CHAPTER 5

FRICTION AND DRY SLIDING WEAR BEHAVIOR OF UNFILLED AND SILANE-TREATED SILICON CARBIDE (SiC) PARTICLES FILLED CARBON FABRIC REINFORCED EPOXY MATRIX HYBRID COMPOSITES

5.1 INTRODUCTION

The fiber reinforced polymer matrix composites are a rapidly growing class of materials, due to their good combination of high specific strength and modulus. They are being widely used in variety of engineering applications. The tribological performance of fiber reinforced polymer matrix composite materials is usually related with the properties of their reinforcement. One method of improving the tribological properties of the composites such as friction and wear behavior is to enhance their hardness, stiffness and compressive strength and also to reduce their adhesion to the counterpart material. This can be achieved by the addition of fillers/fibers with the matrix medium. The current study presents the experimental investigation of dry sliding wear and friction behavior of C-E composites and particulate filled C-E hybrid composites. It also discusses the role of addition of filler materials with the FRP composites on wear and friction properties.
5.2 FRICTION AND DRY SLIDE WEAR BEHAVIOR

The bi-directional carbon fabric epoxy reinforced composites exhibit improved mechanical properties such as tensile strength, tensile modulus, hardness and elongation. This is due to the loading of silane-treated SiC filler, as discussed in the previous chapter. Hence, with reference to the results of mechanical properties of C-E composites with and without silane-treated SiC fillers, the tribological study for friction and dry slide wear behavior of the composites were carried out and the observations are discussed in this section.

5.2.1 Result and Discussions

The influence of applied load and sliding velocity on dry sliding wear and friction behavior of unfilled and silane-treated SiC filled bi-directional carbon fabric epoxy matrix hybrid composites are explained in the following sections.

5.2.1.1 Co-efficient of friction

The tribological performance of FRPCs is determined to a great extent by the properties of fibers (Lancaster 1968, Srivastava et al 1992, Tripathy et al 1993). This is also true in the case of hybrid FRPCs. The co-efficient of friction values of the unfilled C-E composite and 5 and 10% silane-treated SiC filled C-E composites under the influence of applied load and sliding velocities are shown in Table 5.1. Differing trends in the coefficient of friction values are observed for silane-treated SiC–C-E and unfilled C-E composite systems, as shown in Figure 5.1.
Table 5.1 Co-efficient of friction values of unfilled and silane-treated SiC filled C-E composites under the influence of applied loads and sliding velocity

<table>
<thead>
<tr>
<th>Load (N)</th>
<th>Co-efficient of friction</th>
<th>Sliding velocity, 2m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C-E</td>
<td>5SiC-C-E</td>
</tr>
<tr>
<td>25</td>
<td>0.26</td>
<td>0.27</td>
</tr>
<tr>
<td>50</td>
<td>0.34</td>
<td>0.38</td>
</tr>
<tr>
<td>75</td>
<td>0.27</td>
<td>0.37</td>
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<table>
<thead>
<tr>
<th>Load (N)</th>
<th>Co-efficient of friction</th>
<th>Sliding velocity, 3m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C-E</td>
<td>5SiC-C-E</td>
</tr>
<tr>
<td>25</td>
<td>0.24</td>
<td>0.27</td>
</tr>
<tr>
<td>50</td>
<td>0.33</td>
<td>0.39</td>
</tr>
<tr>
<td>75</td>
<td>0.23</td>
<td>0.36</td>
</tr>
</tbody>
</table>

The coefficients of friction of silane-treated SiC-filled C-E composites are very sensitive to variations of applied load. With respect to the coefficient of friction for all the samples, an increase in sliding velocity seems result in a slight decrease in the coefficient of friction for all the applied loads. On the other hand, in the case of silane-treated SiC-filled C-E composites, a slight increase in the coefficient of friction can be observed when the applied load is increased from 25 to 50 N. At 2 m/s, the increase of applied load from 25 to 50 N seems to result in a slight increase in the coefficient of friction. However, a sharp drop of coefficient of friction appears to occur when the applied load is further increased from 50 to 75 N in the case of unfilled C-E samples. Comparatively, at all experimental test conditions, unfilled C-E seems to indicate lower coefficient of friction. Furthermore, for an increase in applied load from 50 to 75 N at a constant sliding velocity, almost constant coefficient of friction can be observed in the case of silane-treated SiC-filled samples. It can be attributed that a thin transfer film (consisting of crushed
Silane-treated SiC particles, broken fibers and powdered matrix) formed on the counterface during the dry sliding wear process helps in maintaining an almost constant coefficient of friction.

