A STUDY OF THE COEFFICIENT OF FRICTION AND WEAR OF UNIDIRECTIONAL AND WOVEN CARBON FIBER/EPOXY COMPOSITE IN SEVERE ABRASIVE CONDITIONS

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Summary: *In this study, the friction and wear behaviour of unidirectional and woven carbon fiber/epoxy composites was both measured and modelled. It was found that under severe abrasive conditions, unidirectional fiber composites with fibers parallel to the sliding direction were more wear resistant and had lower coefficients of friction than composites with fibers transverse to the sliding direction. The wear mechanisms of the two orientations were found to be markedly different when the wear surfaces and debris were analyzed using SEM and optical microscopy. Furthermore, two models are proposed for predicting the specific wear rates and coefficients of friction of woven composites based on the wear properties of the unidirectional composites.*

1. INTRODUCTION

Fiber reinforced polymer composites are replacing metals in many high-stress applications due to their favourable properties. They often have higher specific strength and stiffness, as well as good chemical and thermal resistance under many operating conditions. In some applications however, composite materials are subjected to wear. These applications include conveyor aids, vanes, gears, bushes, seals and bearings, pumps handling industrial fluids/slurries containing abrasives, sewage, earth moving, and mining. While there have been many studies of the friction and wear properties of fiber reinforced polymer composites [1,2,3,4,5,6,7], few studies have examined the wear process of unidirectional or woven fiber reinforced polymer composites under severe abrasive wear situations.

Severe abrasive wear occurs when composite materials come into sliding contact with a rough surface, such as asphalt. In this study, the friction and wear behaviour of unidirectional composites were observed under various severe abrasive wear conditions and the results are reported. Furthermore, models for predicting the coefficient of friction and specific wear rate of woven carbon fiber composites are presented.

2. EXPERIMENTAL METHODS

2.1 Sample Preparation

Laminate panels were fabricated by manually laying up woven and unidirectional prepregs and were cured to a thickness of approximately 2.5mm. Three different types of prepregs were used in this study: Unidirectional (UD), plain woven (PW). The epoxy resin was a proprietary formula provided by Barrday Advanced Material Solutions.

The prepregs were cured by vacuum bagging while being pressed with an external pressure of 0.25MPa and a temperature of 130°C in a hydraulic press for 90 minutes. The cured panels were allowed to cool to room temperature and specimens with the dimensions of 25.4mm x 25.4mm were cut from the laminate panels.

2.2 Wear Testing

Wear testing was done in order to measure the friction coefficient and specific wear rate of the different types of composites in various wear conditions. Unidirectional composites were tested with the fibers parallel to the sliding direction (UDp) and with the fibers transverse to the sliding direction (UDap). Woven composites were tested with the warp fibers parallel to the sliding direction.

The wear testing apparatus was a modified linear belt sander fitted with a variable speed motor. A double cantilever beam apparatus was used to keep the specimen parallel to the sanding belt, and the specimen was loaded with a weight. A load cell and a potentiometer were installed to monitor and record the friction force and specimen thickness at 10Hz. Specimens were tested with two sliding speeds (2 and 4m/s), three normal pressures (8, 16, and 34kPa), and three sandpaper grits (120, 80, and 36). More details are provided in [8].

The specimens were weighed before and after the wear process and the specific wear rate was calculated according to the following equation:

$$W_R = \frac{\Delta m}{\rho l d}$$

Where, W_R (m^3/N.m) is the specific wear rate, Δm (kg) is the loss of mass of the specimen due to wear, ρ (kg/m^3) is the density of the specimen, l (N) is the applied normal load, and d (m) is the sliding distance. The average friction coefficient was calculated from the load cell data using the following formula:

$$\mu = \frac{F_{avg}}{L}$$

Where F_{avg} is the average frictional force recorded during the wear tests. Five specimens were tested for each group and the average is reported.

3. FRICTION AND WEAR OF UNIDIRECTIONAL COMPOSITES

In general, the coefficient of friction was found to be higher when the composite panels were abraded on coarser sandpapers. However, when using a 22N applied load, the coefficient of

friction remained constant even when the sandpaper roughness was increased from 80 grit to 36 grit. The specific wear rates of the composites were found to respond to roughness in a similar manner.

