Investigation of wear resistance for variable configurations of woven glass-fiber reinforced composite materials

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Abstract
Glass fiber composites are widely used in different engineering applications due to their valuable properties of superior weight and strength compared with metals. The tribological properties of these composites vary significantly with the operational conditions and fiber distribution. In this study three orthogonally aligned and chopped fibers were used to manufacture four types of composites with similar volume fraction. The orthogonal (woven) fibers have three different configurations with different width of warp and weft and different aligning distance. Weight loss under dry contact was examined using a tribometer (ASTM G65) with a flat specimen on a steel ring. This study showed that for the composite with the thinnest warps and wefts, and those with the largest distance between adjacent yarns, Archard wear coefficient was the lowest and this also corresponded the lowest weight or volume loss at all speeds. It was found that toughness can specify the wear resistance more than hardness. Only the composite with chopped glass fiber showed a steady wear rate with sliding speed, while the wear rate for the composite with woven fibers increases with sliding speed. The wear mechanism was mainly by the formation and removal of a brittle layer that appeared as a result of friction heat, and this caused partial cutting and removal of the fibers. The penetration of resin into the woven matrix is more important for higher wear resistance than the density of the yarns in the woven fibers.

1. Introduction

Composite materials made from polymers have been used for a number of different tribological applications in different industries. Their attractive properties are light weight, high strength (with respect to their weight comparing to metals), corrosion resistance, low coefficient of friction without lubrication, and this has made them the material of choice in many engineering applications [1–3].

The composite structures rely mainly on thermoset epoxy resins and adhesives which act as matrix materials for the reinforcements. The advantages of these materials, such as resistance to moisture, ease of fabrication, limited shrinkage, and high strength compared with their weight, has led to applications in aerospace, marine, automotive sectors, and Prosthetic Limbs [4–8].

The reinforcement of polymers with fibers improves the mechanical properties, in proportion to the percentage of reinforcing material, as shown in previous studies, such as [1, 9–12]. However, the variation of wear resistance and tribological properties of composite materials may be more complicated, and they are strongly influenced by the operating conditions of the different applications [1, 13, 14].

The form of contact between parts made of polymers or composite materials varies depending on different engineering structures. Investigating the failure by wear for these parts under a variety of operation conditions enriches the knowledge on the behaviour of these materials and provides information keys for the design of improved manufacturing processes and materials.

Previous studies in this field have investigated various composite materials made of different reinforcements, matrix, and fillers. The most widely used reinforcements are glass fiber which is woven or
randomly distributed to form a fabric-like texture that can be used to produce different composite structures. Other reinforcements have been used with material properties that meet the needs of different applications. Some of these materials are listed below:

(i) Chopped glass-fiber-reinforced composite and polyester [1];
(ii) Woven glass fabrics and aramid fibers in polyester or epoxy resin [15];
(iii) Woven E-glass woven fabric in vinyl ester matrix [12];
(iv) Woven carbon fiber reinforced polymer [16];
(v) Woven satin-weave hybrid PTFE (Polytetrafluoroethylene)/Nomex fabric in phenolic resin filled with graphite, graphene, and graphene oxide [17];
(vi) Woven carbon fiber treated with a silane coupling agent in an epoxy resin matrix.

The mass or volume fraction of fiber in the composite matrixes varies according to the required properties and the manufacturing technique. Irrespective of whether the fiber configuration was chopped or woven, a number of studies investigated fiber reinforced composite with volume or mass fraction around 30% [1, 15, 18]; and other studies considered a higher fraction of up to 60% [15, 17, 19, 20].

