Tribological behavior of MWCNT filled carbon fiber reinforced polymer composite under different sliding conditions and different environments

Anshul Jain¹*, Kalyan Kumar Singh¹, Jiban Jyoti Kalita¹, Nisha Sharma¹
¹Department of Mechanical Engineering, Indian Institute of Technology (ISM)
Dhanbad, Dhanbad, India

E-mail: anshul.16mt000869@ese.ism.ac.in; anshul.jain.1428@gmail.com

Abstract. Fiber reinforced polymer composite materials find its application in a wide domain due to its mechanical properties. Some of the applications may include sliding motion under various environments making the study of their tribological behavior necessary. In this paper, investigation is done on the tribological behavior of carbon fiber reinforced polymer (CFRP) composite with 3 wt. % multi-walled carbon nano-tubes (MWCNTs) as the secondary reinforcement. The experiment was performed on pin on disc type tribometer at room temperature with a constant rpm of 700 rpm and different parameters i.e. sliding velocity, different environmental conditions (like dry, oil lubricated) and different normal loading conditions. The results showed the dependence of wear and friction characteristics of the test material on these parameters by evaluating specific wear rates and coefficient of friction. The experimental results were further examined by FESEM analysis of some of the samples.

1. Introduction

Composite materials may be classified as metal matrix composites, polymer matrix composites, and ceramic matrix composites. Polymer-based materials find various applications in industries due to their thermal properties, lubrication ability etc. [1]. The self-lubricating properties of polymer matrix composites makes it desirable for various tribological applications, which resulted in a number of research being carried out on tribological behavior of polymer composites [2-5]. Self-lubrication of polymer comes from the transfer film, which acts a lubricant, reducing the friction as compared to metals [6]. One of the most used polymers is epoxy resins due to its thermosetting properties.

Reinforcing fibers in epoxy resin may improve or deteriorate its wear resistance [2]. Different kinds of reinforcements may be used in composite materials such as glass fibers, carbon fibers graphite etc. however, amongst them, carbon fibers possess best thermal, mechanical and wear properties [7]. The desirable tribological properties at higher temperature makes carbon composites a choice in aircraft brakes since their first use in the year 1969 [8-10]. Selection of fiber reinforcements plays a crucial role in composites as they often affect the fibers/matrix interface, which as a result affects the mechanical properties of the composite structures [11]. However, during the sliding conditions, the most encountered reasons behind wear are fiber-matrix debonding, fiber fracture etc. [12-16]. Promising properties of polymer composites opens up a new domain of opportunity for research in their tribological behavior by analyzing the effect of new reinforcements [17-19]. Researches have been carried out with different kinds of reinforcements (particles, fibers etc.), different reinforcement materials, different kinds of fibers (short, long, unidirectional, woven etc.), different orientations,
different concentrations etc. It has been observed that composites with woven fibers have balanced properties in the corresponding plane [20]. Omrani and Barari [21] concluded that the increment in volume percentage of carbon fibers in epoxy polymer composite enhanced wear and friction properties. Formation of a tribofilm is one of the key factors in tribological performance of polymer materials [22-24]. Selection of fillers also affects the wear and friction behavior of polymers. Selection of filler materials may be done on the basis of one’s objective. Some affects by forming a transfer film, while some enhances the thermal conductivity of polymers, and thereby reducing the wear by reducing the thermal softening of polymers [25-27]. One of the best filler materials are nanoparticles, as they possess the potential to form high quality tribofilm [28-30]. One of the most promising nanoparticles for tribological applications is carbon nano-tubes. There are single walled carbon nano-tubes (SWCNTs) and multi walled carbon nano-tubes (MWCNTs). CNTs have excellent mechanical and thermal properties. Dispersion of CNTs is a crucial factor in determining the degree by which it may improve a material’s tribological properties [31]. Anshul et.al [32] concluded in his paper that with the introduction of MWCNTs in FRP composite, the wear resistance and frictional behavior improves. Schadler et al. [33] concluded CNTs improve compressive strength of epoxy composites. This results in lower actual area of contact in tribological applications, and hence, lower wear. Sandeep et al. showed in his paper the effect of sliding parameters on tribological behavior of FRP composites [20].

