

THE EFFECT OF FIBER ORIENTATION ON THE DRY WEAR BEHAVIOUR OF CARBON FIBRE-REINFORCED EPOXY COMPOSITES

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Abstract

Carbon fibre-reinforced epoxy composites containing unidirectional carbon fibres was fabricated by moulding technique. The effect of fibre orientation on the dry wear of the composites and its epoxy matrix was investigated in a pin-on-disc type of configuration against SiC emery paper. Response surface methodology (RSM) was applied to analyze the weight loss results. The experimental results indicated that the maximum weight loss was found when the fibres were oriented anti-parallel to the sliding direction in each case. Furthermore, the weight loss increased with increasing the speed and load. Analysis of variance indicated that the weight loss was highly influenced by rotational speed and load, respectively. However, the least effect was obtained for the materials type.

Key words: composite, epoxy, carbon fibre, fibre orientation, load, weight loss

1. INTRODUCTION

Polymer based composite materials are characterized through a number of advantages over traditional structural materials since they offer such unique properties as high specific strength in combination with light weight, high electrical insulating characteristics, non-magnetic properties, low friction and corrosion resistance. Fibre-reinforced composites have been used successfully for many decades as many engineering applications such as aerospace, automobile, chemical, construction and marine industries and sport equipment because of the high specific strength/modulus, availability and design flexibility when compared to metal based counterparts (Paiva et al. 2005; Paiva et al. 2009). Polymer composites containing different fillers and/or reinforcements are frequently used for these purposes. Compared with short fibers, particulate and whiskers, carbon fibres as reinforcement have much higher structural ordering and tightness properties in polymer composites, and have been continuously growing during the last few years in improving the high mechanical strength/modulus of polymer composites in both longitudinal directions (Han et al.2012). Thus, it makes carbon fiber irreplaceable in wide sectors of engineering technology such as for automobile, aircraft, ships, construction and sport equipment (Paivaa et al.2009; Colombo et al. 2012). However, carbon fiber involves costly production. 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 composite (Wonderly et al 2005; Şahin 2015; Rahmani et al 2014; Ary Subagia et al 2014; Zhou et al 2008; Han et al 2012; Tarpani et al 2006; Jagannatha and Harish 2015). Over the last two decades, in the multiple studies involving sliding movements, various reinforcements (Friedrich et al. 2005; Suresha et al.2009) and matrixes were investigated, such as short carbon fibres/graphite fillers (Kurokawa et al 2003; Wang et al. 2010; Zhou et al. 2009) or a mix of different reinforcements (Suresha et al. 2001; carbon/glass fibre (Jia et al. 2005; Davim and Cardoso 2009). Friction and wear behaviour of unidirectional carbon fibre-reinforced epoxy composites containing various unidirectional carbon fibres was investigated on a pin-on-flat plate configuration (Şahin and Patrick 2016). The carbon fiber improved the tribological properties of thermoset epoxy by reducing wear rate. The wear rate decreased with decreasing load while friction coefficient increased with decreasing load. The literature on the tribological behaviour of carbon fiber based on different orientations for reinforced epoxy composite is rather limited although fibre orientation on the wear rate is very important (Dhieb et al. 2011; Suresha and Chandramohan 2007;

Dwiedi and Chand 2009, Prasad 2014, and Zhang et al. 2010), hence this aspect has been taken up in the present work.

Based on the effect of fiber orientation, several researchers have reported on the tribological aspects; some of their results are contradictory in nature (Modi et al.2001). Most of the above findings on the friction and wear study of polymer composites are based on either randomly oriented or unidirectionally oriented fiber composites. Dhieb et al. (2011) found that sliding with stainless steel in a direction parallel to the fiber orientation resulted in a lower coefficient of friction than under sliding in anti-parallel direction for bulk epoxy and carbon fiber reinforced epoxy composite under reciprocating sliding. The coefficient of friction measured for the bulk epoxy against stainless steel and alumina was around 0.65, whereas the values measured for the epoxy reinforced with carbon fibers were significantly lower. The reduced wear volume of the composite was largely influenced by the carbon fiber reinforcement due the auto-protecting film formed on the contact area. Suresh et al. (2007) investigated the friction and dry sliding wear behaviour of [08/908] S and unidirectional (UD) oriented carbon-epoxy (C-E) composites using block-on-roller test set up. Both fiber orientation (P/AP) and sliding velocity influenced the wear of C-E composites. The P oriented composite showed the higher wear rate due to brittle fracture, but AP oriented composite indicated the lower wear rate because of the development of thin film on the counter surface (Dwiedi and Chand 2009).