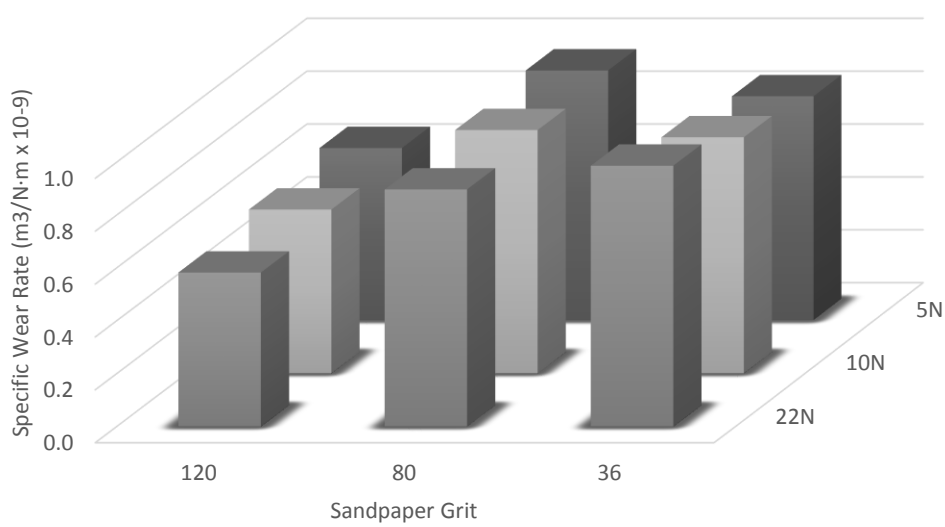
The coefficient of friction was found to decrease when normal load increased. However, the specific wear rate of the composites remained relatively constant regardless of the normal load.

Finally, when comparing the coefficient of friction and specific wear rate of the composites with different fiber orientations, UDp composites were found to have a lower friction coefficient, and a significantly lower specific wear rate compared to UDap composites.

From an energy standpoint, the specific wear rate and the coefficient of friction are related by the following relationship:

$$\kappa = \frac{\mu}{E_v}$$

Where, E_v (J/m^3) is the energy required to remove a volume of material. In this equation, the coefficient of friction (J/N·m) is a measurement of amount of energy that is absorbed by the material through mechanisms such as cracking, delamination, and wear. However, it was observed that the UDap panels had almost double the specific wear rate of the UDp panels, but with only a slightly higher coefficient of friction. This observation suggested that the wear mechanisms of UDp and UDap panels were markedly different and the energy required to remove material from the UDp panels was much higher.



