INFLUENCE OF HARDENER / RESIN RATIO TOWARDS FRICTIONAL PROPERTIES OF FIBRE-REINFORCED EPOXY COMPOSITE LAMINATES

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Abstract

The study presents a frictional analysis on woven and unidirectional glass fibre-reinforced epoxy composite materials, fabricated using vacuum infusion method at varying hardener/resin ratio. Tensile tests are conducted using a universal testing machine to determine the tensile modulus of elasticity for the tested materials while frictional characteristics of the these materials are measured using a pin-on-disk tribometer. It is found that the tensile modulus of elasticity for woven and unidirectional glass fibre-reinforced epoxy composite materials reduce for hardener/resin ratio with higher phr values. On the other hand, reducing friction force is measured for these materials when phr values are increased. By correlating tensile modulus of elasticity with frictional properties, it is shown in the present study that the coefficient of friction for woven and unidirectional glass fibre-reinforced epoxy composite materials reduces with lower tensile modulus of elasticity (higher phr values). The lower coefficient of friction observed is believed to be influenced by the larger deformation capacity of a more hardener rich epoxy based composite system..

Keywords

Fibre-reinforced composite; Modulus of elasticity; Coefficient of friction; Hardener/ resin ratio; Tribometer

1.0 INTRODUCTION

In Southeast Asia (SEA), energy demand for the transportation sector is rapidly on the rise [1]. This presents a challenge in reducing greenhouse gas emissions in view of the heavy reliance on fossil fuels in the transportation sector. Hence, decarbonisation efforts are essential for the transportation sector, where one of the key focuses is on improving energy efficiency of vehicles. Nowadays, energy efficient vehicles typically come in the form of either hybrid or electric powertrain systems. However, numerous components or materials used to build such vehicles are still heavily dependent on the use of legacy alloys [2], which could contribute to heavier vehicles, leading to lower fuel efficiency.

In such a scenario, fibre-reinforced materials come into the picture as lighter materials for use in energy efficient vehicles. Fibre-reinforced composite materials typically contain reinforced elements bonded by matrix materials. Among the common types of matrix materials, epoxy resin is considered one of the most important groups because of their wide range of properties [3-5]. Plenty of research works have been conducted for epoxy resin based material systems for engineering applications. Examples of the work are extensively reviewed by Bello et al. [2]. In-line with the concept of Green Tribology introduced by Nosovsky and Bhushan [6], it is also essential that natural fibres, instead of synthetic fibres, be considered as reinforcements for polymer-based composite materials. To date, as reported Kumar et al. [7], numerous types of natural fibres have been explored for their usage in industries such as automotive industry. Aside from having fiber reinforcements, adding particles, such as polytetrafluorothylene (PTFE), to fibre-reinforced polymer composite materials could result in better tribological properties as observed by Vohra et al. [8]. However, care must be taken when choosing the methods in adding such particles [9]. Recently, Johar et al. [10] proposed a generalised thickness-dependent non-Fickian moisture absorption model for fibre-reinforced composites. The model has the advantage to predict the moisture uptake behaviour of composite materials under moisture ageing condition, which could significantly alter the mechanical properties of the material when being used in real life applications.

It is essential that characterisation of fibre-reinforced composite materials are conducted to determine the mechanical properties of such materials. Tensile tests are typically performed to determine the tensile behaviour of the material together with quality assurance and structural analysis [11] (Paiva et al., 2006). It is also to note that the mechanical behaviour of the matrix system can be critical in affecting the performance of fibre-reinforced composite materials. As an example, the effect of hardener/resin ratio on the mechanical properties of epoxy system has also been investigated by d'Almeida and Monteiro [12]. They observed that epoxy rich systems were typically brittle in nature. This was believed to be as a result of the formation of rigid macromolecular structure. On the other hand, hardener rich systems had larger deformation capacity, which was also observed in another work by the same authors for epoxy-matrix/glass microsphere composite materials [13].

