Abrasive Size and Fiber Direction Effects on the Wear Behaviour of CFRP Composite under Rotary Abrasion

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Abstract. Rotary wear tests were performed on unidirectional graphite fiber reinforced epoxy to study the effect of fiber orientation and abrasive particle size on the wear resistance and mechanism of the graphite/epoxy polymer composite. The tests were performed at a constant load of 1250 grams for 10000 cycles with abrasive particle sizes of 15 and 55 μm using Taber rotary platform abrasion tester. The surface topology and material removed along the wear track were obtained for a range of fiber orientations. The surface roughness was found to decrease as the fiber orientation increased from 0° to 90°. Negative skewness indicated the presence of numerous valleys on the surface. These variations in the surface roughness parameters were more pronounced for higher particle size of 55 μm. Maximum wear occurred at 135°. Further, the wear mechanism and type of damage were identified through SEM micrographs. Distinct damage could be identified at 0°, 45° and 90°.

1. Introduction
The innovations in the development of polymer composites has allowed its extensive application in the aerospace and automobile industries. These composites have tailorable properties with high strength to weight ratio, excellent fatigue and corrosion resistance in comparison to metal alloys[1,2]. Additionally, when polymer composites are being used in sliding wear applications, such as, ball joints in the car chassis, the wear performance should be thoroughly characterized [3]. Although the wear resistance of polymer composites have been studied extensively as a function of volume fraction of the fiber, type of fiber and matrix material[4–6], only a few studies have reported the effect of fiber orientation[7,8]. A thorough knowledge of wear behaviour of polymer composites is critical to further extend its use to other applications. The degree of abrasiveness of the fibers, thermal stability, thermal conductivity of the matrix and coefficient of friction play an important role in characterizing the wear behaviour[9]. Polymer composites reinforced with short fibers such as carbon and glass fibers were reported to significantly improve the wear resistance. The abrasive wear debris from the carbon fiber was observed to have smoothening effect on the roughness of the counterface. The thermoset and thermoplastic polymer matrices have distinct modes of failure, thermoset polymers do not soften due to frictional heat and the generated heat induces chemical degradation and wear on the surface. These polymer composites do not yield due to softening and catastrophic failure[10]. Solid lubricants are added to these matrices to form a transfer film between contacting surfaces to prevent the chemical degradation. Specifically, for epoxy matrix the addition of graphene resulted in good wear life and lower value of coefficient of friction. Owing to the anisotropic behavior of composites with continuous fiber, a few studies have reported the wear behavior as a function of fiber orientation[7,8]. The sliding wear test was performed in
directions normal, anti-parallel(90 degrees) and parallel(0 degrees) to the fibers. The wear rate was reported to be the lowest in the normal direction and inconclusive between the parallel and anti-parallel directions. This warrants for additional investigation to identify the wear rate at a range of fiber contact angles. This study investigates the wear rate of unidirectional graphite/epoxy laminate with 0 to 180° fiber orientations. This is accomplished using Taber rotary abrader under a constant load of 1250 grams for an abrasive particle size of 55 and 15 μm. As the platform rotates, the fiber contact angle changes from 0 to 180 degrees. The depth of material removed, surface roughness was studied for a range of fiber orientations. Additionally, the wear mechanism was identified through the SEM analysis of the wear tracks.

2. Materials and Experiment methods
The material used in this study was a graphite/epoxy unidirectional laminate with 55% fiber volume fraction, IM-6 graphite fibers embedded in 3501-6 epoxy resin. Unidirectional specimen of 100mm x 100mm x 2mm were fabricated using diamond saw from a panel of dimension, 1m x 0.5m x 0.002m. Specimen were tested on Taber rotary platform abrasion tester, shown in Figure 1 a at 72 rpm under a constant load of 1250 grams for 10000 cycles and the wear debri was removed continuously through suction. The experiments were performed according to ASTM D4060.

Sand paper strips with an average particle size of 15 and 55 microns were used as the counter face on the Tabor wheel. Since counterface plays a dominant role in determining the wear, the sand paper was replaced every 500 cycles to minimize the variations arising from blunting of the sharp edges. As the abrader completes one full rotation, the abrasive particles encounter fibers oriented from 0 through 180. For the all the experiments the abrasive wheel was positioned at 0 degree fiber orientation at the beginning of the wear test. Surface roughness measurements were performed using Mahr surface profilometer and Keyence VR300. The 2D surface roughness was quantified maximum peak to valley height roughness, Rt, and ten point average roughness, Rz, and maximum profile valley depth, z over a profile length L are defined by equations 1 through 2,

\[
R_t = | \max(z) - \min(z) | \tag{1}
\]

\[
R_z = \frac{1}{5} \left[ \sum_{i=1}^{5} \max(z_i) + \sum_{i=1}^{5} \min(z_i) \right] \tag{2}
\]

The 3D area height parameters, SαZ and SxZ, were defined by equations 3 and 4,

\[
S_α = \frac{1}{A} \left( \iint |Z(x, y)| \, dxdy \right) \tag{3}
\]

\[
S_z = S_p + S_v \tag{4}
\]

Where, Z(x, y) is the profile height as a function of x and y and, Sp is the largest peak height, and Sv is the deepest valley depth.

