Chapter 5
Tribological Performances of Woven Carbon Fabric/Epoxy Composites Under Dry and Oil Lubrication Condition: An Experimental Investigation

Santosh Kumar and K. K. Singh

Abstract Tribological performance of carbon fiber reinforced epoxy polymer composites (CFRP) in dry and oil lubricating condition. The tests were conducted on a pin-on-disk machine under different applied loads and at a constant sliding velocity. CFRP composite laminates were manufactured by wet lay-up technique followed by vacuum bagging. All the samples were rubbed against a counter-surface of steel (En-31) having hardness of 60 HRC and average surface roughness (R_a) of 0.3 μm. Tribological performances in terms of wear and frictional characteristics were evaluated on the basis of total weight lost during experimentation and specific wear rate of the material and coefficient of friction, respectively. The experimental results show that maximum specific wear rate of CFRP composites with a value of 1.56×10^{-5} mm^3/Nm and 2.77×10^{-5} mm^3/Nm under oil lubricated and dry sliding condition, respectively. The eroded surfaces of CFRP coupons were characterized by Field Emission Scanning Electron Microscope (FESEM) to find out wear mechanism under dry and oil condition.

Keywords Carbon fabric · Wear · Friction

5.1 Introduction

Fiber-reinforced polymer (FRP) composite offers various properties not limited to high-specific strength, specific modulus, internal vibration damping, and superior wear resistance combined with low density. Because of their unique properties, it has been extensively used as advanced composite material [1, 2]. Carbon fiber-reinforced polymer (CFRP) composite exhibits outstanding mechanical as well as tribological properties and is largely used in the field of aerospace, transportation, automotive, biomedical, sporting goods, and mining industries. There are many wear situation encountered by FRP composite materials such as pumps handling industrial fluid,

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gears, sewage and abrasive contamination fluids, seals and bushes in agricultural and mining equipment [3–5]. During the past three decades, investigations based on the friction and wear characterization of FRPs are extensively done under dry sliding condition and found that excellent improvement in tribological properties. Nevertheless, CFRP composites exhibit high specific strength, excellent thermal stability and conductivity, and potentially lubricating ability due to their laminated appearance [6]. Vishwanath et al. [7] carried out the friction and wear test for three different woven roving glass fabrics reinforced polyvinyl-butyral-modified phenolic composite under dry sliding condition. Adhesive wear test was performed against a cast iron counter-face. The results reveal that wear rate strongly influenced by glass fabric geometry. Bijwe et al. [8] also studied the influence of three different weave carbon fabric reinforced polyetherimide composites slid against mild steel disk in dry wear mode. They were found that twill composites had better performance. Suresha et al. [9] performed experiments to assess the tribological behavior of carbon/epoxy and glass/epoxy laminates, respectively, against a hard steel disk under dry sliding condition. The results revealed that CFRP composites possess better wear resistance compared to its glass fiber counterparts, irrespective of the speed and applied load. Tribological aspects such as sliding distance, applied load, and velocity are found to be important parameters affecting friction and wear behavior of FRP composite materials. Therefore, tribological behaviors of FRP composites are studied in order to enhance such properties. In general, many researchers were investigated friction and wear behavior for polymer composite under dry sliding condition. However, very few studies have been reported for tribological performance of FRP composite under oil lubricated condition [10–13]. Zhang et al. [14] inspected the tribological characteristics of neat epoxy and epoxy-based composites based on their friction and wear behavior. Such properties were evaluated against stainless steel under diesel lubricated condition. Test result showed that incorporation of short glass or carbon fiber in epoxy improved the tribological properties. Chen et al. [15] investigated wear and frictional properties of carbon/phenolic-resin laminates against stainless steel. The tests were carried out under dry as well as pure and seawater sliding condition. Results reveal that composite had the highest specific wear rate under pure water followed by under dry and seawater. Sandeep Agrawal et al. [16] demonstrated that in GFRP laminates minimum wear rate is found under oil lubricated environmental condition and maximum wear rate found under inert gas sliding environmental condition.

In this study, the comparative investigation of tribological characteristics of woven CFRP composites subjected to dry and oil lubricated sliding conditions.

5.2 Experiment

5.2.1 Material Specification

Epoxy resin (L-12) is well-known thermosetting polymer used as matrix material and K-6 hardener was added for room temperature curing. Epoxy possesses good mechanical as well as tribological properties due to cross-linked polymer and also has low-cost polymer as compared to others. Epoxy (L-12) resin and curing hardener (K-6) were supplied by Atul Industries Pvt. Ltd., India. Bidirectional woven carbon fabrics of 600 GSM were used as reinforcement in epoxy resin.