Effect of fibre orientation and applied load on the tribological behaviour of jute fibre reinforced polyester composites were determined (Prasad 2014). It is found that wear resistance was maximum in TT sample, where fibres were normal to sliding direction. Wear rate under sliding mode followed this trend; WTT < WLT <WLL sample showed higher capability to sustain the load whereas lowest wear resistance in this case. The coefficient of friction found the highest for TT sample and lowest for LT sample. Unidirectional, bidirectional and 45° orientation of PALF reinforced Bisphenol-A (BPA) composite are subjected to different loadings. Among three types of fiber orientation in composite, bidirectional composite showed the least specific wear rate and coefficient of friction. The coefficient of friction for all the three types of fiber orientations in composite decreased with increase in normal load, due to self-lubrication of the testing samples, as the normal load increased, more material is removed and the removed material was held at the mating surfaces of composite and abrasive disc which is resulted in self lubrication. Yamamoto and Takashima (2004) concluded that under boundary lubricating conditions, PEEK reinforced with glass fiber was little improved in friction and wear characteristics, since both PEEK and glass fiber had poor resistance to wear in water. Besides,it was described that the fiber aligned perpendicular to sliding direction exhibited higher wear resistance than those parallel to sliding direction. The effects of fiber orientation on the tribological behavior of a short carbon fiber (SCF)/PTFE/graphite (10 vol.% for each) filled PEEK composite under 1 MPa to 5 MPa indicated that the effect of fiber orientation showed strong dependence on the nominal pressure (Zhang et al.2010). Under higher pressures, i.e. 3–5 MPa, the composite displayed a higher wear resistance when the fibers are orientated at the anti-parallel rather than the parallel and the normal directions. Abrasive wear behaviour of the some other composites were also carried out with experimental and statistical method (Sharma et al. 2010; Basavarajappa et al.2010; Harsh and Tewari 2003 and Modi et al.2001). Therefore, the aim of the present work was to study the effect of fibre orientation on the dry sliding wear behaviour of the unidirectional carbon fibre-reinforced epoxy composites under different loads using RSM approach in a pin-on-disc 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 was commercial SR 8500 epoxy resin and hardener was SD 860x supplied by MCtechnic Ltd., Netherlands. The filler materials used in this study was carbon fabrics supplied by MCtechnic Ltd. The carbon plain weave fabrics was 200 g/m² and its diameter was about 7-10 µm. The manufacturing process involved the mixing of the epoxy resin with a hardener at a ratio of 100:28. Then the catalyzed resin mixtures were

spatulated on composite panel of 150x150 mm² in size with a thickness of 4.0 mm mold plate. The reinforced of 10 layers were soaked by the resins. A bottom layer and top layer of thee laminate was covered by the mold sheets, which were coated with a release agent for easy separation after curing. The specimens required for abrasive wear studies (5x5x4 mm³) were cut from the laminate composites by using a water jet machining. Three different types of specimens were prepared for this study. The weight fraction of the carbon fibres were 52 %. Hereafter these composites and epoxy were referred as an EP, CU52 coded number, respectively. These CU (continuous unirectional) composites are also called as “P” orientation and “AP” orientation, respectively.