The tests normally provide information on the wear resistance or the failure mechanisms under different conditions, with the aim of identifying the optimum conditions for the use of these materials. Although rubbing and measurements of the relative motion between two bodies are the main techniques used in standardized tribometer machines, the variation in the operation parameters and testing media provide indirect information for addressing a range of lines of research. For example, some test configurations provide information on the effect of dry contact between metallic surface with the composite surface under conditions of repeated fatigue cycles and accumulated frictional heating. Other test configurations may expose the surface of the composite to scratching by hard particles, such as in three-body abrasive ASTM D-638 rubber wheel and sand particles. Accordingly, the same composite may show different wear resistance under different testing configurations due to different wear mechanisms. The standard testing machines that are in widespread used can be listed as block-on-shaft, pin-on-disc, three-body abrasive with rubber wheel, three-body abrasive with steel drum wheel, and two-body abrasive of a rotating cylindrical drum device with abrasive cloth [1, 12, 15–21]. In most these tribometers the testing parameters are speed, load, and sliding distance. Also the testing for different machine configurations can be in dry contact, wet contact using water or lubricant, or three body contact using solid abrasive particles such as silica. Varies surface examination techniques such as Scanning Electron Microscopy (SEM), x-ray diffraction (XRD) and Energy-dispersive x-ray spectroscopy (EDS), which had been used in previous studies, can be used to analyze the wear mechanism [22, 23]. These images are then analysed and compared in order to identify the failure of the composite in general or more specifically the fibers and the bonding matrix. The findings of previous studies showed that the wear rate may be affected by different variables such as the testing parameters, the reinforcement materials, the volume or mass fraction of the reinforcement materials, and additives (fillers) to improve the adhesion. For example Pihtili and Tosun [1] investigated the wear of two types of specimens: glass-fiber-reinforced composite and polyester. The analysis of the SEM images for the tested specimens reflected higher wear resistance for the glass-fiber-reinforced material over plain polyester. The tests also showed higher effect for the load than the speed with regard to the weight loss arising from an increase in the thickness of the brittle layer breaking off the surface of the specimens. However, the comparison between the effect of two different parameters of load and speed is limited to the range included in the tests and the performance may change for a wider range of these parameters. Accordingly, a more practical comparison would be made by choosing different values of the same parameter under controlled conditions for the other parameters.

Another study from Pihtili and Tosun [15] investigated the wear behavior of two woven glass fiber materials and aramid fiber-reinforced composite materials under two speeds, two loads, and different sliding distance using a block-on-shaft wear tester. The study showed that the applied load on the specimens has more effect on the wear than the speed, within the range of load and speed used in the study. Also the weight loss was higher in the composite reinforced with glass fiber of a higher weight per unit area namely woven 500 compared to woven 300. Although this study showed that the wear resistance of the aramid fibers in epoxy matrix is considerably less than the glass fiber in a polyester matrix, this comparison may not be valid due to the use of a different volume fraction of 30% for glass fiber, and 60% for aramid fiber. It is expected that due to the relatively low load and speed used in [15], the wear observed was mostly in the matrix rather than the fibers.

B Suresha, et al [12] investigated the three-body abrasive wear of glass woven fabric reinforced vinyl ester composites where two different fiber fabrics of weight per unit area where used. The wear tests were conducted
under different abrading distances at two loads. The results indicated that the wear volume for both type of composites increases with higher load and sliding distance. The study also found that the higher wear volume occurs in the composite manufactured with fiber fabric of less weight per unit area. Although this may indicate the effect of fiber in reducing wear, it is mentioned in this study that the silane coupling agent was used to improve the interfacial adhesion for the composite of the fiber fabric with higher weight per unit area, which may be the main reason for the lower wear rate. The microscopic examination for the worn surfaces in [12] revealed fiber breaking, cutting, and ploughing for both composites under the testing conditions.

Other studies investigated the effect of different environments on the wear resistance of fiber reinforced composites. Agrawala, et al [16] examined the tribological properties of carbon fiber reinforced polymer using a pin-on-disc tribometer under dry, and lubricated contact. This study, [16], also investigated the effect of an Argon gas environment on the contact between the EN 31 steel disc and the carbon fiber reinforced pin. The study showed a proportional increase in wear and coefficient of friction with increasing load, speed and sliding distance under all the investigated environments. The highest wear and coefficient of friction observed in the Argon environment, and the lowest were in the lubricated environment. The microscopic examination showed fiber damage in the form of micro-cracking and micro-cutting which weakens the bonding between the fiber and the matrix leading to eventual removal from the matrix.

Another study considered the effect of moisture on the abrasive wear rate of a carbon and glass fiber reinforced polyetherimide matrix. The specimens for the three body abrasive tests were of a different moisture content which are represented by dry specimens and moisturised specimens that had been kept in water for 40 days. These tests resulted in a higher wear rate for moisturised specimens than dry specimens, with a higher effect on the carbon fiber composite. Based on the microscopic examination, it is expected that the heat generated during the test had softened the polyetherimide matrix which is then followed by microcracks and void generation. Also, in the carbon fiber composite, a separation between the matrix and fibers was observed, as well as cracks and plastic deformation in the matrix.

In the current study, the aim was to investigate the effect of different glass fiber configurations, with same volume fraction, on the wear resistance of a glass fiber reinforced polyester matrix. In addition to using three different woven glass fiber fabrics, chopped fibers were also used in order to study the effect of a random fiber distribution. Although variable sliding speed was investigated in the literature, the speed was mostly compounded with another variable or compared with the effect of another variable, such as load, which does not reveal the pure effect of this variable. To circumvent this in the current study, the effect of a wider range of sliding speeds was investigated under conditions in which all the operating parameters of load and sliding distance, manufacturing procedure, and fiber volume fraction could be fixed.