Aside from using such composite materials in reducing the weight of vehicles, it is also worth considering the application of such materials for rotating elements in energy efficient vehicles, especially electric vehicles. Hybrid bearing systems made of composite materials are getting common in such vehicles in order to cater for the high speed electric motors in achieving more effective heat dissipation properties. Besides this, composite materials are also heavily considered as alterative brake pad materials [14]. However, research work in characterising frictional and wear performance of fibre-reinforced composite materials is still lacking. One of the earlier works reported is by Tsukizoe and Ohmae [15]. They measured friction and wear of unidirectionally oriented fibre-reinforced composite materials when sliding against carbon steel. They found that wear of their tested composite materials are influenced by modulus of elasticity and interlaminar shear strength of the materials themselves.

Using a pin-on-disk tribometer, friction and wear properties of woven glass fibre-reinforced epoxy composite systems were also determined by Suresha et al. [16]. The tested composite materials were fabricated also by having graded fillers as additional reinforcements. For pure glass fibre-reinforced epoxy composite materials, the coefficient of friction was measured between 0.43 and 0.61. When fillers were added to the composite materials, a drop in coefficient of friction of up to 31% was observed. More recently, Sudheer et al. [17] investigated the effect of hybrid fillers towards the mechanical and wear performance of glass fibre-reinforced epoxy composite materials. Their study focused on the deformation and failure mechanisms of the tested materials under tensile loading and dry sliding. For glass fibre-reinforced epoxy composite, they measured the coefficient of friction to be as high as 0.44. Depending on the types of hybrid filler used, they observed an inconsistent trend where coefficient of friction values were shown to either increase or decrease. This indicates the importance of filler compatibility with the fibre-reinforced composite system.

Most of the reported literature tend to focus on the wear behaviour of their tested fibre-reinforced composite materials with little emphasis on correlating frictional performance to the mechanical properties of the materials. This is essential in determining the frictional power losses of a mechanical system. Aside from adding fillers, it is also essential to have an adequate combination of polymeric matrix and reinforcement arrangement (e.g. fibre orientation) in the structural composite systems [11]. Therefore, as an initial approximation, the present study intends to determine the frictional performance of glass fibre-reinforced epoxy composite laminates fabricated at different hardener/resin ratio. The study also attempts to correlate mechanical properties of glass fibre-reinforced epoxy composite laminates with measured coefficient of friction when sliding against cast iron material. The selected tribological contact pair is similar to the application of a braking system, where the composite material represents the brake pad and the cast iron pin represents the brake disk.

2.0 MATERIALS AND METHODS

The reinforcements used in this study were 550 g/m^2 unidirectional glass fabric and 400 g/m^2 woven glass fabric. As for the resin, 1006 epoxy resin was used. Woven glass fabrics and epoxy resin were supplied by S&N Chemicals SdnBhd, whereas unidirectional glass fabrics were purchased through Ehwan Engineering. The study on hardener/resin ratio included in the present analysis is based on the amount of hardener by weight per hundred parts of epoxy resin by weight (phr). The values of phr ranging between 60 and 100 with an interval of 10 phr are selected in fabricating the tested composite laminates. It is recommended by the manufacturer of the selected epoxy resin that a harderner/resin mix ratio with phr value of 60 be utilised for optimum mechanical properties. Hence, phr of 60 is selected as the lower limit for this study in view of the concerns that lower phr values might result in the incomplete curing of the epoxy resin during the fabrication process.

Five-ply laminates, consisting of woven and unidirectional glass fibre sheets, are used to fabricate the fibre-reinforced epoxy composite test specimens using vacuum infusion process at different phr values. For this fabrication method, it involves the application of vacuum bagging process together with a vacuum pump, which functions to spread the resin evenly across the laminates through plastic tubing. Such process is expected to improve the fibre-to-resin ratio, reducing the excess amount of resin within the laminates. By using this process, an average laminate layer thickness of approximately 0.6 mm is achieved for both types of glass fibre-reinforcements. For baseline comparisons, neat-epoxy test specimens are also prepared at the studied phr values. These specimens are then cured at room temperature using a steel mould.

