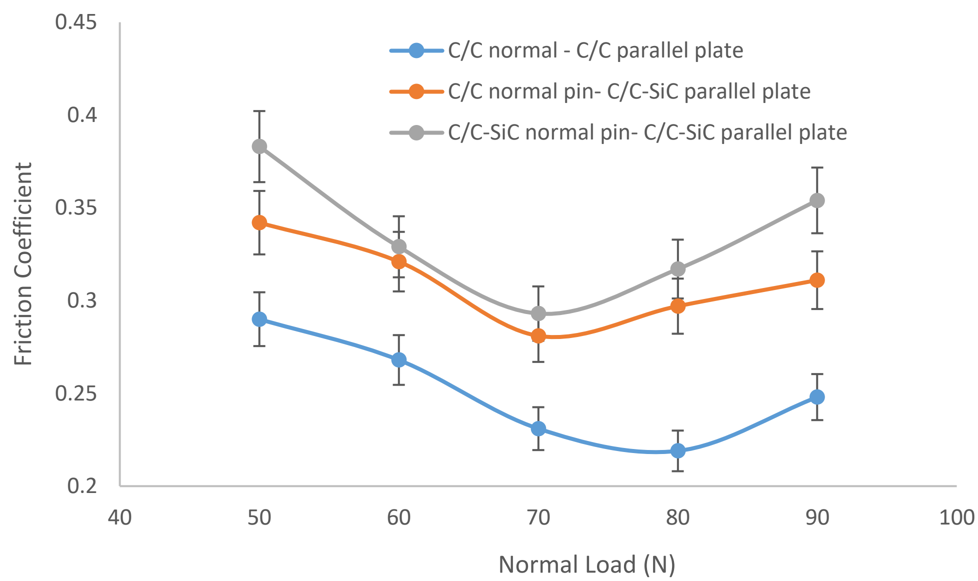


Fig. 6.2. Variation of friction coefficient with normal load in case of normal orientation of laminated composites.

Fig. 6.3 shows the variation of wear loss of composite pin (normal orientation) with load. It can be observed from Fig. 6.3 that C/C pin exhibited highest wear loss in complementary pair whereas

C/C-SiC pin exhibited lowest wear loss in self-mated pair. Wear loss first increased with increase in load and after that decreased.

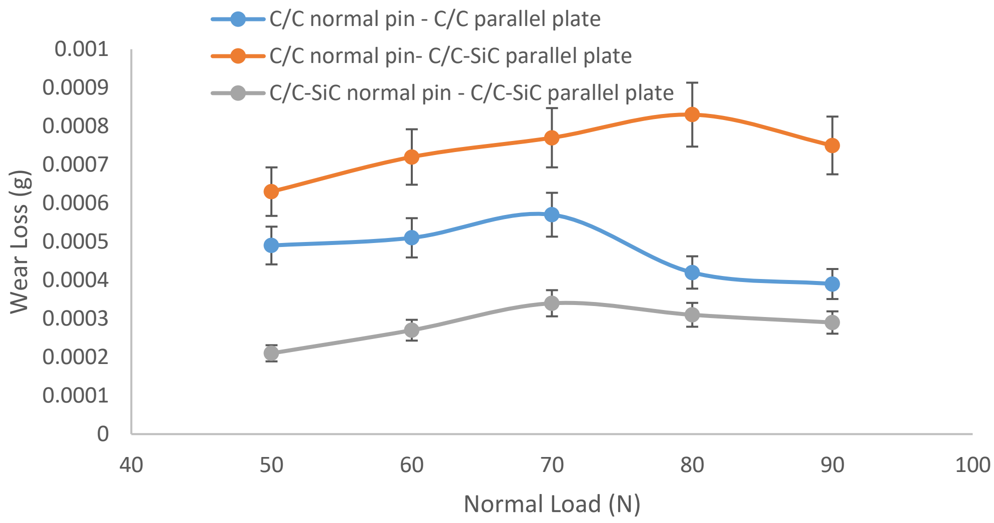


Fig. 6.3. Variation of wear loss of pin (normal orientation) with normal load.