5.2.2 Material Fabrication

Wet lay-up technique further assisted by vacuum bagging was used to fabricate CFRP laminates. Eight layers of carbon fabric were taken to obtain 4 mm thickness for laminates fabrication. Each of the samples was symmetric laminates with stacked sequence of [(0°/90°)/(−45°/+ 45°)/(−45°/+ 45°)/(0°/90°)/(0°/90°)/(−45°/+ 45°)/(−45°/+ 45°)/(0°/90°)]. Firstly, epoxy and hardener were mixed in the ratio of 10:1. The solution was then applied on the woven carbon fabric using a brush to accomplish the desired stacking sequence. The excess resin was removed using a roller after application of solution to each layer. For further removal of excess resin, vacuum bagging was used at the pressure of 650 mm of Hg for 35 min. After this, a load of 40 kgf was applied for 24 h. Samples of dimensions 8 mm × 8 mm were cut from the laminate composites were glued to the aluminum pins of diameter 6 mm (Fig. 5.1).

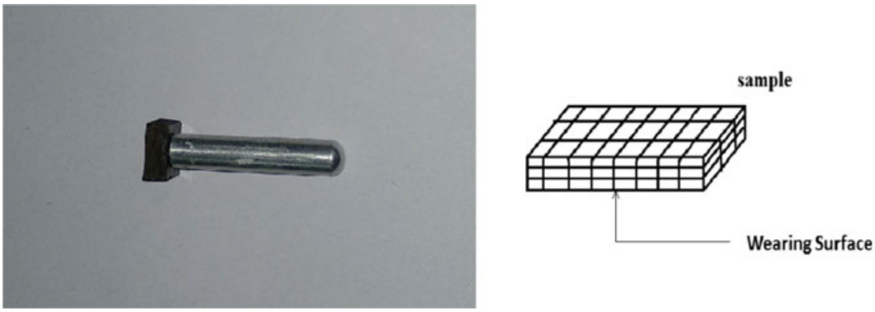

Fig. 5.1 Test sample glued with Al pin

5.2.3 Tribological Testing

The tribological tests were performed on pin on disk (TR-20) by DUCOM. The operating parameters which were taken as follow: sliding velocity 2.61 m/s; variable applied load (25, 50, 100 N); sliding time, 5 min and sliding distance, 0.786 km. In this study, the experiment was performed in dry and oil environment condition at room temperature. SAE20 oil was continuously supplied through elastomer tube onto the wear track under gravity. En-31 steel disk with surface hardness of 60 HRC and R_a (average surface roughness) of 0.3 μm was used counterpart. Each specimen was weighted before and after the experiment. The sliding direction of the specimen fibers was kept parallel and anti-parallel.

5.3 Results and Discussion

5.3.1 Weight Loss and the Specific Wear Rate

The weight loss and specific wear rate (K_0) of CFRP composite samples were calculated with different applied load (25, 50 and 100 N) and others parameters kept constant as discussed above in dry and oil lubricated condition. Weight loss under different normal load for different samples under dry and oil lubricated condition is displayed in Fig. 5.2a. It is observed that weight loss is increasing with increase of applied loads for both lubricating conditions. K_0 is one of the factors to determine the tribological characteristics more precisely as compared to material mass loss. The specific wear rate of a material is calculated as;

$$\text{Specific Wear Rate}(K_0) = \frac{\Delta m}{\rho \times L \times d}\left(\frac{\text{mm}^3}{\text{N} - \text{m}}\right) \quad (1)$$

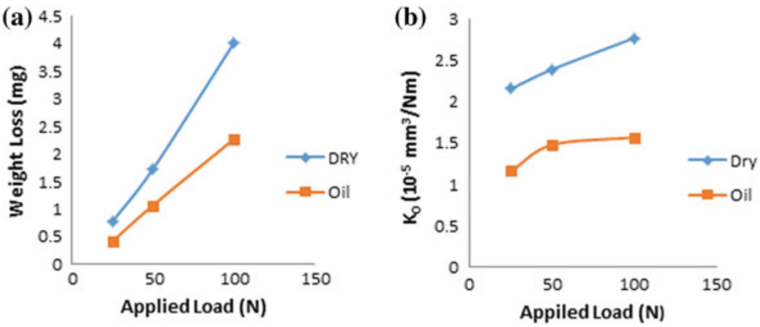

Fig. 5.2 Graphs depicting **a** Weight loss versus applied load; and **b** Specific wear rate (K_0) under different environmental condition at a constant velocity of 2.61 m/s

where

Δm mass loss (kg)
ρ density of the composite sample (kg/mm^3)
L normal applied load (N)
d sliding distance (m).

From Fig. 5.2b, it may be observed that with the increment in normal applied load, the value of specific wear rate increases. It is obvious that with the increment in load, weight loss increases. From the above formula, it may be noted that both numerator (weight loss) and denominator (load) increases with the increment in normal applied load. So as per the observations, the increased value of specific wear rate determines that rate of increment of weight loss is higher than that of change in value of normal applied load. Nevertheless, the specific wear rate is lower in oil lubrication as compared to dry is due to boundary lubrication formation between the pair surfaces.