**Figure 5.1** Effect of applied load on the coefficient of friction of unfilled and silane-treated SiC-filled C-E composites with sliding velocities (a) 2 m/s and (b) 3 m/s
5.2.1.2 Effect of sliding distance on wear volume loss

The selection of the suitable sliding distance for the friction and wear study of C-E composites both with and without the use of fillers were tested by many trials for different sliding distances, under the dry slide wear conditions with 50 and 75 N loads. Figure 5.2 gives the wear loss of unfilled C-E composites as a function of the sliding distance. The wear loss of C-E composite seems to considerable increase with an increase in sliding distance until the sliding distance reaches 5 km, following this, there seems to be a drastic increase in the wear loss with an increase in sliding distance (>5 km) results. On the other hand, in the range of sliding distance used in this study, the wear loss slope is steeper for C-E composite, when the sliding distance is greater than 5 km.

In general, the friction and wear properties always describe the whole tribological system than what is given by material property alone. Such systems always consist of a counterpart, the specimen material, a media in between (e.g., lubricant), the environment and the stress conditions over a certain range of time. After the specimen has accomplished a running-in period, a steady-state is reached, where the frictional coefficient and the frictional force remain approximately constant. Even at this state, the heat generation and the heat flow reach a state of equilibrium. Depending on the tribological conditions, the mechanisms involved in the wear process may change significantly, especially the topography of the sample and the steel counterface. Hence, the maximum sliding distance of 5 km has been selected for further tribological tests for the next stage of experiment.
5.2.1.3 Effect of applied load and sliding velocity on the wear volume loss

The results of wear tests with composite samples having different wt% of silane-treated SiC in C-E are shown in Figures 5.3(a) and 5.3(b). So, wear volume loss of unfilled C-E, 5 and 10% silane-treated SiC filled C-E with the load of 25N to 75N under the sliding velocities 2 and 3 m/s were plotted as line graph in Figures 5.3(a) and 5.3(b) respectively. From the figure, it can be noticed that wear volume loss increases with an increase in load/sliding velocity for the composites tested. The wear volume loss of silane-treated SiC-filled C-E composites is lower than that exhibited by the unfilled C-E composites for a sliding distance of 5 km sliding distance. It is also clear that there is an initial increase in the wear volume for all the composites. Further, there is a gradual increase in the wear volume with sliding velocity and load in the case of unfilled and silane-treated SiC-filled C-E composites. The wear volume loss of filler loaded C-E was small and wear volume loss is caused mainly by matrix wear.
Figure 5.3 Wear volume loss as a function of applied load for composites at a sliding velocity of (a) 2 m/s and (b) 3 m/s.
Lancaster (1972) reported the wear analysis of carbon-reinforced polymer materials with fillers sliding against the metal surface. The fillers were influenced in wear processes by modifying the topography of the counter surface as a result of transfer and abrasion. Bahadur and Gong (1992) investigated that the wear level of a polymer matrix composite materials sliding against the metal surface was mainly influenced by its ability to form a transfer film on the surface. Suresha et al (2007) reported that silane-treated SiC-filled glass-epoxy (G-E) composites gives a maximum wear resistance when compared to graphite-filled G-E composite and unfilled G-E composites.