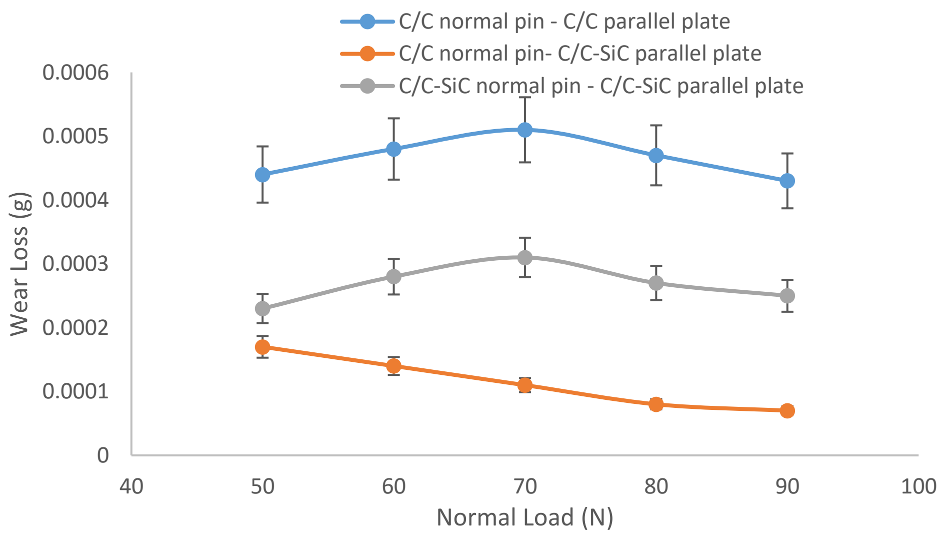


Fig. 6.4. Variation of wear loss of parallel plate (pin having normal orientation) with normal load.

It can be observed from Fig. 6.4 that C/C plate exhibited highest wear loss when used in self-mated pair whereas C/C-SiC plate exhibited lowest wear loss when used in complementary pair. Wear loss of C/C-SiC plate decreased with increase in load when used in complementary pair.

6.5.2. Variation of friction coefficient and wear loss with load in case of parallel/parallel orientation combination of laminates

It can be observed from Fig. 6.5 that friction coefficient exhibited by self-mated C/C-SiC pair was higher than friction coefficient of C/C self-mated and C/C and C/C-SiC complementary mated pair when loaded in parallel/parallel combination of laminates. Friction coefficient of complementary mated pair increased with time whereas for C/C self-mated pair, it was almost stable. Friction coefficient of self-mated C/C-SiC pair first increased with increase in time and after that it stabilized at some value.