2. Material and specimen preparation

Four types of glass fiber are used as a reinforcement phase, three of these are an orthotropic glass fiber in the form of woven fabric, and the fourth one is an isotropic (chopped strand mat) glass fiber. The configuration of these fibers, namely Woven I, Woven II, and Woven III can be seen in figure 1. The fibers can be characterized by the width (w) of the warp and weft as well as the distance (d) between adjacent warps or wefts. For Woven I, w = 2.7 mm and d = 0.8 mm, Woven II, w = 0.4 mm and d = 2.5 mm, and Woven III, w = 0.6 mm and d = 0 mm.

Polyester resin is used as the matrix phase for the composite material of the specimen. A volume fraction of 50% is used to mould the composite specimen for the conducted tests.

The mould used in the experimental work consists of two pieces of rectangular glass. The glass fiber composite was manufactured in the form of plates with dimensions of 30 × 30 × 4 cm using a glass mould in a
hand layup process. These plates are cut to smaller flat pieces of $27 \times 40 \times 4$ mm to be used as the specimens in the testing machine.

The surface of the mould was cleaned first with acetone and then coated with wax. The main purpose of the wax is to enable extraction of the composite specimen from the mould. In order to prepare the composite specimen, an amount of resin is spread uniformly over the mould by means of a brush, then the first layer of mat is laid. The resin is spread uniformly over the first layer using a brush, before the second layer of mat is laid and a steel roller is rolled over the fabric, to enhance wetting and impregnation and then the second layer of mat is laid. This process is repeated until all fabric layers are in place. The casting operation is done at room temperature for approximately eight hours. The amount of resin and the number of mat layers are decided according to the equal volume of the resin and glass fiber, the volume of the rectangular glass mould, the density of the resin, and the density of each type of glass fiber mat which are shown in table 1. The densities shown in this table were measured using Archimedes’ principles. The EDS analysis for the polyester resin and the fibers are shown in table 2.

### 3. The wear tests

The testing machine (ASTM G65), shown in figure 2, includes a steel disc with hardness considerably higher than that of the tested specimens which ensures the occurrence of wear and deformation within the composite samples. The diameter of this disc is $203.2$ mm and it can be rotated at different speeds. The flat specimens with dimensions of $27 \times 40 \times 4$ mm can be held against the side of the disc to form a ‘block-on-ring’ tribometer as shown in figure 2. The machine is designed to rotate the steel disc at different speeds from 0–400 rpm. The contact pressure between the specimen and the disc can be adjusted by adding weights to the counter lever arm. The test machine is equipped with a pneumatic jack system for disengaging between the contact specimen and wheel automatically after reaching the desired number of cycles.

The sliding distance had been fixed at 425 m, which is equivalent to 665 cycles, for all tests. Since no significant damage had been observed on the specimens for distance less than the chosen value, under a load of 3 kg which was fixed for all tests, this sliding distance was chosen. Many previous studies showed the effect of increasing load on the wear loss; therefore, this factor was not investigated in the current study and it was fixed to 3 kg which is found to be the minimum load to show a considerable wear on the surface for the chosen sliding distance. The tests were conducted at five different rotational speeds ($133, 200, 276, 333, 400$) rpm that cover the range of the allowable speeds in the testing machine. These rotational speeds are equivalent to tangential speeds of ($1.416, 2.125, 2.931, 3.541, 4.25$) m s$^{-1}$ and to the test duration time of ($300, 200, 145, 120, 100$) seconds. Each test was repeated four times in order to minimize errors in finding the average of the wear rate at each speed and for each composite.

### Table 1. Density of glass fiber, polyester resin and composite materials.

| Glass fiber mat     | Composite g cm$^{-3}$ |  
|---------------------|-----------------------|
| Isotropic           | 1.3839 ± 0.0150        |
| Woven I             | 1.4114 ± 0.01396       |
| Woven II            | 1.3073 ± 0.0072        |
| Woven III           | 1.4432 ± 0.0121        |
| Polyester resin     | 1.2619 ± 0.0255 g cm$^{-3}$ |