The influence of silane-treated SiC filler in the G-E composite during the sliding process resulted in less wear of fiber in the G-E composite leads to lower fiber damage. The silane-treated SiC particles form transfer layer on the counter surface with G-E, which in turn minimizes the wear loss. In this study, for a higher load of 75 N, the increase in wear volume loss was observed to be marginal in the case of silane-treated SiC-filled C-E composites. The silane-treated SiC-filled C-E composite exhibited lower wear volume loss when compared to unfilled C-E composites. During the dry sliding wear test, in silane-treated SiC-filled C-E composites, the silane-treated SiC particles was found to protrude out from the sample surface when it was in contact with the counter surface of the disc. Instantly, the silane-treated SiC particles along with the C-E abrade the counter surface and formed the transfer layer on the counter surface of the disc, resulting in a significant reduction of wear volume loss.
Wear volume loss of unfilled and silane-treated SiC filled C-E composites under three different loads (25, 50 and 75 N) with the sliding velocities 2 and 3 m/s are shown in Table 5.2. The wear volume loss measured under the test conditions (3 m/s and 75 N Figure 5.3 (b)) were 0.9028 mm$^3$ (minimum wear volume) for 10 wt% silane-treated SiC-filled C-E, 1.1649 mm$^3$ for 5 wt% silane-treated SiC-filled C-E. In the case of unfilled C-E composites, it was 1.4831 mm$^3$ (maximum wear volume). The order of wear resistance behavior of composites is as follows: 10 > 5 > 0% by weight of silane-treated SiC. Moreover, it should be noted that 10 wt% silane-treated SiC-filled C-E (10SiC-C-E) composite exhibited a highest wear resistance under different sliding velocity/loads. This behavior can be attributed to the presence of hard silane-treated SiC particles, which act as effective barriers to prevent large-scale fragmentation of epoxy. The carbon fabric strengthens the composite, while the ceramic filler silane-treated SiC acts as an abrasion-resistant material. From the graphs, it can be observed that the average wear resistance of the 5wt. % silane-treated SiC-filled C-E and 10wt. % silane-treated SiC-filled C-E composites are 21% and 35%,
respectively. These values are much higher when compared to those of unfilled C-E composites. The results of present study are in good agreement with the findings reported in literature (Lancaster 1972, Suresha et al 2007).

5.2.1.4 Effect of applied load on specific wear rate

Table 5.3 shows the specific wear rate of unfilled and silane-treated SiC filled C-E composites under three different loads (25, 50 and 75 N) with the sliding velocities 2 and 3 m/s. The specific wear rate as a function of applied load at 2 m/s and 3 m/s is shown in Figures 5.4(a) and 5.4(b). It is evident that the increase of silane-treated SiC content from 0 to 10 wt% has led to a remarkable decrease on specific wear rate. This kind of variation has been reported for glass fabric-reinforced epoxy composites (Suresha et al 2007). The wear of C-E composite consists of two wear modes: polymer matrix wear (which includes matrix plastic deformation and cracks in the matrix) and fiber wear (which involves fiber sliding wear, fiber cracking, fiber rupture and fiber pulverising).

The reduction in specific wear rate with an increase in silane-treated SiC content in C-E composites, especially at a higher load (75 N), is due to the transfer film formed on the counterface. As it is commonly known, the wear behaviour of a polymer sliding against a metal is strongly influenced by its ability to form a transfer film on the counterface (Lu et al 1993, Wang et al 2003, Mody et al 1988). During sliding, the transfer film decreases the adhesion between polymer composite and metal counterface, and impairs the ploughing action of metal asperities at counterface over the soft polymer surface. On the other hand, once the film is formed, a subsequent interaction occurs between the silane-treated SiC-filled C-E and a layer of similar material (Mody et al 1988, ASTM G99-05 2010). As the polymer/carbon is a self-lubricant material, the wear loss of silane-treated SiC-filled C-E composite is closely related to the formation and development of a transfer
film. At the start of sliding, all the asperities of the two surfaces are in contact with each other. Once the shear forces are applied, the asperities deform. The silane-treated SiC particles protrude from the surface of the sample. At first, the epoxy matrix wears and only bi-directional carbon fibers are in contact with the countersurface. As the sliding velocity increases, the wear rate also increases. This is because at a high load, the interface temperature increases, causing the carbon fiber to fracture.