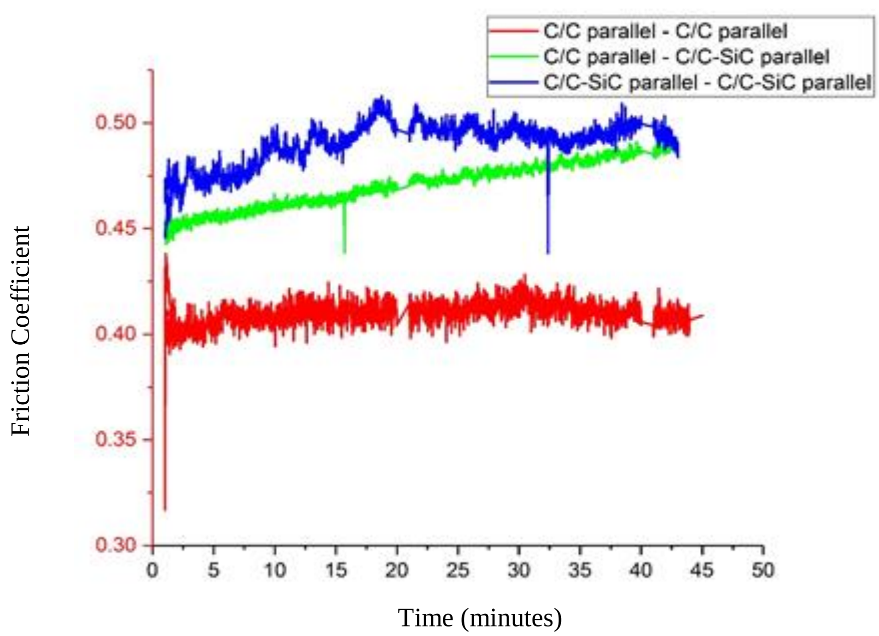


Fig. 6.5. Variation of friction coefficient with time in case of parallel/parallel combination of laminated composites (at 80N load).

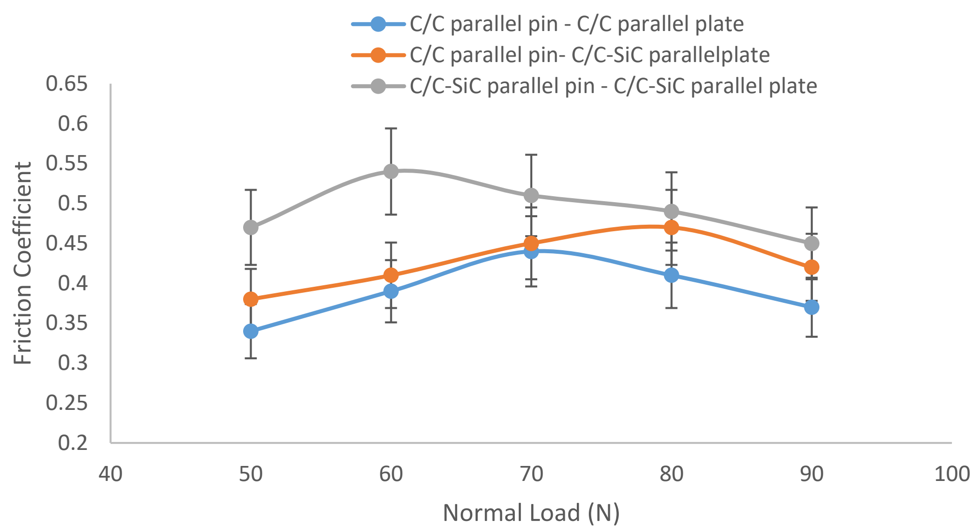


Fig. 6.6. Variation of friction coefficient with normal load in case of parallel orientation of laminated composites.

Fig. 6.6 shows the variation of friction coefficient with load when the composite pin and composite plate were loaded with parallel orientation of laminates. It can be observed from Fig. 6.6 that friction coefficient first increased with increase in load and after that decreased which was in opposite trend as shown for normal/parallel combination of laminates. C/C-sic self-mated pair showed highest friction coefficient whereas C/C self-mated pair exhibited lowest friction coefficient. The difference between friction coefficient of C/C-sic self-mated pair and C/C – C/C-sic complementary mated pair was less at high loads.