### Table 2. The EDS analysis for the composite.

| Elements | Norm. wt.% Resin inside wear track | Norm. wt.% Resin outside wear track | Norm. wt.% Glass fiber |
|----------|-----------------------------------|-----------------------------------|------------------------|
| C        | 67.29                             | 78.87                             | 45.15                  |
| O        | 29.56                             | 16.65                             | 42.37                  |
| Si       | 1.52                              | 2.31                              | 3.23                   |
| Na       | 1.21                              | 1.43                              | 2.76                   |
| Ag       | 0.42                              | —                                 | —                      |
| Cl       | —                                 | 0.74                              | —                      |
| Ta       | —                                 | —                                 | 5.68                   |
| Te       | —                                 | —                                 | 0.8                    |
All the specimens were cleaned with compressed air and weighed, using a sensitive digital scale with an accuracy of ±0.001 gram, before and after each test. The specimen was fixed in a holder that had been designed to prevent any sliding during the test.

4. Results and discussions

4.1. Visual analysis of the worn surfaces

The wear scars on the worn surfaces of the examined specimens were large enough to be investigated visually. The visual inspection on the four specimens used for each speed, show similar wear scar features, and a set of specimens is shown in Figure 3 as representative of the observations from all the tests. It can be seen from the images in this figure that the severity of wear—in terms of material removal—varies clearly in Isotropic and Woven II if it is compared with that in Woven I and Woven III. It can also be seen that the effect of speed is different among the four types of composites. The isotropic composite shows slightly higher wear at low speed which is almost the same trend for Woven II except at V5 where fiber breakage can be seen. On the other hand, the severity of wear increases in Woven I and Woven III for increasing rotation speed of the rubbing steel ring.

4.2. Wear mechanism

The main wear mechanism observed was due to the removal of a brittle layer which is formed due to a temperature rise under loading. For Woven III this layer was thick and clearly separated from the fiber texture while no such distinction can be seen in Isotropic and Woven II. The main reason for this is thought to be the formation of a sandwich structure for the composite of dense fibers such as in Woven III. This leads to make the upper layer—at contact with the rubbing surface—consist mainly of the polyester bonding material which forms the brittle layer at high temperature. As the fallen particles of the brittle layer are carried away from the contact zone in the tribometer, no three-body abrasive wear is expected, and the removal of this layer was mainly due to the traction force. The generation and removal of the brittle layer was highly influenced by the sliding speed since the friction induced temperature increases proportionally with it. At high speed, the quick removal of the resin layer leaves the fiber layer exposed to the high shear from the rotating steel disc and causes cuts in the fibers as shown in figure 4 using an optical microscope with high magnification. On the other hand, for the Isotropic composite, the homogenous distribution for the fibers in the resin increases the resistance of the composite to the formation of brittle layers, which is also true for Woven II since the resin is homogenously penetrating the fiber textile which has big distance (d) between adjacent warps or wefts.

As mentioned in the introduction, other studies showed the direct relationship between the wear rate and the sliding speed. However, the current study has investigated a wider range of sliding speed under higher contact pressure and thus higher surface traction. The optical investigation of the worn surface in previous
study, such as [10, 16, 15], showed relatively slight damage of the fibers, with the wear mechanism mainly attributable to the removal of the external matrix layer. In the current study, the depth of wear track and the damage of the fibers observed microscopically, demonstrated that the conducted tests had investigated the wear resistance of the whole composite and the effect of fiber configurations.

Woven II which was tested at 333 rpm was chosen for the SEM examination as a representative for the other tested composites. The higher magnification using SEM provides further details about the interaction between the fiber and the resin matrix as well as the damage features, as shown in figure 5. Despite the separation between the resin and the fibers in Woven II, the size of this separation is much bigger in Woven I and Woven III and can be observed visually or at low magnification using optical microscope. The images in this figure reveals the initiation of the surface damage by microcracks formation which are mainly formed at the interface between the fiber and the matrix and at the edge of the wear track. Figure 6 shows the EDS for the fiber and the resin matrix inside and outside the wear track which show no sign for the counterpart transmission and confirm the occurrence of wear only in the composite material.

4.3. Weight loss results
The weight loss for all the investigated composite materials are shown in figure 7. The volume loss shown in figure 8 was determined from measurements of the density and the weight loss. The examined woven
Figure 4. Observed damage at V5 (a) Isotropic (b) Woven I (c) Woven II (d) Woven III.
composites show the weight and volume loss variation with sliding speed. The Isotropic composite showed a steady wear rate response at all ranges of speed used in the tests with a general trend of higher wear rate with increasing speed. Among the three woven composites, Woven II shows less wear rate, specifically at higher speed.