The resulting situation at the interface is complex owing to the fiber being trapped. These broken fibers wear the sample further due to the effect of third body abrasion. When epoxy comes in contact, adhesive wear occurs and the wear rate also increases. Further, the wear process is controlled by carbon fabric reinforcement. In the present study, an attempt has been made to improve wear resistance by addition of silane-terated SiC fillers. During sliding, the silane-treated SiC particles get smeared at the interface, forming a thin film on the counterface, which in turn reduces the specific wear rate. The addition of carbon fibers and fine silane-treated SiC particles strengthen the combination of the interface between the reinforcement and the epoxy matrix and increased the elastic modulus of the C-E composites, thus explaining the significant reduction in specific wear rate.

Table 5.3  Specific wear rate of unfilled and silane-treated SiC filled C-E composites under different loads/sliding velocities

<table>
<thead>
<tr>
<th>Load, N</th>
<th>Specific wear rate X 10^-6, m^3/Nm for sliding velocity of 2m/s</th>
<th>Specific wear rate X 10^-6, m^3/Nm for sliding velocity of 3m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C-E</td>
<td>5SiC-C-E</td>
</tr>
<tr>
<td>25</td>
<td>1.6952</td>
<td>1.0968</td>
</tr>
<tr>
<td>50</td>
<td>3.6723</td>
<td>2.7412</td>
</tr>
<tr>
<td>75</td>
<td>3.9549</td>
<td>2.9237</td>
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</table>
Figure 5.4 Specific wear rate as a function of applied load for composites at a sliding velocity of (a) 2 m/s and (b) 3 m/s

5.2.1.5 Worn surface morphology

The SEM examinations of worn surfaces of unfilled and silane-treated SiC-filled C-E composite samples against steel counter surface under 25 and 75 N loads and at 2 and 3 m/s sliding velocity are given in Figures 5.5 (a)-(d) and 5.6 (a)-(d), respectively.
Figure 5.5  SEM pictures of worn surface of unfilled C-E composites at (a) 25 N, 2 m/s, (b) 25 N, 3 m/s, (c) 75 N, 2 m/s and (d) 75 N, 3 m/s (Arrow indicate the sliding direction)

Figure 5.5 (a)-(d) presents the worn surface features of unfilled C-E samples under different sliding conditions (25 N, 2 m/s and 3m/s, 75 N, 2 m/s and 3m/s). At a lower load/sliding velocity, the worn surface of unfilled C-E was found to be relatively smooth and associated with microcracks (both in transverse and longitudinal direction) in the matrix (Figure 5.5(a)). At a higher sliding velocity, however, the damage to the fiber was found to be more, resulting in more fiber breakage. A few fibers were removed from the surface of the composites (Figure 5.5(b)). At a higher load (75 N), the wear volume loss was found to increase significantly. This in turn was found to cause an accelerative breakage of the matrix especially, in the interfacial
region. It also resulted in the bending of fibers in the transverse direction (Figure 5.5(c)). Further, the surface damage remarkably increased due to the impact of imprints left by the separating fibers (Figure 5.5(d)). The broken fibers and removal of matrix from the composite surface could further decrease the wear resistance of C-E composite owing to a third body abrasion effect. Therefore, the specific wear rate of the unfilled C-E composites was progressively increased with an increase in load/sliding velocity.

Figure 5.6 SEM pictures of worn surface of 10Silane-treated SiC filled C-E composites at (a) 25 N, 2 m/s, (b) 25 N, 3 m/s, (c) 75 N, 2 m/s and (d) 75 N, 3 m/s (Arrow indicate the sliding direction)
The SEM examinations of worn surfaces of silane-treated SiC-filled C-E composite samples against steel counter surface under 25 and 75 N loads and at 2 and 3 m/s sliding velocity are given in Figures 5.6 (a)–(d). At both lower and higher loads, it can be seen that the silane-treated SiC-filled C-E sample shows less broken fibers and less debris (Figures 5.6 (a–d)) when compared to the unfilled C-E sample (Figures 5.5(a–d)). Also, the debris and the length of the fragmented fibers are found to be very minimum in the case of silane-treated SiC-filled C-E sample.