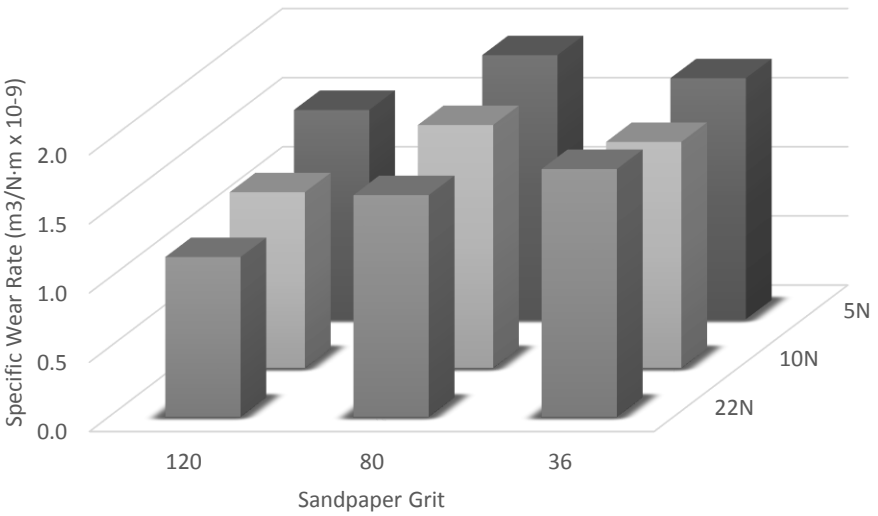
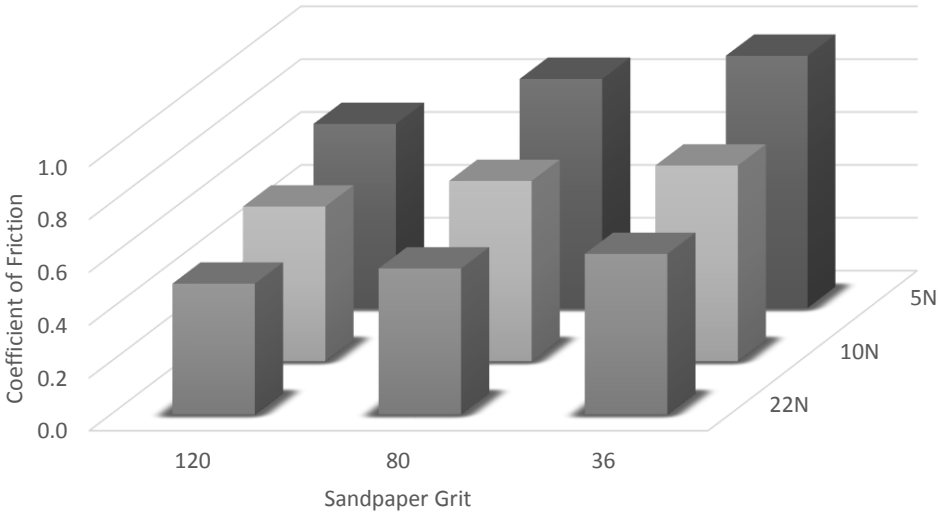


Figure 1: Specific wear rate of unidirectional composites. Top: UDp, Bottom: UDap. (Sliding speed = 2m/s)



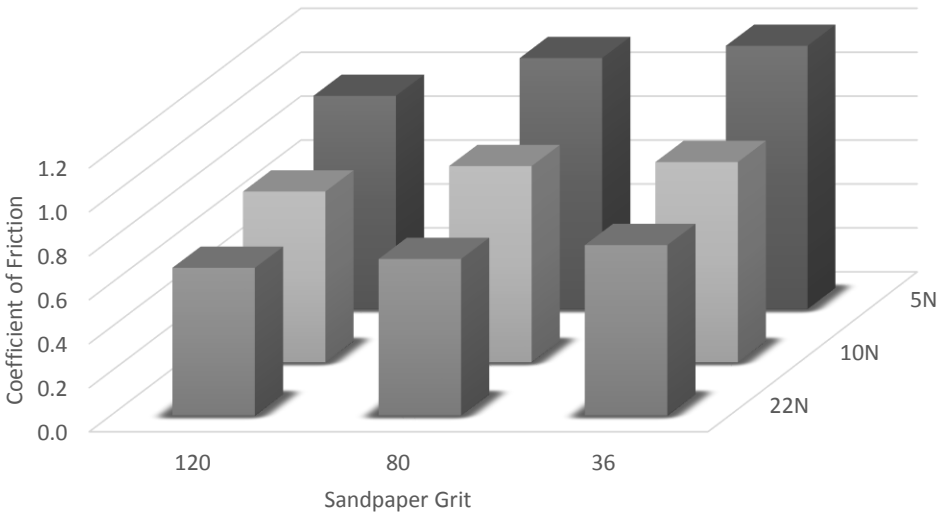


Figure 2: Coefficient of friction of unidirectional composites. Top: UDp, Bottom: UDap. (Sliding speed = 2m/s)

By analyzing the wear surface of the panels using scanning electron microscopy and wear debris using optical microscopy (Figure 3), it was found that the two types of panels had quite different dominant wear mechanisms. The SEM micrograph of the UDp panel showed that wear predominantly involved a fiber thinning process [9] before fibers were delaminated and removed from the panels. Although the fiber debris particles were found to be long, they were only a few fibers thick. In the case of the UDap panels, the wear surface was found to have many defined deep grooves. This ploughing mechanism was responsible for the higher coefficient of friction of the UDap composites as it consumes more energy compared to the fibre thinning observed in the UDp panels. Furthermore, the wear particle removed from the UDap samples were bulkier and thicker, which resulted in higher wear rate.