A second order polynomial could be fitted to the weight and volume loss of the measured data. However, the scatter in the data varies and can be considerable for example in Woven II. This prediction also shows a common weight and volume loss point at a rotation speed around 240 rpm.

4.4. Hardness and toughness

In addition to the wear rate tests, hardness and impact toughness tests were carried out with these materials and the results are shown in figures 9 and 10 respectively. The average of five measurements was taken to find the hardness for each sample. Similarly, four measurements were used to find the average of the impact toughness using unnotched specimen in Charpy impact tester according to ISO 179. Figure 9 shows that Woven III has the highest hardness and interestingly the mass and volume loss for this composite is not the lowest especially at high speed. Furthermore Woven II has the lowest hardness and shows the lowest wear rate compared with the other woven composites. A comparison of figures 8 with 9 shows that there is no clear correlation between the hardness and wear resistance, as had been shown in previous studies such as [18]. Figure 10 indicates that the toughness may be more related to the wear resistance and Woven II shows the highest toughness and a comparatively high wear resistance.

4.5. Wear coefficient

According to the Archard relationship, the wear coefficient $K$, for two materials in relative motion, is related to the wear volume $V$, applied load $F$, sliding distance $S$, and the hardness of the softer material $H$ according to equation (1) [24].
In the current study, the wear coefficient $K$ is calculated as a representation for the wear rate and oppositely wear resistance. Figure 11 shows that Woven II has the lowest wear coefficient at a rotation speed higher than 200 rpm. Also, the wear coefficient of Woven II is less than the Isotropic composite at all speeds, and the $K$ value for these two composites are more steady with speed variation than Woven I and Woven III. Since the load and

$$V = \frac{KFS}{H}$$

Figure 6. EDS for (a) resin inside wear track (b) resin outside wear track (c) glass fiber.

Figure 7. Weight loss for all the composite materials tested under different rotation speed for the rubbing steel ring.
sliding distance were constant in each of the conducted tests, the variation of $K$ reveals the change in hardness under different sliding speeds. This may be due to the increase in contact temperature under different speeds. The values of $K$ are inversely proportional to the toughness of the tested materials specifically at a speed higher than 276 rpm (equivalent to tangential velocity of $2.93 \text{ m s}^{-1}$). This shows that the toughness of the glass fiber composite may be a better indicator for the wear resistance than the hardness in the glass fiber composite materials. Also, the overall average of the wear coefficient at all tested speeds, shown in figure 12, confirms the wear resistance is lowest in Woven II, followed by Isotropic, Woven I, and finally Woven III.

5. Conclusions

This study investigated the wear resistance of four types of glass fiber composites namely Isotropic, Woven I, Woven II, and Woven III. All the woven fibers are orthogonal and the differences are in the width $w$ of the warps and wefts, and the distance $d$ between adjacent warp and weft where $w = 2.7 \text{ mm}$ and $d = 0.8 \text{ mm}$ for Woven I, $w = 0.4 \text{ mm}$ and $d = 2.5 \text{ mm}$ for Woven II, and $w = 0.6 \text{ mm}$ and $d = 0 \text{ mm}$ for Woven III. All the tested composites have the same volume fraction of glass fiber and they were all tested under similar load, sliding distance, and number of cycles. The main conclusions of this study are listed below.
The random distribution of fibers in the composite material shows more stable wear under variable sliding speed comparing with the fibers aligned in 0°–90° (woven fibers).

The variation of the wear rate with speed is in line with previous studies; however, the wider range of speed and load used in the current study shows that the composite having least wear resistance changes with increasing speed.

The Archard wear coefficient may be a better identifier for wear rate and according to the value of this coefficient Woven II has the highest wear resistance at all testing speeds.

The measured toughness of the composite materials may be more related to the wear resistance than the hardness.

According to the Archard law of wear, the sliding speed does not affect the wear volume; however, only the composite manufactured with an isotropic distribution of the glass fiber showed that, whilst all the examined composites manufactured from woven fibers showed a correlation with sliding speed.

Figure 10. Impact toughness for the tested composite materials.

Figure 11. Wear coefficient for all the composite materials tested under different rotating speed for the rubbing steel ring.
The overall average for the wear coefficient at all tested speeds.

- The wear rate and wear mechanism for all the examined composite showed slight difference at low sliding speed and a considerable difference at high sliding speed.
- The main wear mechanism observed was the removal of a brittle resin layer which is formed due to the high friction temperature. Accordingly, dense fibers with least d, such as Woven III, showed a higher wear rate because of the separation, lower penetration, between the resin and the fiber, and thus easier removal of the brittle layer.

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