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Tribological behaviour of unidirectional carbon fibre-reinforced epoxy composites

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Abstract. Tribological behaviour of unidirectional carbon fibre-reinforced epoxy composites containing 42wt.% (CU42) and 52wt.% (CU52) carbon fibres fabricated by moulding technique was investigated on a pin-on-flat plate configuration. It is the first time to measure static and dynamic coefficient of frictions and wear rates of epoxy composites under heavy loading conditions. Microstructures of composites were examined by scanning electron microscopy (SEM). The experimental results indicated the carbon fiber improved the tribological properties of thermoset epoxy by reducing wear rate, but increased the coefficient of friction. At higher load, average wear rates were about 10.8×10⁻⁵ mm³/N.m for composites while it was about 38.20×10⁻⁵ mm³/N.m for epoxy resin. The wear rate decreased with decreasing load while friction coefficient increased with decreasing load. Moreover, friction coefficient of composites of CU42 tested at 90 N load was measured to be in the range 0.35 and 0.13 for static and dynamic component, respectively.

1. Introduction

Fibre-reinforced composites have been used successfully for many decades as engineering applications such as aerospace, automobile, chemical, construction and ship/marine industries and sport equipment due to high specific strength and high modulus, wide varieties of availability and design flexibility as compared to metal based counterparts [1, 2]. The application of carbon fibers as reinforcement in polymer composites has been continuously growing during the last few years. The main advantages of such fibers are their specific strength and specific modulus, excellent thermal stability, simplicity of production, low specific gravity, low coefficient of friction and wear, weight savings and performance [3].

The mechanical properties of polymer based composites are greatly influenced by many factors such as the effect of fiber loading, fiber length, fiber, matrix, fibre diameter, processing, interface between the fibre and matrix and orientation having a significant influence on mechanical behavior of polymer composites [4, 5]. The mechanical properties such as hardness, tensile strength, tensile modulus, ductility are improved as the fibers reinforcement content increase in the polymeric matrix materials [6-11]. Over the last two decades, the investigation on wear and friction characteristics of many types of polymer composites were reported, such as carbon fibre reinforced polyamide polymer composite [12,13,14], carbon fibre epoxy composite [15,16,17], carbon fibre/glass epoxy composite [18-23] and fibre length and particle sizes on epoxy composite [24,25] and nano-size effect [26,27].
Also, influence of parameters such as fibre content, fibre angle, type of resin/fibre, process parameters and, especially fibre orientation on the wear rate is very important [5,28-30]. Thus, the aim of the present work is to study the friction and dry sliding wear behaviour under two fiber contents and different loads at a fixed sliding speed for carbon unidirectional-fibre-reinforced epoxy composites using a pin-on-flat wear tester.

2. Experimental

2.1. Materials

Both unfilled and carbon-reinforced epoxy composites were manufactured by hand lay-up technique. The carbon fibers were used as a reinforcement and the resin used in this work is commercial SR 8500 epoxy resin and hardener is SD 860x supplied by MCTechinic Ltd., Neitherland. The filler materials used in this study is carbon fabrics supplied by MCTechinic Ltd. The carbon plain weave fabrics is 200 g/m² and its diameter is about 7-10 µm. The manufacturing process involves the mixing of the epoxy resin with a hardener at a ratio of 100:28. Then the catalyzed resin mixtures are spatulated on composite panel of 150x150 mm² in size with a thickness of 4.0 mm mold plate. The reinforced of 7 and 10 layers are soaked by the resins. A metal roller is used to compact the laminate so that a uniform thickness could be obtained. A bottom layer and top layer of the laminate was covered by the mold sheets, which were coated with a release agent for easy separation after curing.

The specimens required for adhesive wear studies (5x5x4 mm³) were cut from the laminated composites by using a water jet machining. Three different types of specimens were prepared for this study. The unidirectional carbon fibres used as filler in range of 0 wt.%, 42 wt.% to 52 wt.%, respectively. Hereafter these composites and epoxy were referred as a CU42, CU52 coded number, and EP coded number, respectively. Microstructure of composites was investigated by SEM of their cross-sections mounted in a transparent resin and polished up to 6 µm by diamond paste.