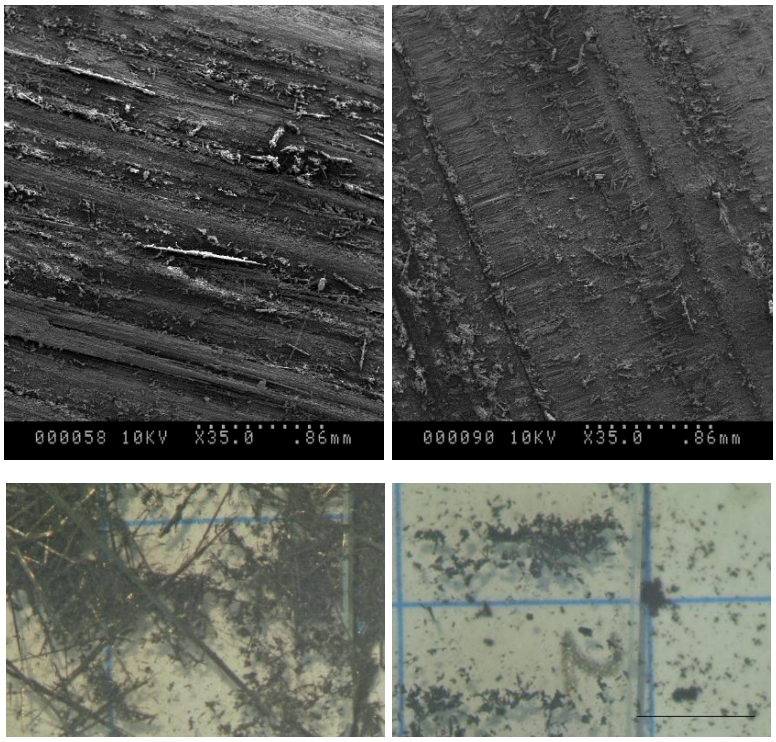


Figure 3: SEM images and optical images of the worn surfaces and debris of unidirectional composites (36 grit, 22N, 2m/s). Left: UDp, Right: UDap.

4. MODELLING THE SPECIFIC WEAR RATE AND COEFFICIENT OF FRICTION OF WOVEN CARBON FIBER/EPOXY COMPOSITES

In this section, two models are presented for the prediction of the specific wear rate and coefficient of friction of woven carbon fiber/epoxy using the data gathered from unidirectional carbon fiber/epoxy composites as input data.

4.1 Model for Specific Wear Rate

Axen et al. modelled wear of particulate reinforced metals [10], and this model was adapted for woven fiber reinforced epoxy composites by Cheng et al [8]. In single phase materials, wear rate can be defined as follows:

$$\frac{dV}{dS} = \kappa L \tag{1}$$

The left hand side of the equation represents the change in volume per sliding distance. κ is the specific wear rate and L is the load.

The specific wear rate and load relationship for a woven composite can be represented by equation (2).

$$L\kappa = L_{\parallel}\kappa_{\parallel} + L_{\perp}\kappa_{\perp} \tag{2}$$

The ∥ symbol represents the properties of the regions where the fibers run parallel to the sliding distance, while the ⊥ symbol denotes the properties of the regions where the fibers are transverse to the sliding direction.

In heterogeneous materials, two scenarios that are possible. In the first scenario, the two phases are worn at the same fixed rate, and each phase would have the same wear rate as when worn individually for the distributed normal stress it is exposed to (equal wear rate or EW). This would be appropriate if the abrasive surface was both flat and rigid. In the second scenario, both phases would be subjected to the same normal stress during the wear process (equal pressure or EP). This might be appropriate if the abrasive surface was very compliant or a fluid (erosion). In this study, we will focus on the EW model as it is more representative of our system.