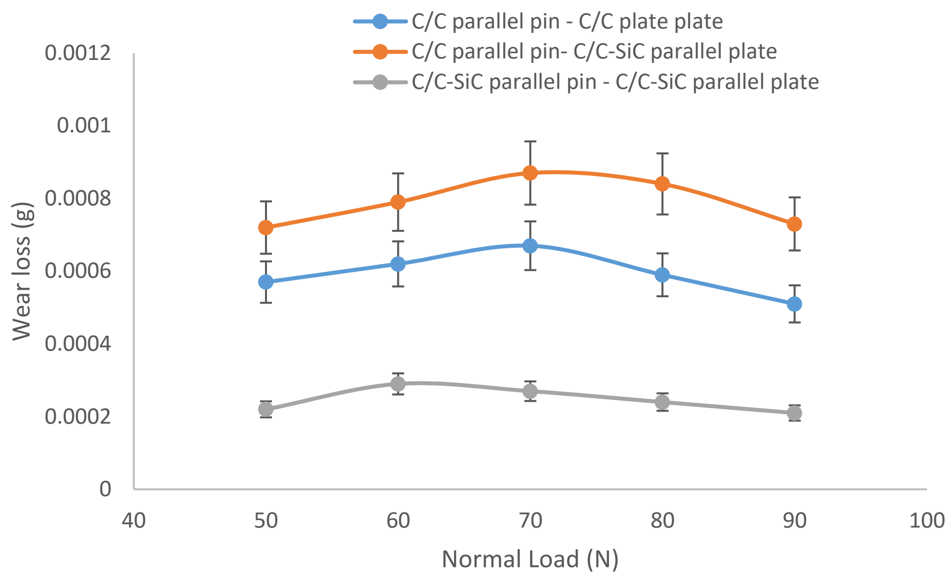


Fig. 6.7. Variation of wear loss of pin (parallel orientation) with normal load.

It can be observed from Fig. 6.7 that C/C parallel pin showed highest wear loss when complementary mated with C/C-SiC plate. The wear loss of C/C-SiC parallel pin showed lowest wear loss in self-mated pair.