5.3.2 *The Friction Coefficient*

Coefficient of friction is used to analyze the friction force between mating surface and frictional behavior of composite materials. Friction results from the asperities at micro-level. Figure 5.3 shows that with increasing load, frictional coefficient increases. Common phenomenon that governs the friction behavior are either increment in the amount of carbon fibers on disk surface in the form of wear debris that acts as solid lubricant or the formation of a tribo-film that reduce the coefficient of friction between the contacting surface. Moreover, after prolonged mating between tribo-surfaces formation of new surface due to removal of previous tribo-surface is inevitable. The formation of new surfaces with different tribo properties leads to uneven profile of new surface that result in higher coefficient of friction. From the experimental result, it was found that the normal applied load has a direct effect on

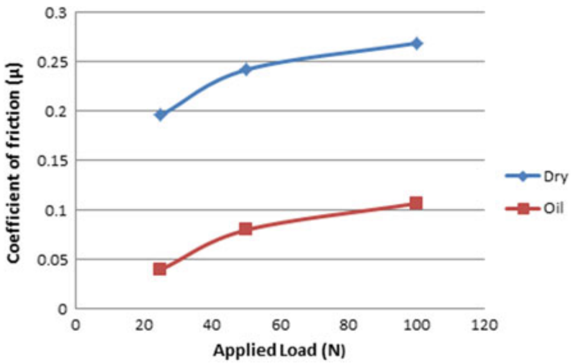

Fig. 5.3 Variation in frictional coefficient under various applied load at $v = 2.61$ m/s

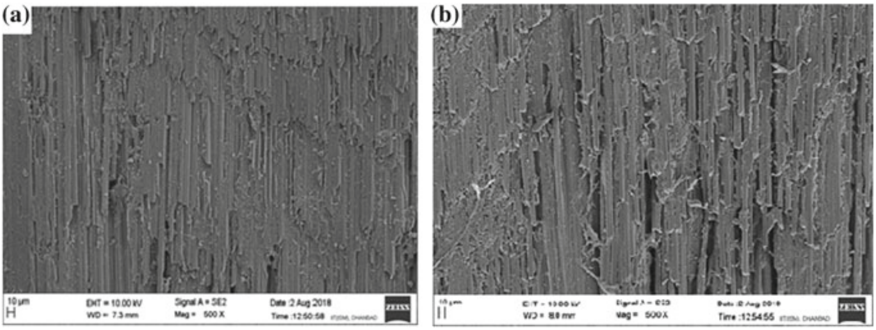

Fig. 5.4 FESEM image of worn out surfaces composite sample under dry condition, **a** 25 N, 2.16 m/s and **b** 100 N, 2.16 m/s

the frictional coefficient which being an increase in the load increase the friction or vice versa.

5.3.3 FESEM Analysis

FESEM examination of worn surfaces CFRP composite samples under normal applied load 25 and 100 N and at 2.61 m/s constant sliding velocity are shown in Figs. 5.4a, b and 5.5a, b. There are four wear mechanisms mainly involved under sliding wear condition for fiber-reinforced polymer composites [17]. It has been also observed from FESEM images that four wear mechanisms involved under dry and lubricated condition. Figure 5.4a, b show worn out surface features of carbon fiber-reinforced epoxy composite samples under normal sliding condition. It could be visibly seen that there is maximum materials removal occurred through fiber wear,

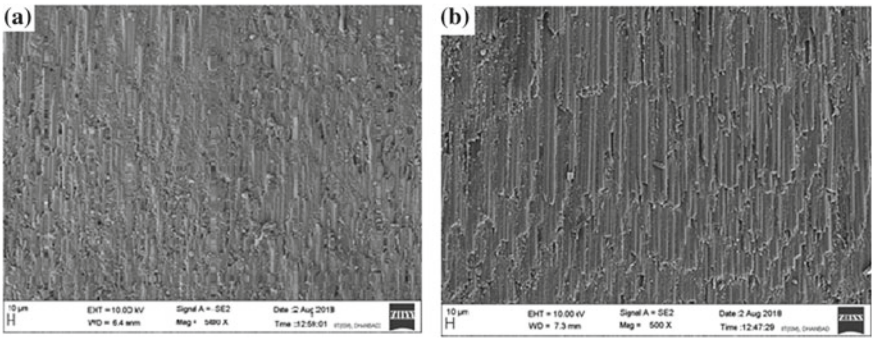

Fig. 5.5 FESEM image of worn surfaces of composite sample under oil lubricated condition, **a** 25 N, 2.16 m/s and **b** 100 N, 2.16 m/s

matrix wear, severe fiber fracture, and interfacial debonding due to higher heat generated at the interface. Figure 5.5a, b show worn surface of carbon fiber-reinforced epoxy samples under oil lubricated condition, in which lower fiber wear and matrix wear observed and very few fibers debonding happened.

5.4 Conclusion

Tribological characterization of CFRP laminates conducted in this work could be concluded as;

1. Wear as well as frictional characteristics of CFRP laminates is highly influenced by sliding medium and applied loads as compared to others parameters.
2. Under oil lubrication conditions, coefficient of friction was found to be minimum because of the induction of thin oil layer leading to lubricating interface of tribo-pair.
3. Specific wear rate and weight loss of composite increases with increasing load normal to the specimen irrespective of the sliding conditions.
4. FESEM observation of worn surfaces shows wear mechanisms involved during wear process are fiber breakage, matrix wear, and fiber debonding.

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