Wear resistance was assessed by the depth of material removed for a range of fiber orientations. The average depth was calculated by measuring the concave volume of material removed over a specific area using Keyence VR300. Additionally, scanning electron microscopy was utilized to evaluate the microscopic behavior of fibers and matrix along the wear track.
Figure 1. a) Experiment set up, Polymer composite mounted on the Taber rotary platform abrasion tester, b) specimen showing wear track with 15 μm abrader after 1000 cycles, c) specimen showing wear track with 55 μm abrader after 10000 cycles.

3. Results and Discussion

With the progression of the rotary wear test, the next ply was visible at certain fiber orientations, shown in Figure 1 b and c. Clearly indicating that the wear rate is dependent on the fiber orientations and particle size. Further, it was discernible that the surface profiles varied with the fiber orientation, shown in Figure 2. The filtered surface profiles showed the presence of deep valleys for 55 μm and appeared smoother for 15 μm abrasive particles. Additionally, the surfaces showed a higher deviation from the nominal surface at 0° and 45° in comparison to 90°. The average surface roughness parameters with standard deviations are plotted in Figure 2 d and e. For 55 μm, the $R_z$ was found to decrease from 6.2 to 4.4 μm and $R_t$ decreased from 7.6 to 5.3 μm from 0° to 90°. Although similar trends were observed for 15 μm abrasive particle size, the variations were more pronounced for higher particle size. Similarly, the skewness and kurtosis of the wear track were analysed to study the asymmetric spread of peaks and valleys on the surface. The skewness was found to be negative for all the fiber orientations owing to the presence multitude valleys on the surface, shown in Figure 2 e, the features below the nominal surface are shown in blue. In tribology, negatively skewed surface is considered good for lubrication owing the valleys trapping the lubricants. The presence of valleys on the surface can be attributed to the epoxy eroding at a higher rate and increasing the interfacial gap between the fibers. Further affirmed through the observation of area surface profiles, Figure 3, with the red peaks aligned along the fiber direction and the blue valleys dispersed around the peaks. The skewness values were found to be more negative at lower particle size, this can be attributed to the higher density of particles randomly oriented on the abrader resulting in higher number of valleys in comparison to higher particle size. Similarly, kurtosis of surface profile is a measure of the sharpness of peaks. The kurtosis was observed to increase with the skewness, indicating that the material was removed by the action of random abrasive particles. The increase in kurtosis indicated the presence of sharper peaks for 15 μm particle size. Further, the volume of material removed over a specific area was measured to calculate the depth of material removed. The variations in the amount of material removed as a function of fiber direction is shown in Figure 3 a. The variations in the depth were observed to be more pronounced, as expected for higher particle size. For 55 μm, the erosion was found to maximize at 45 and 135°, with a maximum of 180 μm at 135°. However, at 0 and 90° the amount of material removed was observed to be the same, concurring with the observations made by [7]. While, for 15 μm, the maximum difference in depth was found to be within 10 μm. The wear mechanism was investigated to understand the differences in the amount of material removed along the wear track.
Figure 2. 2D surface roughness, a) Profiles of the wear track along the radial direction after 10000 cycles at, a) 0°, b) 50°, c) 90°, d) $R_s$, $R_z$ as a function of fiber orientation, e) skewness vs kurtosis for 55 μm and 15 μm particles.
Figure 3. Area profiles at a) 0°, b) 45°, c) 90°, average $S_a$ and $S_z$ values are given on the top right, d) depth of material removed as a function of fiber orientation.

The SEM micrographs of the wear tracks showed broken fibers and epoxy debris dispersed along the wear track. Upon observation of damages to the fibers and the matrix, distinct wear mechanisms can be identified at different fiber orientations. Figure 4 a and b show the wear track created by 55 μm abrasive particles at 0°. Extensive fiber crushing, region A and fiber pull out, point B were found along the wear track. When the abrasive particles impinge along the fiber direction, the fibers may buckle and fracture, shown in region C. In addition, the epoxy matrix appeared to have failed by brittle fracture.
Figure 4. Wear track with 55 microns abrasive particles at fiber orientations of a, b) 0°, c, d) 45°, e, f) 90°.

Figure 4 c and d show the wear track at 45°. At this orientation, fiber cutting was observed to be dominant, shown in region D. Micro-cutting of fibers leads to the highest amount of wear in polymer composites and could be attributed to observing high wear at this angle. Large chunks of fibers are removed in addition to matrix cracking and fracture, contributing to the increased wear rate and visibility of the next ply in the region. At 90°, when the abrasive particles impinge normal to the fibers, a bending load is imparted to the fibers. In addition, the repeated impact resulted in the formation of microcracks, region E along the circumference of the fibers. The microfatigue resulted in crack growth and fiber fracture, region F.

4. Conclusion
The effect of fiber orientation on the wear resistance and mechanism was investigated in this study. The variation in surface profiles of the wear tracks were quantified in terms of roughness parameters,

- The $R_z$ and $R_t$ were found to decrease as the fiber contact angle increased from 0° to 90°.
- A multitude of valleys were observed on the surface resulting in negative skewness of the surface. The skewness and kurtosis was found to increase with the decreasing particle size. This can be attributed to the higher density of particles on the surface.
- For 55 μm, the depth was found to maximize at 45 and 135°, with a maximum of 180 μm at 135°. A significant difference in the amount of material removed could not be observed between 0 and 90°.
- Distinct wear scars could be identified at 0°, 45° and 90°. Extensive fiber and matrix crushing was observed at 0°. While, microcutting of fibers was the dominant mechanism at 45°. Owing to the bending load on the fibers at 90°, fiber bending and fracture were observed to be dominant.
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6. Reference
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