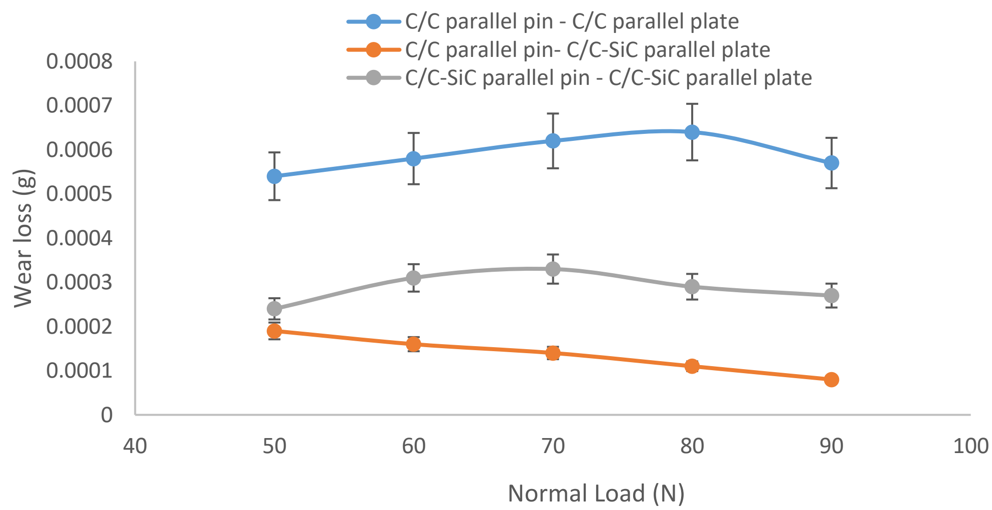


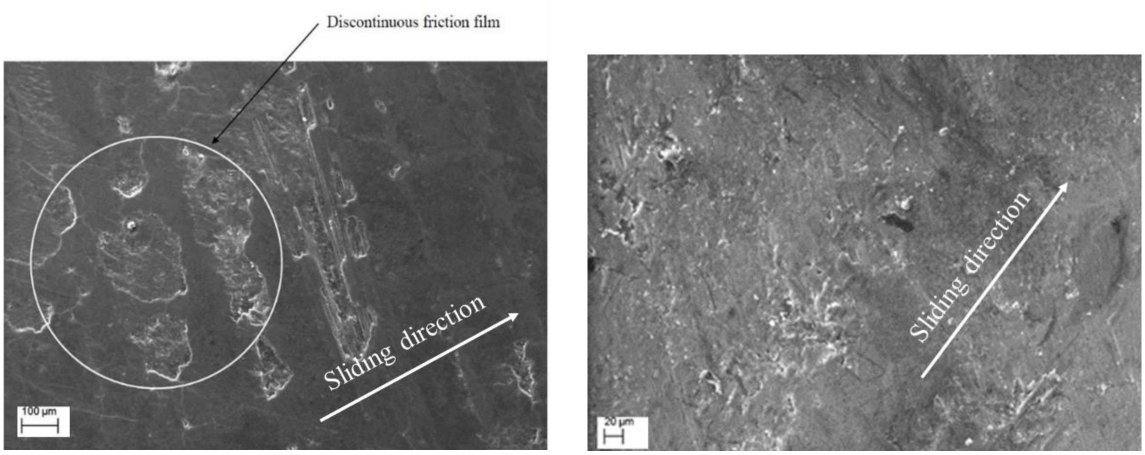
Fig. 6.8. Variation of wear loss of parallel plate (pin having parallel orientation) with normal load.

It can be observed from Fig. 6.8 that wear loss of C/C-SiC plate decreased with increase in load in case of complementary mated pair. However, for self-mated C/C and C/C-SiC pair, wear loss first increased and after that decreased.

6.5.3. Discussion

Friction coefficient of C/C self-mated pair in normal/parallel combination was lower as compared to C/C-SiC self-mated and C/C-SiC and C/C complementary mated pair. This was attributed to the formation of flaky wear debris in case of C/C composites [151]. Surface porosity was less in case of normal orientation of laminates. Thus flaky wear debris easily formed friction film on the surface of composite with normal orientation of laminates as debris pulverized, which reduced friction coefficient value. In case of C/C and C/C-SiC complementary mated pair, the hard SiC particles penetrated in the surface of C/C composite and caused grain abrasion as the hardness of C/C composites is less than SiC [184]. This increased the friction coefficient of C/C and C/C-SiC complementary mated pair. Due to generation of carbon wear debris, friction film was formed which led to decrease in friction coefficient. However due to presence of hard SiC particles, disruption of friction film also occurred. Reciprocating sliding occurs in confined region due to small stroke length. Thus wear debris was not ejected from in between the interacting surfaces and continuous formation of friction film took place. This continuous formation and disruption of friction film simultaneously led to more fluctuations in friction curve of C/C and C/C-SiC complementary mated pair. C/C-SiC self-mated pair exhibited highest friction coefficient and increased with increase in time. The highest value was attributed to its high superficial hardness which provided resistance to sliding as micropeaks which were meshed with microvalleys experienced shearing, breaking, deformation and cutting under braking energy [152].

It was observed that in case of normal/parallel combination of laminates, friction coefficient first decreased with increase in load and decreased after that. In case of C/C self-mated pair, friction film formation took place which decreased the friction coefficient with increase in load. When the load was increased further, repeated flexion of friction film in opposite direction led to its disruption. Repeated flexion was more prominent at high loads. This formed discontinuous friction film at the surface of composite which led to increase in friction coefficient at higher loads. Fig. 6.9(a) shows the discontinuous friction film formed at the surface of composite pin with normal orientation of laminates.