2.1 Tensile Testing - Universal Testing Machine

Typically, classical and readily available equations related to contact mechanics and tribology require modulus of elasticity as one of the inputs in determining the behaviour of the contact conjunction. Hence, in the present study, as an initial approximation, tensile modulus of elasticity for the glass fibre-reinforced epoxy composite laminates are determined using the Universal Testing Machine at different phr values. The laminate samples are cut into sizes of 250 mm × 25 mm in accordance to ASTM D3039 [18]. As for the neat-epoxy, the samples are dog bone-shaped according to ASTM D638 [19]. For unidirectional laminates, it is essential to be able to determine the mechanical properties in either 0° and 90° directions as highlighted by Soden et al., 2004 [20]. Hence, for unidirectional glass-fibre reinforced epoxy composite laminates, the tensile tests are conducted at 0° and 90° orientation as suggested by ASTM D3039. The measurements using a Universal Testing Machine with a load cell of 5 kN are repeated five times for each of the laminate configurations with different fibre sheet types and also at various phr values. An extensometer with gauge length of 25 mm is attached to the specimen to measure the strain rate.

2.2 Friction Testing - Pin-on-disk Tribometer

Frictional properties of the fabricated laminates are measured using a pin-on-disk tribometer, configured to comply with ASTM G99 [21] requirements. The setup of the friction test for composite laminates are given in Figure 1. For ease of sample preparation, the laminates are cut into square shapes of 85 mm × 85 mm instead of the typical circular shape used for pin-on-disk tribometers. Then, the square-shaped laminates are attached to a platform on the tribometer to be then rotated against a stagnant cast iron pin with spherical end cap of 10 mm diameter. For the selected cast iron, the measured hardness is 87 HRB with chemical composition of 3.51% Carbon, 3.2% Silicon, 0.4% Manganese, 0.018% Phosphorus, 0.01% Sulphur with the remainder being iron. An applied normal load of 20 N is selected for the current friction study for a total sliding distance of 2500 m. Friction force measurements of the studied laminates and neat-epoxy samples are repeated three times each at room temperature condition. It is to note that as a first approximation, aside from simulating a conjunction similar to brake pad/disk contact, the present study also selects the use of cast iron pin in order to be consistent with most of the frictional analysis on composite materials as reported in literature [22-25].

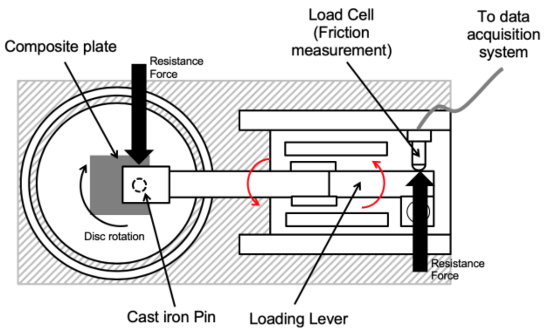

Figure 1 (a)

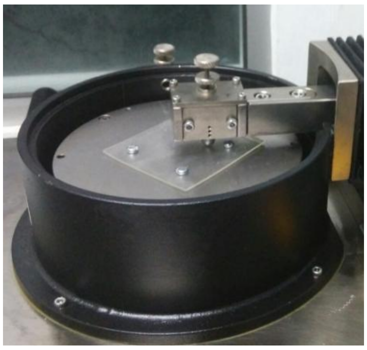

Figure 1 (b)

Figure 1: Friction force setup on pin-on-disk tribometer for glass-fiber-reinforced epoxy composite plates.
(a) Schematic diagram for pin-on-disk tribometer setup;
(b) Actual setup on pin-on-disk tribometer (e.g. neat-epoxy sample).

3.0 RESULTS AND DISCUSSION

The tensile modulus of elasticity for the fabricated woven and unidirectional glass fibre-reinforced epoxy composite laminates are determined as illustrated in Figure 2 using a universal testing machine. At phr value of 60, which is expected to produce optimum mechanical properties for the composite laminates, the measured tensile modulus of elasticity for unidirectional glass fibre-reinforced epoxy composite laminates is approximately 22.45 GPa (at 0° fibre orientation) and 6.93 GPa (at 90° fibre orientation), respectively. At the same phr value, the tensile modulus of elasticity for woven glass fibre-reinforced epoxy composite laminate is determined to be 13.58 GPa. These modulus of elasticity values correlate reasonably well to those measured by Eksi and Genel [26]. In Figure 2, it is also shown that the tensile modulus of elasticity values for both woven and unidirectional glass fibre-reinforced composite laminates reduce linearly with the phr value. Such trend correlates with the trend observed for the neat-epoxy samples. It is to also note that the error bars shown represent the standard error values from the tensile modulus of elasticity measurements.