In this paper, an investigation has been carried out to determine the effect of different sliding conditions (i.e. normal load, sliding velocity, and sliding distance) and different sliding environments (i.e. dry sliding condition, oil lubricated condition) on tribological behavior of CFRP composites doped with 3 wt. % MWCNTs.

2. Experiment

2.1. Material preparation

In this paper, samples of CFRP composite with 3 wt. % of MWCNTs were tested. A symmetrical laminate of eight layers (resulting in thickness of 4 mm) of bi-directional woven (600 GSM) carbon fiber in the stacking sequence of [0°/±45°/90°], was prepared using hand layup technique assisted by vacuum bagging method. MWCNTs (provided by United Nanotech Innovations Pvt. Ltd., Bengaluru, India) of 98% purity were used as secondary reinforcement. In order to prepare the laminates, MWCNTs were ultrasonically mixed with epoxy resin (L-12) in required proportion for forty five minutes to make 3 wt. % resin-MWCNTs solution. After proper dispersion of MWCNTs, hardener (K-6) (both resin and hardener provided by Atul Limited, Gujarat, India) is added to the above mentioned solution in the ratio of 10:1 and were mixed in ultrasonicator for next ten minutes. The solution thus prepared was applied on the carbon fibers using brush to make the laminates in the desired stacking sequence. The laminate was then kept in the bag and extra resin was removed using vacuum pump. The pressure of 680 mm of Hg was maintained for 30 minutes after which, a weight of 40 kg was kept on laminate in atmospheric condition for the next twenty four hours. The samples of 6mm x 6mm x 4mm were cut from the prepared laminate and were glued to aluminum pins of 6mm diameter.
2.2. Experimental procedure

The experiment was performed on pin-on-disc type wear tester (TR-20: Made by DUCOM, Bengaluru, India). The counter-surface used was steel disc (En-31) having $R_a$ value of 0.2-0.5 microns and hardness of 60 HRC. The experiment was performed at room temperature, rpm was kept constant at 700 rpm and rubbing time was kept constant at 600 seconds.

The disc was cleaned with acetone. The samples were weighed on a weighing machine with a least count of 0.01 mg before performing the experiment. Parameters like rpm, run time, track diameter and normal load were set. The samples were placed so as to keep the fiber orientation to be parallel to the sliding direction at contact area. Samples were further weighed after the experiment in order to determine the weight loss. The experiment was repeated for different values of normal load (50 kgf, 100 kgf and 150 kgf), different values of track diameters (80 mm, 90 mm and 100 mm) resulting in sliding velocities of 2.93 m/s, 3.29 m/s and 3.66 m/s respectively [Track diameter (m) * (RPM/60)] and sliding distances of 1758.4 m, 1978.2 m and 2198 m respectively [sliding velocity (m/s) * sliding time (s)]. The experiment was performed in both dry environment condition (atmospheric condition) as well as oil lubricated condition for all sets of parameters. The oil used in the experiment was SAE-20 engine oil and a flow rate of 0.04 ml/min was maintained during the experiment. The wear and friction behavior of the samples were examined by comparing the values of specific wear rate and coefficient of friction for each set of parameters. Specific wear rate may be determined as:

$$Specific\ Wear\ Rate\ (K_w) = \frac{\Delta m}{\rho \cdot L \cdot d \left( \frac{mm^3}{N - m} \right)}$$

where,
- $\Delta m$ = mass loss (kg)
- $\rho$ = density of the sample (kg/mm$^3$)
- $L$ = normal load (N)
- $d$ = sliding distance (m)
3. Results and Discussion

3.1. Weight loss
Adhesive wear of FRP composite takes place from thermal softening of the layers due to increased temperatures resulting from friction. Wear results in weight loss of the samples. The degree of weight loss depends on parameters like normal load, sliding velocity, sliding distance and sliding environment. Figure 2(a), 2(b) and 2(c) show the dependence of weight loss on different normal loading conditions and different sliding environments for given sliding velocity.