2.2. Friction and wear tests

The experimental apparatus is a pin-on-flat wear-testing machine with a reciprocating motion. A pin specimen is fixed to a reciprocating stage or to a pin specimen holder by setting screws. The pin is then mounted in a steel holder in the wear machine so that it is held firmly perpendicular to that of the flat surface. The normal load is applied through a spring and lever system that pulls down a transverse bridge structure over composite specimen. Friction force is measured with a strain-gauge detector installed on the wear testing machine. The coefficient of static friction is the friction force that exists between two objects when neither of the objects is moving [5]. The coefficient of kinetic friction is the force between two objects when one object is moving, or if two objects are moving against each other. The material loss of testing samples is calculated from weight loss of composites. Carbon fibre reinforced composite (CFRC) is slid in a reciprocating motion against cold rolled steel AISI 42CrMo4 grinded to perpendicular to the sliding direction. The steel counter face is fixed to a base plate sizes of 58 x 38 x 4 mm with an average surface roughness of 0.42 µm perpendicular to the sliding direction. The sliding stroke is 15 mm. Both composite specimens (CU42, CU52) are tested fibres parallel to sliding direction (p-orientation). The total sliding distance is about 2016 m/3024 m. The wear pin is cleaned in acetone prior to and after the wear tests, and then weighed on a microbalance with 0.1 mg sensitiveness. The wear rate is calculated by measuring the mass loss, density and known sliding distance and load. The specific wear rate (Ks) is then expressed on volume loss basis.

During sliding, the mechanical energy is mainly dissipated as heat. This may lead to deterioration of mechanical properties, which turn often decrease of friction and wear performance [31]. This limits the life time of components made from polymer composites. This is especially a problem in applications involving high contact pressure (p) and sliding speed (v) since this results in a high specific wear rate of energy disipation ($Q_d$), i.e. the rate of dissipated energy per unit apparent contact area:

$$Q_d = \mu * p * v$$  \( (J/m^2 \ s) \)  \( (1) \)
It is seen that $Q_d$ is directly proportional to $\mu$ and $pv$ condition. Therefore, for polymer composites tested under heavy conditions, the thermal properties must be improved or frictional heating must be reduced by e.g. applying lubricating resins or fillers, which is the case of this study.

3. Results and discussion

3.1. Microstructure
Figure 1 shows a typical microstructure of unidirectional fibre reinforced epoxy composites, which are included 42 wt.% and 52wt. % carbon fibres under SEM, respectively. This SEM image at lower magnification indicates a cross-sectional of longitudinal fibres and epoxy matrix, but it does not contain any porosity in the structure. Figure 1 (a) shows the SEM of the microstructure for a CU42 composite. The distributions of carbon fibres in the matrix seemed not to be very uniform. Its dimensions are about 7-10 µm. SEM image in Figure 1 (b) indicates that the distributions of fibres in the matrix seemed to be more uniform than that of CU52 fibre-reinforced composites. Its dimensions are the same with the previous one.

![Figure 1](image1.jpg)

**Figure 1.** Cross-sectional view of unidirectional carbon fibre-reinforced epoxy composites taken by SEM. (a) Micrograph of CU42 composite, showing fibre distributions in the microstructure, (b) Micrograph of CU52 composite, indicating a more uniform fibre distributions.

3.2. Coefficient of friction
The normal force and the tangential friction force of pin-on-flat for composites and its polymers against the smooth steel were measured in real time using a load cell. Typical plots of variations in the static and dynamic coefficient of friction as a function of the applied load for CU42 fibre-reinforced composites at a fixed speed are shown in Figure 2. In this figure, the symbols used as CU42-us and CU42-udy indicates the static COF and dynamic COF, respectively. The friction coefficient of the studied epoxy composite/steel tribo-pairs at lower load was measured to be in the range 0.45 and 0.17 for static and dynamic component, respectively. Also, the static and dynamic friction coefficients appeared to vary similarly as a function load, but the dynamic friction coefficient exhibited lower values than the static component.
Figure 2. Variations in static and dynamic coefficient of friction as a function of applied load for CU42 fibre-reinforced composites, sliding at 0.42 m/s against the smooth steel under two different loads.

Figure 3 shows the variations in static and dynamic coefficient of friction as a function of number of cycles for CU42 fibre-reinforced composites, sliding at 0.42 m/s against the smooth steel under 90 N load and 160 N load. The dynamic friction coefficient exhibited lower values than the static component. However, the static and dynamic friction coefficients appeared to vary similarly as a function sliding distance. The steady state friction coefficient was obtained at $2.5 \times 10^4$ when tested at 90 N load. The static and dynamic friction coefficient obtained was about 0.40, 0.17, respectively. It decreased considerably with increasing the load (Fig. 3b). This might be due to decreasing the ploughing component and thermal softening the surface. In addition, variations in static and dynamic friction coefficient for CU52 fibre-reinforced composites is plotted as a function of time in Fig. 4 under different loads. The friction coefficient increased rapidly throughout the first meters of sliding and subsequently decreased because the running-in period decreased considerably. It was observed for the carbon and glass fibre reinforced of PEEK composite against steel at long sliding [22]. After the initial running in period the friction coefficient stabilized as a friction of sliding distance, which is the case for running time of present results. PEEK CF30 presented the less COF (0.18), followed by PEEK (0.21). However, when the conditions changed the COF increased. COF and wear rate of carbon fibre epoxy matrix composites measured [32]. Initial COF recorded was 0.65 that for the peak after wear in was 0.74. Thus, the COF for composite/composite contact should be considered as being high. Friedrich et al.[26] studied COF for two PA66 composites with and without nano-TiO$_2$. At the beginning of the running in stage, the sliding performance was similar to both. However, the COF and contact temperature for nanocomposites were abruptly reduced after an initial stage of the contact period, lasting about an hour.