If both the composite and the abrasive surface are rigid and flat, then the parallel and antiparallel regions should wear at an equal rate at steady state. Since the wear resistance of the regions are different, the normal load must be distributed such that the more wear resistant regions bear a higher fraction of the normal load. The result is an inverse rule-of-mixtures equation (IROM) for the specific wear rate of a woven composite material in EW mode [8]. The symbol α represents the area fraction of the parallel and antiparallel regions:

$$\frac{1}{\kappa} = \alpha_{\parallel}\frac{1}{\kappa_{\parallel}} + \alpha_{\perp}\frac{1}{\kappa_{\perp}} \tag{3}$$

4.2 Model for Coefficient of Friction

The following derivation by Axen et al. [11] was developed for particulate reinforced metal composites. This has been adapted for woven carbon fiber/epoxy composites in Cheng et al. [12]. Following a derivation similar to the one for the specific wear rate model, the coefficient of friction for woven composites was found to be related to the coefficient of frictions and specific wear rates of the parallel and antiparallel fiber regions by a modified rule-of-mixtures equation:

$$\mu = \mu_{\parallel}\frac{\alpha_{\parallel}\kappa_{\perp}}{\alpha_{\perp}\kappa_{\parallel} + \alpha_{\parallel}\kappa_{\perp}} + \mu_{\perp}\frac{\alpha_{\perp}\kappa_{\parallel}}{\alpha_{\perp}\kappa_{\parallel} + \alpha_{\parallel}\kappa_{\perp}} \tag{4}$$

4.3 Model and Experimental Results Comparison

The model for the specific wear rate for plain woven composites are compared to the experimental results, shown in Figure 4. It was found that the model was quite accurate in most of the conditions, especially when abraded with relatively fine sandpaper. Under these conditions, the more wear resistant parallel fiber zones were protecting the less wear resistant transverse fiber zones as the model predicted. However, the model under-predicted the specific wear rate when testing was done on the coarser 36 grit with 22N of applied load. This is most likely due to the out-of-plane fibers in the woven composites affecting the wear mechanisms, as more of them were exposed when the asperities penetrated deeper into the composite surface.

Out-of-plane fibers at the cross-over points of warp and weft fibers are known to be less wear resistant than in-plane fibers [13], which led to the higher wear rate.

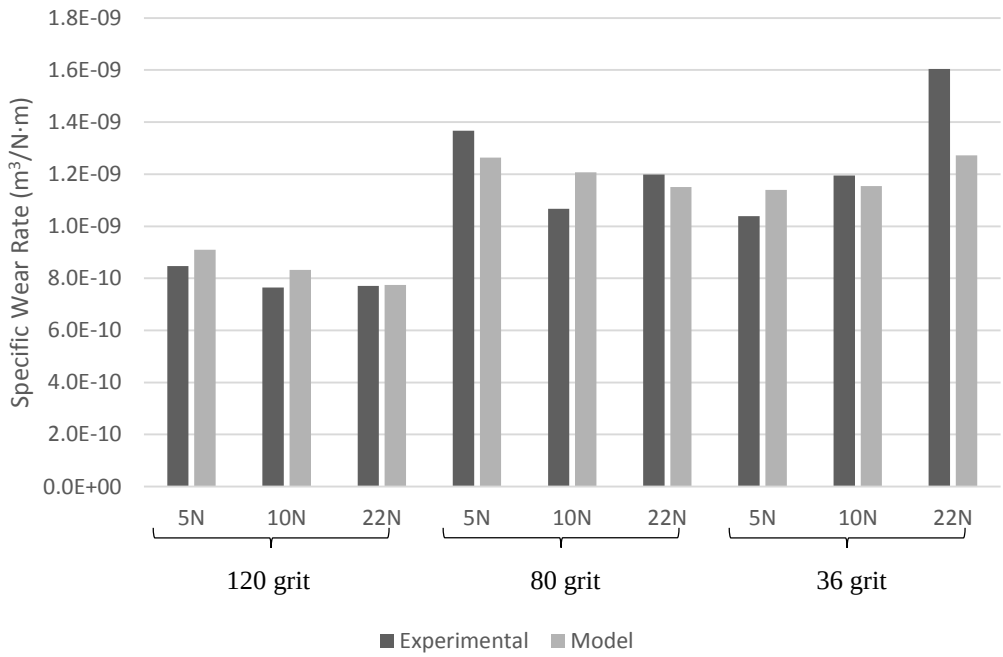


Figure 4: Specific wear rate of plain woven composite compared to model predictions. (Sliding speed = 2m/s)

The model for the coefficient of friction was quite accurate in all of the testing conditions, as shown in Figure 5. This again shows that the more wear resistant parallel fibers were able to protect the less wear resistant transverse fibers in the weave.