It may be observed in figures 2 (a)-(c) that for a given value of sliding velocity, the value of weight loss increases with the increase in normal load. It was observed during the experiment that specimen temperature and disc temperature was increased with the increase in normal load and with the increase in sliding velocity (track diameter, as rpm is constant). So increase in normal load results in increased thermal softening, and hence, easy removal of surface layer from the material resulting in increased weight loss at higher normal loads.

It may be observed from figure 2 (a)-(c) that for any given value of sliding velocity and normal load, weight loss is higher in dry environmental condition as compared to that in oil-lubricated condition. There are two factors to be considered for such observations. On one hand, the lubricating oil used forms a film between the surfaces in contact resulting in lesser friction and wear, therefore lesser weight loss. On the other hand, oil used also works as a coolant to the contact surface and much of the heat generated from sliding gets diffused resulting in lesser thermal softening and hence, lower weight loss.

Figure 2 (a)-(c) show that with the increment in sliding velocity, the weight loss increases for a given normal load and given sliding environment. Here, it may be noted that with constant value of rpm and sliding time, both sliding velocity as well as sliding distance increases. Increment in sliding distance implies more rubbing, and therefore, more wear and weight loss. Also, higher sliding velocity implies higher degree of thermal softening and therefore, more wear and increased weight loss.

Figure 2: Weight loss for dry and oil lubricated medium at sliding speed of (a) 2.93 m/s; (b) 3.29 m/s; (c) 3.66 m/s

3.2. Specific Wear Rate
The tribological behavior of material depends on many factors and hence, it cannot be determined solely on the basis of weight loss. So tribological behavior was analyzed on the basis of specific wear rate. Figure 3(a), 3(b) and 3(c) show the specific wear rate ($K_w \times 10^{-5}$) for a given sliding velocity at different values of normal loads. Figure shows that for a given value of sliding velocity, the specific wear rate increases with the increment in normal load because increment in normal load results in higher thermal softening which leads to a wear so high such that the specific wear rate increases. Also, figure 3 (a)-(c) show that with the increment in sliding velocity, specific wear rate increases for a
given value of normal load as the increase in track diameter leads to increment of sliding velocity and sliding distance. Figure 3 (a)-(c) indicate the role of sliding medium on specific wear rate of the material. Specific wear rate in dry environment condition is greater than oil environment condition. Since all the other factors remained the same and weight loss (or mass loss) is lower in case of oil lubricating condition, so is the value of specific wear rate.

3.3. Coefficient of Friction
Tribological behavior includes both wear and friction behavior. Weight loss and specific wear rate indicates the wear characteristics while coefficient of friction indicates the friction behavior of the material. Figure 4(a), 4(b) and 4(c) show coefficient of friction for different values of normal load at given sliding velocity. The value of coefficient of friction so used was the mean value of coefficient of friction obtained for the whole duration of experiment (for each set of parameters). It may be observed that with the increment in normal load, coefficient of friction increase. Coefficient of friction may increase if ploughing effect due to wear debris is encountered. Also, increase in normal load results in higher wear due to thermal softening and exposure of new contact surface which increases the coefficient of friction. However, coefficient of friction may also decrease as exposed carbon fibers leads to reduced coefficient of friction. In this study, it was observed that coefficient of friction increased with the increment in normal load. This may be because factors causing increment in coefficient of friction were dominant as compared to other factors causing reduction in coefficient of friction. Coefficient of friction for dry sliding condition is greater as compared to that for oil lubricated condition. Oil lubrication forms a tribo-film between the sliding surfaces, thereby reducing the interaction of uneven surfaces and hence the value of coefficient of friction.
3.4. Microscopic Analysis

Figure 5, 6 and 7 show the microstructure of the tested surface for the sliding velocity 3.29 m/s at different normal loads tested under dry and oil lubricated condition at 500 x magnification.