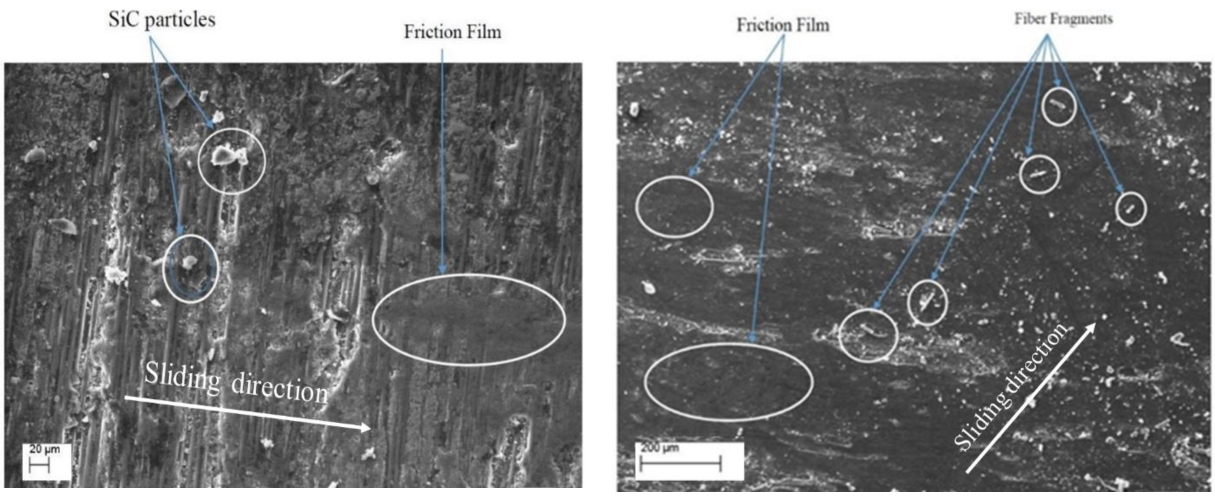


(a) (b)

Fig. 6.9. SEM images showing (a) discontinuous friction film in C/C normal pin tested with C/C parallel plate at 80 N load, and (b) C/C normal pin tested with C/C-SiC parallel plate at 80 N.

Fig. 6.9 (b) shows C/C normal pin tested with C/C-SiC parallel plate at 80 N load. It was observed that surface was rough as compared to C/C self-mated pair. The asperities of the C/C-SiC parallel plate caused ploughing of C/C normal pin. In case of low loads, friction film was formed due to generation of carbon wear debris. But at high loads, the ease of disruption of formed film was more as grain abrasion increased at high loads which led to increase in friction coefficient. Some cracks on the surface were also observed due to repeated sliding in opposite directions. These cracks loosen the matrix in case of C/C normal pin which led to detachment of matrix material.

C/C-SiC self-mated pair showed highest friction value. SiC particles got detached from the matrix as reciprocating sliding caused repeated flexion in opposite direction and induced cyclic stresses in opposite directions. SiC particles are hard to cut or pulverize even at high loads. Thus, SiC particles acted as third body particles which prevented direct contact of interacting surfaces and thus reduced friction coefficient. However as the load was increased further, the loose SiC particles embed in the surface and caused abrasion which increased friction coefficient. Fig. 6.10(a) shows the surface of C/C-SiC normal pin tested in self-mated pair at 80 N load. SiC particles can be observed. A bit of friction film can also be observed which resulted from pulverization of debris from carbon matrix.



(a) (b)

Fig. 6.10. SEM images showing (a) ejected SiC particles and formed friction film in C/C-SiC normal pin tested with C/C-SiC parallel plate at 80 N load, and (b) friction film and fibre fragments in wear debris of C/C parallel pin tested with C/C parallel plate at 80 N load.