Moreover, the breakages of fiber with very less matrix wear in addition to network of very small cracks at 25 N load and 2 m/s sliding velocity can hardly be noticed. These observations are consistent with the experimental wear volume data presented earlier (Figures 5.3(a–b)). Figure 5.6(a) shows a smooth surface with microcracks in the epoxy matrix under dry sliding situation when compared with (Figure 5.5(a)) unfilled C-E sample. Microcracks in the transverse direction, micro-grooves, few silane-treated SiC particles and matrix debris can also be observed from the photomicrograph (Figure 5.6(a)). The lubrication effect of carbon fiber and higher hardness of silane-treated SiC hinder the wear of silane-treated SiC-filled C-E composite (Figures 5.3(a–b)). In addition, the smaller size of the wear debris produced and the removal of filler and matrix from the surface in the sliding direction for silane-treated SiC-filled C-E composites demonstrate the role of the fillers in impeding large-scale fragmentation process (Figure 5.6(b)). The better wear resistance exhibited by the silane-treated SiC-filled C-E composites depends largely on factors such as increased bonding strength between the matrix and fiber/filler materials and less voids induced by the filler.
In this study, the silane-treated carbon fiber and silane-treated SiC filler are used in the preparation of composites and, hence, resulted in better wear performance in terms of reduced wear rate at higher load/sliding velocity. Figure 5.6(c) and 5.6(d) show the worn surfaces of silane-treated 10% SiC-filled C-E composites tested under 75 N load and sliding velocity of 2 and 3 m/s, respectively. In comparison with Figures 5.5 (c)–(d), it is clear that the worn surfaces were much smoother at the same sliding conditions and the carbon fiber detachment was significantly limited with the addition of silane-treated SiC particles. As shown in Figures 5.6 (c) and 5.6 (d), even under a relatively high load, the worn surface preformed relatively smoother and was characterized by microsurface damage of the matrix, microcutting of fibers and removal of fibers.

Accordingly, the fiber debris resulted from composite (Figure 5.6(d)) is much thinner and smaller when compared to unfilled C-E (Figure 5.5 (d)) under the same sliding conditions. As carbon fiber and fine silane-treated SiC particles act as a hard phase in the soft polymer matrix, the true contact area is in contact with the counterface under higher load/sliding velocity test conditions. As a result, it plays a major role in reducing the plough and the adhesion between the relative sliding parts. The reinforcement influences the tribological behavior of silane-treated SiC-filled C-E in two ways: (i) it could lead to fractures in the interface of the constituents (ii) it could reduce the plough and the adhesion between the two sliding components. These two roles simultaneously influence both friction and wear behavior, according to the sliding test conditions. Therefore, with the addition of silane-treated SiC particles, the fibers were maintained in the matrix with a very gradual wear process even at high load and velocity conditions, which led to an enhanced load-carrying capacity of the composite. Furthermore, C-E
filled with higher silane-treated SiC loading (10 wt %) show more stable wear performance under all test conditions. The additional lubricants seem to contribute to a stable development of the transfer film on the counterface even at extreme sliding conditions. This transfer film (consists of carbon, silane-treated SiC and epoxy matrix) formed on the counterface during sliding process appears to be responsible for the improved wear resistance of silane-treated SiC-filled C-E composites.

5.3 SUMMARY

The dry sliding wear behavior of unfilled and silane-treated SiC filled C-E hybrid composites were investigated by using the Pin-on-Disc wear test rig and the main outcomes are listed below.

1. The coefficient of friction of unfilled and silane-treated SiC filled C-E composites decreased slightly with an increase in sliding velocity for the all applied loads.

2. Incorporation of silane-treated SiC particulates in C-E composites appeared to decrease the coefficient of friction and improve the wear resistance when compared to unfilled C-E composites.

3. For all the unfilled and silane-treated SiC filled C-E composites, an increase in applied load/sliding velocity increased the sliding wear loss. The wear volume loss of silane-treated SiC filled C-E showed the minimum value compared to unfilled C-E composites. The specific wear rate was also found to be minimum in the case of silane-treated SiC filled C-E composites.
4. In the C-E composites, the loading of silane-treated SiC particles seemed to increase the wear resistance. The presence of silane-treated SiC particles in the C-E composites acts as an effective barrier to prevent the large scale fragmentation of epoxy.

5. SEM studies of worn surfaces support the mechanisms involved and indicate microcracking, fiber cutting, and removal of matrix, exposure of fibers, fiber cracking and removal of broken fibers.