Figure 5 (b) shows least surface damage as compared to that of remaining surfaces. Figure 5-7 show that in part (a) the surface damage is significantly higher than that in part (b) because of the medium used. Figure 5 shows damage only at the surface. Figure 6 shows surface damage along with the exposed fibers indicating the degree of wear which leads to matrix-fiber debonding at some spots. Figure 7 shows the fiber fracture along the higher degree of surface cracks.

Figure 5: FESEM images of specimen surface for 5 kgf normal load under (a) dry sliding condition; (b) oil lubricated condition
Figure 6: FESEM images of specimen surface for 10 kgf normal load under (a) dry sliding condition; (b) oil lubricated condition

Figure 7: FESEM images of specimen surface for 15 kgf normal load under (a) dry sliding condition; (b) oil lubricated condition

4. Conclusion

Conclusion of this study may be summed into following points:

a) Wear and friction behavior of CFRP composites doped with 3 wt. % of MWCNTs depends on factors like normal load, sliding velocity, sliding distance, and sliding environment.

b) As the normal load increases, weight loss, specific wear rate increases while coefficient of friction may or may not increase for a given value of sliding velocity and given sliding environment.

c) Increment in sliding velocity increases the weight loss, specific wear rate and coefficient of friction for a given value of normal load and given sliding environment.

d) Weight loss, specific wear rate and coefficient of friction was always observed to be lower in case of oil lubricated condition as compared to that with dry sliding condition, keeping rest all the parameters constant.
References

[1] De Baets P, Glavatskikh S, Ost W and Sukumaran J 2014 Polymers in tribology: challenges and opportunities In: 1st International conference on polymer tribology University of ljubljana.

[2] El-Tayeb N S M and Yousif B F 2005 Wear and friction behavior of CGRP and WGRP composites subjected to dry sliding In: Proc. of WTC 2005 world tribology congress III (Washington, DC, USA) Paper no. WTC 2005-63097.

[3] Bahadur S and Zheng Y 1990 Mechanical and tribological behavior of polyester reinforced with short glass fibers Wear 137 (2) 251–66.

[4] Pihitili H and Tosun N 2002 Effect of load and speed on the wear behavior of woven glass fabrics and aramid fiber reinforced composites Wear 252 979–84.

[5] Pihitili H and Tosun N 2002 Investigation of the wear behavior of a glass fiber reinforced composite and polyester resin Compos. Sci. Technol. 62 367–70.

[6] Bahadur S 2000 The development of transfer layers and their role in polymer tribology Wear 245 92–9.

[7] Suh N. Tribophysics. Englewood Cliffs, New Jersey: Prentice-Hall, 1986.

[8] Rohini D G and Rama R K 1993 Carbon–carbon composites—an overview Def. Sci. J. 43 (4) 369–83.

[9] Ruppe JP 1980 Today and the future in aircraft wheel and brake development Can. Aeronaut. Space J. 26 209–15.

[10] Awasthi S and Wood J L 1998 Adv. Ceram. Mater. 3 449–56.

[11] Gao S L, Mader E and Zhandarov S F 2004 Carbon fibers and composites with epoxy resins: topography, fractography and interphases Carbon 42 515–29.

[12] Kishore, Sampathkumar P, Seetharamu S, Vynatheya S, Murali A and Kumar R K 2000 SEM observations of the effects of velocity and load on the sliding wear characteristics of glass fabric–epoxy composites with different fillers Wear 237 20–7.

[13] El-Tayep N S and Gadelrap RM 1996 Friction and wear properties of E-glass fiber reinforced epoxy composites under different sliding contact conditions Wear 192 112–7.