2.2. Wear tests

The experimental apparatus was a pin-on-disc type of wear-testing machine. A pin specimen was fixed to a rotational stage or to a pin specimen holder by setting screws. The pin was then mounted in a steel holder in the wear machine so that it was held firmly perpendicular to that of the flat surface. The normal load was applied through a spring and lever system. The material loss of testing samples was calculated from weight loss of composites. Carbon fibre reinforced composite (CFRC) was slid in a circular rotational motion against SiC emery paper fixed on the steel of AISI 4140 grinded to perpendicular to the sliding direction. The steel counter face was fixed to a base plate sizes of Ø160 x x 14 mm with an average surface roughness of 0.30-0.50 µm perpendicular to the sliding direction. Test specimens were prepared from two fabricated composite materials. These two types of specimens were prepared to satisfy these orientations as illustrated in Fig.1. The composite specimens (CU52) were tested fibres in parallel (P orientation) direction and perpendicular to sliding direction (AP orientation). The total sliding distance was about 125 m. The wear pin was cleaned in acetone prior to and after the wear tests, and then weighed on a microbalance with 0.1 mg sensitiveness. The weight loss was calculated by measuring the mass loss method.

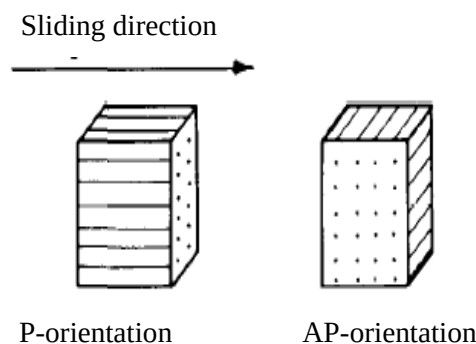


Fig. 1. Test specimen with two different orientations.

2.3. Experimental design

The response surface methodology (RSM) design of experiment approach eliminates the need for repeated experiments and thus saves time, material, and cost. This approach identifies not only the significant control factors, but also their interactions influencing the weight loss predominantly. This experiment specifies three principle wear testing conditions including the applied load (L), rotational speed (S) and material's orientation (M) of the tested materials as the process parameters. Codes and levels of control parameters and their levels were shown in Table 1. This table showed that the experimental plan had three levels. A standard RSM plan with notation L15 was chosen, as shown in Table 1.

Table 1. Control parameters and their levels.

Symbol	Controlling parameters	Level 1	Level 2	Level 3
L	Applied load, N	5 (-1)	10 (0)	15 (+1)
S	Speed, rpm	80 (-1)	140 (0)	200 (+1)
M	Material's orientation	AP (-1)	E (0)	P (+1)

An orthogonal array and ANOVA were applied to investigate the influence of process parameters on the wear behaviour of the composites.

3. RESULTS AND DISCUSSION

3.1. Analysis of weight loss

The experimental data was analyzed using the software MINITAB 16 specially used for design of experiment applications. The experimental lay out and results of the abrasive wear of epoxy composites at different conditions were shown in Table 2. The tests relevant to this table were carried out at a fixed speed, but indicated parameters of loads. The average weight loss of composites and its matrix experiments were plotted as a function of the control factors in Fig.2. The mean response refers to the average values of the performance characteristics at different levels. Among the control factors, the factor B (speed) showed the highest effect on the weight loss due to increased penetration ability on the layered structure with increasing depth ability (Fig. 2b), followed by the factor A (load) and the factor D (orientation), respectively (Fig. 2a,b). Furthermore, this table exhibited that the effect of fibre orientation was not significant on the weight loss of the tested samples. The wear resistance of epoxy polymer was a lower than those of P and AP orientations of the composites. This was the reason that the average weight loss obviously increased for the composites because the penetration ability of SiC abrasives on the counter face disc increased with increasing the hardness/strength of laminate structure of the composites. It is revealed that the mean weight loss obtained was at the lower value for the resin due to filling the valley with epoxy associated with higher speed.