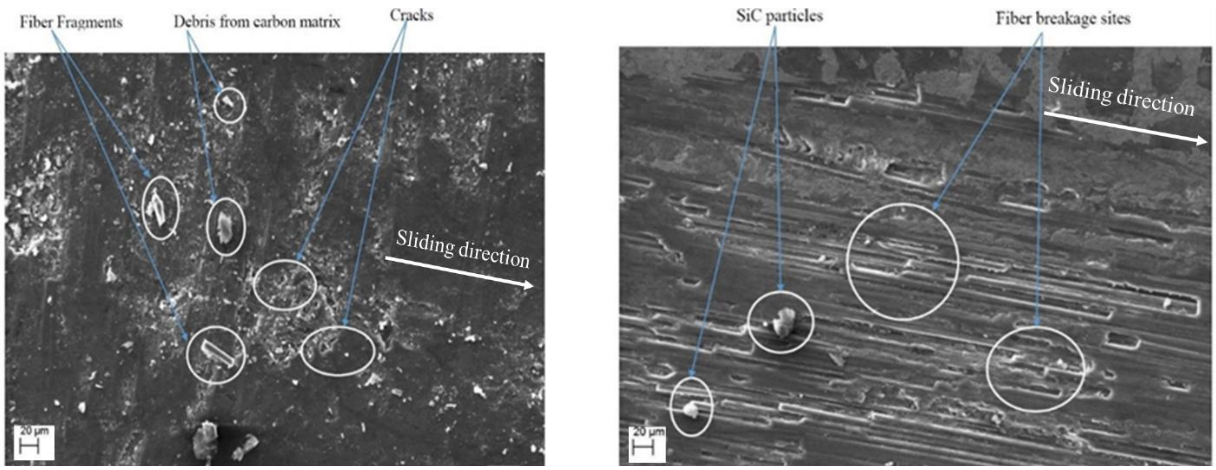
Friction behavior in parallel/parallel combination of laminates was different from friction behavior in normal/parallel combination of laminates. Parallel/Parallel combination of laminates exhibited higher friction coefficient values as compared to normal/parallel combination of laminates. Tribological behavior in case of parallel/parallel combination is different from normal/parallel combination as area proportion of fibers in interacting surfaces varies with orientation of laminates which effects overall friction coefficient due to local friction coefficients [155]. The proportion of fiber filaments touching counter surface also varies with the load and laminate orientation which affects friction coefficient [185]. In case of parallel/parallel combination, the interaction of fiber/fiber interaction was more as compared to normal/parallel combination. Fibers provide more resistance to sliding due to its breakage. Thus friction coefficient in case of parallel/parallel combination was more as compared to normal/parallel combination.

In case of parallel/parallel combination of laminates, friction coefficient of C/C self-mated pair didn’t increased with time whereas friction coefficient of C/C parallel and C/C-SiC parallel complementary mated pair increased with time. The increase in friction value of complementary mated pair was attributed to increase in interaction (with time) between SiC particles in C/C-SiC parallel plate and carbon fibers in C/C parallel pin as surface wore out. However in case of C/C and C/C-SiC self-mated pairs, penetration of asperities was less as the hardness of both the interacting surfaces was same.

Composites in parallel/parallel orientation exhibited opposite trend as shown by normal/parallel combination. In case of C/C self-mated pair, fibers interacted with each other due to more surface porosity in case of parallel orientation of laminates. Fiber breakage also occurred. Thus as the load was increased, more fiber filaments came in contact with each other which increased the friction coefficient value [185]. However as the load was increased further, the carbon fiber fragments and carbon particles from matrix in the wear debris pulverized and formed a friction film which decreased the friction coefficient. In case of normal/parallel combination, fiber breakage was very less.

Fig. 6.10(b) shows C/C parallel pin tested with C/C parallel plate at 80 N load. Fiber fragments in wear debris can be observed. Formed friction film on the surface can also be observed.

The increase in friction coefficient of C/C parallel and C/C-SiC parallel combination was attributed to increase in penetration depth of SiC particles in C/C composites as the load was increased. SiC also interacted with carbon fibers in C/C composites and led to breakage of fibers. As breakage of fibers required more braking energy, this increased friction coefficient with increase in load.



(a) (b)

Fig. 6.11. SEM images showing (a) fibre fragments and cracks in C/C parallel pin tested with C/C-SiC parallel plate tested at 70 N load, and (b) fibre breakage sites in C/C-SiC parallel pin tested with C/C-SiC parallel plate tested at 70 N load.

Fiber fragments in wear debris can be observed in Fig. 6.11(a). Some carbon particles from matrix can also be observed. These carbon particles made friction film at high loads. But that friction film was easily abraded by SiC particles. However the surface porosity in case of parallel orientation of laminates was more. Some cracks were also generated at high loads due to confined area sliding in reciprocating motion. These generated cracks and surface porosity entrapped wear debris in it and formed a smooth surface which decreased friction coefficient at higher loads.