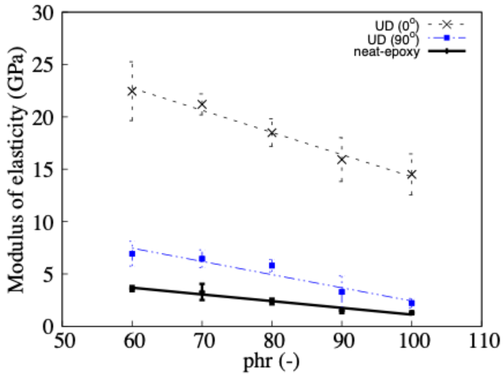

Figure 2 (a)

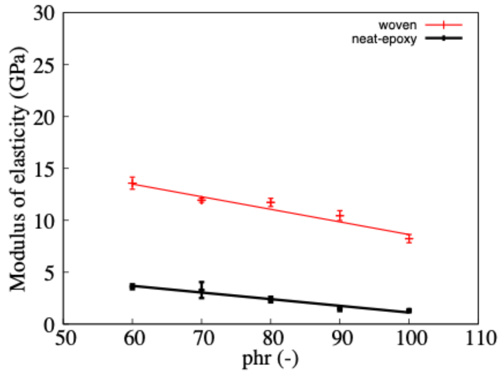

Figure 2 (b)

Figure 2: Modulus of elasticity measured for glass fiber-reinforced epoxy composite laminates at varying amount of hardener per hundred parts of epoxy resin (phr).
(a) Unidirectional glass fibre-reinforced epoxy composite laminates;
(b) Woven glass fibre-reinforced epoxy composite laminates.

Figure 3 shows the measured friction force for the tested glass fibre-reinforced epoxy composite laminates at various phr values. It can be observed that the friction force for neat-epoxy samples exhibit a maximum parabolic trend with increasing phr values, generating a peak friction force at approximately 13.89 N. However, the deviation range of the measured friction force between maximum and minimum values at different phr values is only marginally around 4.75%, which could mean that the observed variation in friction force might be due to measurement fluctuations. When glass fibre-reinforcements are introduced to the epoxy matrix, friction force values of these laminates are shown in Figure 3 to drop quite significantly. For both woven and unidirectional glass fibre-reinforced epoxy composite laminates, the friction forces are observed to decrease with higher phr values. The friction forceat higher phr values is shown to drop by as much as 15.23% for woven glass-fibre and 21.16% for unidirectional glass fibre, respectively. The error bars plotted in Figure 3 represent the standard error values for the measured friction force for each of the tested samples.

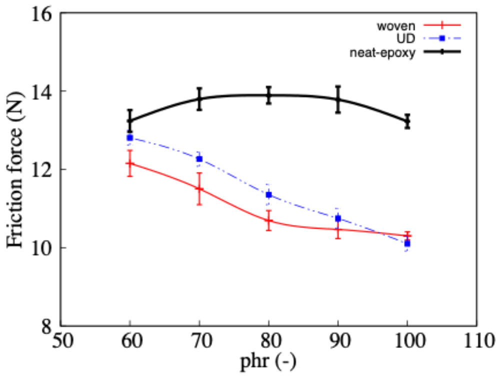

Figure 3: Friction force measured for glass-fibre-reinforced epoxy composite at varying amount of hardener per hundred parts of epoxy resin (phr).

As shown in Figure 2, increasing harderner/resin ratio in terms of phr values results in reduced tensile modulus of elasticity of glass fibre-reinforced epoxy composite laminates. On the other hand, increasing phr values actually leads to a fairly significant drop in friction force as being illustrated in Figure 3. By combining the findings from Figure 2 and Figure 3, Figure 4 plots the correlation between frictional properties and tensile modulus of elasticity for the studied fibre-reinforced epoxy composite laminates. For woven glass fibre-reinforced epoxy composite laminates, the coefficient of friction (CoF) generated when sliding against a cast iron pin exhibits an increasing trend with larger tensile modulus of elasticity values at a constant applied normal load. Similar increasing trend can also be observed for unidirectional glass fibre-reinforced epoxy composite laminates when plotted against both tensile modulus of elasticity measured at 0° and 90° fibre orientations.