[14] Findik F 2014 Latest progress on tribological properties of industrial materials Mater. Des. 57 218–44.

[15] Kukureka S N, Hooke C J, Rao M, Liao P and Chen YK 1999 The effect of fiber reinforcement on the friction and wear of polyamide 66 under dry rolling–sliding contact Tribol. Int. 32 107–16.

[16] Srivastava V K and Pathak J P 1996 Friction and wear properties of bushing bearing of graphite filled short glass fiber composite in dry sliding Wear 197 145–50.

[17] Zhou S, Zhang Q, Wu C and Huang J 2013 Effect of carbon fiber reinforcement on the mechanical and tribological properties of polyamide/polyphenylene sulfide composites Mater. Des. 44 493-9.

[18] Aderikha V N and Shapovalov V A 2011 Mechanical and tribological behavior of PTFE polyoxadiazole fiber composites. Effect of filler treatment Wear 271(S) 970-6.

[19] Karšli N G, Demirkol S and Yilmaz T 2016 Thermal aging and reinforcement type effects on the tribological, thermal, thermomechanical, physical and morphological properties of poly (ether ketone) composites Composites Part B 88 253-63.

[20] Agrawal S, Singh K K and Sarkar P K 2016 A comparative study of wear and friction characteristics of glass fiber reinforced epoxy resin, sliding under dry, oil lubricated and inert gas environments Tribol. Int. 96 217-24.

[21] Omrani E, Barari B, Moghadam A D, Rohatgi P K and Pillai K M 2015 Mechanical and tribological properties of self-lubricating bio-based carbon-fabric epoxy composites made using liquid composite molding Tribol. Int. 92 222-32.
[22] Bahadur S 2000 The development of transfer layers and their role in polymer tribology Wear 245 92–9.
[23] Ye J, Khare H S and Burris D L 2013 Transfer film evolution and its role in promoting ultra-low wear of a PTFE nanocomposite Wear 297 1095–102.
[24] Xue Q J and Wang Q H 1997 Wear mechanisms of polyetheretherketone composites filled with various kinds of SiC Wear 213 54–8.
[25] Kang I, Heung Y Y, Kim J H, et al. 2006 Introduction to carbon nanotube and nanofiber smart materials Composites Part B 37 (6) 382-94.
[26] Salvetat J P, Bonard J M, Thomson N H, Kulik A J, Forro L, Benoit W, et al. 1999 Mechanical properties of carbon nanotubes Appl. Phys. A 69 (3) 255-60.
[27] Iijima S, Brabec C, Maiti A and Bernholc J 1996 Structural flexibility of carbon nanotubes J. Chem. Phys. 104 (5) 2089-92.
[28] Burris D L and Sawyer W 2005 Tribological sensitivity of PTFE/alumina nanocomposites to a range of traditional surface finishes Tribol. Trans. 48 147–53.
[29] Wang Q, Xue Q, Shen W and Zhang J 1998 The friction and wear properties of nanometer ZrO2-filled polyetheretherketone J. Appl. Polym. Sci. 69 135–41.
[30] Bahadur S and Sunkara C 2005 Effect of transfer film structure, composition and bonding on the tribological behavior of polyphenylene sulfide filled with nano particles of TiO2, ZnO, CuO and SiC Wear 258 1411–21.
[31] Sawyer W G, Argibay N, Burris D L and Krick B A 2014 Mechanistic studies in friction and wear of bulk materials. Annu. Rev. Mater. Res. 44 395-427.
[32] Jain A, Rawat P and Singh K K 2018 Wear and Frictional Behavior of Three Phased Glass/Epoxy Composite Laminate Reinforced With MWCNTs Mater. Today: Proc. 5 8112–20.
[33] Schadler L S, Giannaris S C and Ajayan P M 1998 Appl. Phy. Lett. 73 3842-4.