When C/C-SiC composites are prepared through LSI technique, silicon is infiltrated into C/C composites through segmentation cracks and microdelaminations. Thus the area proportion of SiC in C/C-SiC composites in parallel orientation was more as compared to normal orientation of laminates. In C/C-SiC parallel self-mated pair, SiC from one surface tried to abrade other by grain abrasion. Due to its high hardness, both the interacting surfaces of friction couple resisted sliding. As the load was increased, SiC penetration was more which increased friction coefficient. Fiber breakage due to SiC penetration also increased friction coefficient. However the eruption of SiC particles from the friction surface prevented the direct contact of interacting surfaces which decreased friction coefficient at higher loads. Fig. 6.11(b) shows C/C-SiC parallel pin tested in self-mated pair with parallel/parallel combination. Fiber breakage with SiC particles at the surface of composite can be observed.

Wear loss of friction mate having parallel orientation of laminates was less as compared to the mate having normal orientation of laminates in normal/parallel combination. This was due to more interaction of carbon fibers in C/C composites and SiC particles in C/C-SiC composites in parallel/parallel combination. Carbon fibers breakage is difficult in C/C composites and SiC particles are hard to cut in C/C-SiC composites. Wear loss of normal pin and parallel plate generally first increased with increase in load and after that decreased. Almost same behavior was exhibited by composites whether it is normal/parallel combination or parallel/parallel combination. In case of C/C self-mated normal/parallel combination, C/C normal pin developed a friction film on its surface but due to more surface porosity of C/C parallel plate, the formed film was disrupted which increased the wear loss as the load was increased. As the load was increased further, the generation of more wear debris filled the pores which decreased wear loss. Thermal conductivity also plays an important role in friction film formation. The longitudinal thermal conductivity of C/C composites is more than radial thermal conductivity [186]. Thus heat pile up was more in case of normal orientation of laminates which helped in easy pulverization of debris. In case of C/C normal pin and C/C-SiC parallel complementary mated pair, SiC acted as third body particles as the load was increased. Although it decreased friction coefficient, but due to its movement in opposite directions, it rolled over the interacting surfaces. It generated local compressive stress whose magnitude varies within a cycle. This led to eruption of material from the surface. This increased wear loss as the load was increased. As the load was increased further, the embedment of SiC particles in between the sites of cross fibers in parallel orientation of laminates formed a smooth surface. The embedment of SiC particles in the surface of C/C composites increased the friction coefficient but due to hardness of C/C-SiC composites, it was not easy to abrade. Thus wear loss was decreased. SiC particles acting as third body and resistance to wear out of C/C-SiC composites due to its high superficial hardness describes the wear behavior of C/C-SiC self-mated pair in normal/parallel combination. Wear behavior of parallel/parallel combination was same as friction behavior. Mechanism elaborating friction and wear was same as both the interacting surface had parallel orientation of laminates.

6.6. Conclusion

The main objective of this work was to investigate the reciprocating sliding behavior of C/C and C/C-SiC composites in self-mated and complementary mated pair for different orientation of laminates of friction mates and applied normal load. The results conclude that

1. In reciprocating sliding, the generation of wear debris and formation and disruption of friction film is governed by load as the severity of repeated flexion in opposite direction and induced compressive stresses depend upon load.
2. The difference in surface porosity, thermal conductivity and interacting surface constituents of C/C and C/C-SiC composites for parallel and normal orientation of laminates led the difference in friction behavior of normal/parallel and parallel/parallel combination of laminates.
3. The friction coefficient exhibited by C/C and C/C-SiC complementary pair generally lies in between the friction coefficient of C/C and C/C-SiC self-mated pairs. If complementary

mated pair is selected for tribological applications in weight sensitive equipments, the C/C composite should be made relatively thick as wear loss of C/C composite in complementary pair was very high as compared to C/C self-mated pair.