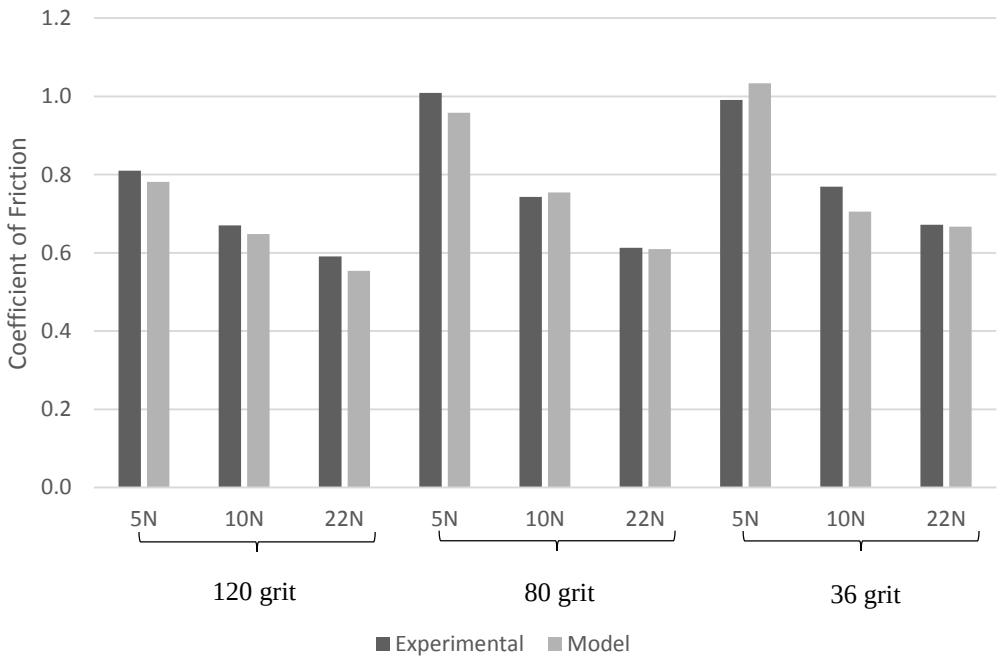


Figure 5: Coefficient of friction of plain woven composite and model predictions. (Sliding speed = 2m/s)

5. CONCLUSIONS

It was found that fiber orientation had a significant effect on both the coefficient of friction and the specific wear rate of unidirectional carbon fiber composites. In all testing conditions, composite panels with fibers parallel to the sliding direction had a slightly lower coefficient of friction and a significantly lower specific wear rate compared to the composites panels with fibers transverse to the sliding direction. SEM and optical microscopy analysis of the wear surface and debris revealed that the wear mechanisms were markedly different for composites with different fiber orientation. Composites with fibers parallel to the sliding direction worn by initially by fiber thinning before large asperities were able to remove individual or small bundles of fibers from the surface. Composites with fibers transverse to the sliding direction worn mostly by microcutting and ploughing. These mechanisms resulted in bulkier wear debris, which led to higher specific wear rate.

Rule-of-mixtures type models for predicting the coefficient of friction and specific wear rate of woven carbon fiber composite were presented. It was assumed that the entire contact surface was worn at the same rate, regardless of the fiber orientation. This implies that the more wear resistant parallel fibers bear a higher fraction of the applied load. It was found that the model for predicting the specific wear rate of woven composites is most accurate on finer sandpaper grit and smaller applied loads. For coarser sandpapers, it seems that the out-of-plane fibers in the weaves negatively affected the wear resistance of the woven composites, which caused the model to under-predict their specific wear rate. The model for predicting the coefficient of friction was found to be reasonably accurate for all wear conditions.

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