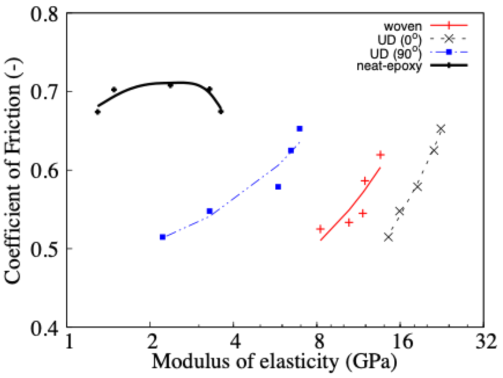

Figure 4: Coefficient of friction measured at varying modulus of elasticity for glass-fibre-reinforced epoxy composite

Theoretically, the modulus of elasticity is selected in the present analysis for the glass fibre-reinforced epoxy composite laminates because this is the most commonly determined mechanical property. During the friction test, ploughing friction is observed, where materials are removed from the tested laminates. According to Gohar and Rahnejat [27], ploughing friction is proportional to the hardness of the material. Generally, hardness of a material is inverse proportional to the contact area, A. The contact area, A can be calculated based on the Hertzian theory for a point contact as follow:

$$A = \pi \left(\frac{3WR}{4E^*} \right)^{2/3}$$

Where E^* is the reduced modulus of elasticity, calculated using

$$\frac{1}{E^*} = \frac{1 - {\nu_1}^2}{E_1} + \frac{1 - {\nu_2}^2}{E_2}$$

From the correlations given, a higher modulus of elasticity value would lead to a smaller contact area. At a constant applied normal load, this in turn could result in a higher hardness value for the material. Eventually, a higher hardness value of the material is expected to generate a larger ploughing friction force. Hence, it can be surmised that higher modulus of elasticity could possibly lead to higher ploughing friction force, correlating with the observed trend observed in Figure 4.

Evidently, the observation above could also be linked to the findings by d'Almeida and Monteiro [12], where hardener rich systems (higher phr values) have a larger deformation capacity. This also reflects on the lower tensile modulus of elasticity values measured at higher phr values. The better deformation capacity at lower tensile modulus of elasticity (higher phr values) would indicate a more compliant material, which could allow for less harsher resistance towards motion during sliding at a given applied normal load. This might result in the observed reduction in friction force for the tested glass fibre-reinforced epoxy composite laminates. However, care must also be taken to not increase the phr values too high to achieve lower friction force, which might result in the faster curing of the hardener/resin blend, failing to effectively spread across the fibre sheets during the vacuum infusion process.

4.0 CONCLUSION

The present study investigates the effects of hardener/resin ratio of glass fibre-reinforced epoxy composite laminates towards their frictional properties when under pure sliding condition. Woven and unidirectional glass fibre-reinforced epoxy composite laminates are fabricated at hardener/resin ratio between phr values of 60 and 100 using vacuum infusion process. The tensile modulus of elasticity for the fabricated composite laminates are measured using a universal tensile testing machine. It is observed that the tensile modulus of elasticity values for both woven and unidirectional glass fibre-reinforced epoxy composite laminates decrease with larger phr values. Then, friction force measurements for glass fibre-reinforced epoxy composite laminates sliding against a cast iron pin are conducted using a pin-on-disk tribometer. Reduction in friction force of as much as 15.23% for woven glass-fibre and 21.16% for unidirectional glass fibre, respectively, are achieved with larger phr values. By correlating the measured tensile modulus of elasticity towards the coefficient of friction, it is shown that the coefficient of friction increases with higher hardener/resin ratio or phr values for both the tested types of glass fibre-reinforced epoxy composite laminates. The measured lower friction force with lower tensile modulus of elasticity (higher phr values) is believed to as a result of a larger deformation capacity of the hardener richer epoxy based composite system.

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