The static friction decreased at higher normal load, which was the same trend for the dynamic friction because the time to establish a steady-state friction shortened. This might be due to a reduced contribution of ploughing component and frictional heat for the polymer, which increased the surface temperature, inducing the adhesive, abrasive wear, plastic deformation and fibre breakage.
Figure 3. Variations in static and dynamic coefficient of friction as a function of number of cycles for CU42 fibre-reinforced composites, sliding at 0.42 m/s against the smooth steel under (a) 90 N load, (b) 160 N load.

Figure 4. Variations in static and dynamic coefficient of friction as a function of number of cycles for CU52 fibre-reinforced composites, sliding at 0.42 m/s against the smooth steel under (a) 90 N load, (b) 160 N load.
In addition, large fluctuations occurred for lower load and the initial stage of friction. Wang et al.[17] found the MoS\(_2\) filler was effective in reducing the friction coefficient of nylon at 100 N load because transfer film formed by nylon and 10MoS\(_2\) plus nylon composite. The COF was reduced by 35% by substituting the glass fibre weave with the carbon/aramid weave, epoxy resin (EP), EP/Glass, Carbon+Aramid (C/A) [31]. The best tribological properties were obtained when the fibres were parallel and anti-parallel to the sliding direction due to lubricating effect of carbon fibre. Average COF for G/EP and CA/EP was about 0.63 and 0.41, but EP was about 0.69. Matsunage et al.[33] measured the COF for carbon fibre/epoxy matrix composites in contact with stainless steel under reciprocating sliding. The COF was varied 0.10 – 0.25 with a maximum for transverse fibre orientation. However, the COF varied between 0.45 and 0.65 for graphite/epoxy composite and carbon/PEEK composites, respectively [34].

3.3. Wear rate

The experimental results of the dry wear of epoxy composites at different conditions are shown in Table 2. The tests relevant to this table were carried out at 0.42 m/s speed, but indicated loads. The specific wear rate of composites and its matrix experiments are plotted as a function of the load in Fig.5. There were no significant difference in wear rate between two volume fractions of composites because of the similar alignment of fibres in the matrix. It is evident from the figure that the specific wear increased considerably with increasing the load for the epoxy matrix, but it decreased slightly with increasing the load for CU42 composite. The average wear rate of tested composites at 90 N load was about 12.36x10\(^{-5}\) mm\(^3\)/N.m, which was decreased with increasing the fibre content. Typical wear data, obtained throughout reciprocative sliding experiments for composite/steel combinations, are plotted as a function of the applied load in this figure for composites.

![Figure 5](image.png)

**Figure 5.** Specific wear rate as a function of load for unidirectional carbon fibre-reinforced composites, sliding at 0.42 m/s tested against the smooth steel.

Other reason was that adhesion component became a more effective due to thermal effects. The temperature at the frictional surfaces increased with increasing the load and the frictional heat on composites could not be distributed in time due to the poor ability of heat transfer. It is found that carbon fibre decreased the wear rate for nylon while wear rate increased and transfer film was formed by nylon and 10MoS\(_2\) plus nylon composite [17]. The aramid fibres did not show exposed fibre ends as opposed to the carbon and glass fibres. It seemed to prevent the micro-cracking of the resin due to...
their toughness. The carbon fibres seemed to be worn thinner and then ultimately fracture into smaller pieces [31]. The main wear mechanisms were slow mean of the matrix on the original surface and cracking of the fibre/matrix interface causing matrix and fibres to be broken off [32].

4. Conclusions
The following conclusions related to tribology of experimental results on carbon fibre-reinforced epoxy composites were drawn:

The microstructure is examined by SEM to see the distributions of fibres in the epoxy matrix. The experimental results indicated the unidirectional carbon fibers improved the tribological properties of the epoxy resin by reducing the wear rate, but increased the coefficient of friction. The wear rates of composites and epoxy under the loads applied varied from $10.8\times10^{-5}$ mm$^3$/N.m and $38.2\times10^{-5}$ mm$^3$/N.m, respectively. The friction coefficient of CU42 and CU52 composites/steel tribo-pairs when tested at 90 N load was measured to be in the range 0.35 and 0.13, 0.45 and 0.17 for static and dynamic component, respectively. Also, the coefficient of friction decreased with increasing the load.

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