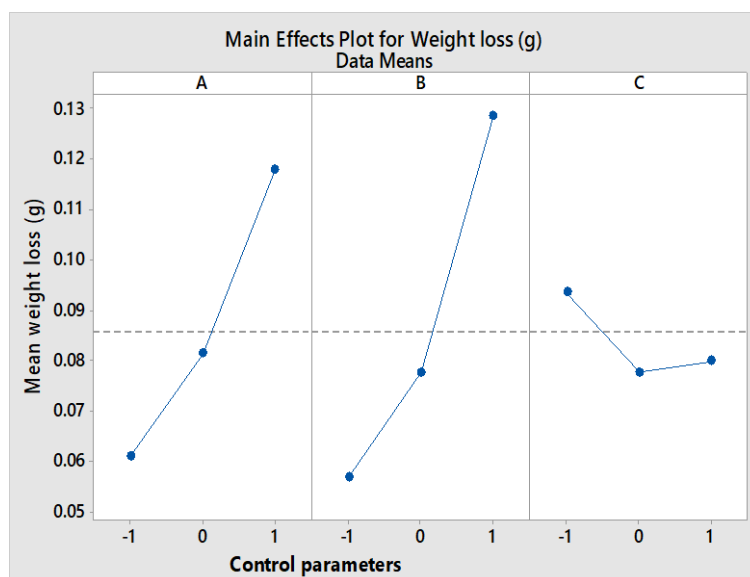


Fig. 2. Average weight loss as a function of control factors for the carbon fibre-reinforced epoxy composites, tested against the SiC abrasive emery paper.

In other words, linear decreases were observed with the sliding speed and load, but decreased slightly for both orientation effect. However, it is noted that the sensitivity of the load was slightly lower than that of the sliding speed (Fig. 2b). These were clearly related to the Archard's equation (Harsh and Tewari, 2002) because it has proven very useful in describing the abrasive wear, which are in good agreement with this work. However, it was contradictory to the some other tests carried out on the composites showed that the abrading distance was more effective on the wear of other parameters (Basavarajappa et al., 2010; Unal et al., 2005). Besides, the effect of load on the wear rate of Zinc based Al_2O_3 composite was more severe than that of abrasive sizes (Modi et al., 2001). Recent work by Şahin (2017) indicated that the sliding speed was not an effective on the wear of the polyamid samples due to the self-lubricated ability, but the abrasive size and sliding distance had great effects on the weight losses for Kestoil samples and Kestamid samples, respectively.

Table 2. The experimental lay out and the abrasive wear behaviour of epoxy composites and their theoretical results at different conditions

Experimental run	Load (N)	Speed (m/s)	Material type (HRB)	Measured weight loss (g)	Theoretical weight loss (g)	Errors (%)
1	-1	-1	-1	0.0302	0.034999	0.4799
2	1	-1	-1	0.089	0.093699	0.4699
3	-1	1	-1	0.106	0.101301	0.4699
4	1	1	-1	0.188	0.183201	0.4799
5	-1	0	0	0.056	0.048071	16.49
6	1	0	0	0.108	0.100471	0.7529
7	-1	0	1	0.0514	0.059229	13.21
8	1	0	1	0.0861	0.093729	0.7629
9	0	-1	0	0.0574	0.046134	1.1266
10	0	1	0	0.089	0.115723	2.6723
11	0	-1	1	0.05073	0.052499	0.1769
12	0	1	1	0.131	0.113774	1.7226
13	0	0	-1	0.082	0.080567	0.1433
14	0	0	-1	0.0766	0.080567	0.3967
15	0	0	-1	0.0831	0.080567	0.2533
Average error, %				0.090548	0.085635	2.640473

3.2. Analysis of variance

The ANOVA results for the abrasive sliding wear behaviour of epoxy composite materials were listed in Table 3. It is clear from the Table 4 that factors A, B and C had statistical and physical significance on the wear because the test-F value was higher than the F5 percentage column value. As it has noted in the last column of the ANOVA table, the P of each factor on total variations, showing the degree of influence on the wear results. On the other hand, the last column of the table indicates p-value for the individual control factors and their possible interactions. It is known that smaller the p-value, greater the significance of the factor/interaction corresponding to it. The mean table for the weight loss (Table 3) indicated that the factor A (load) ($p=0.009$), and the factor B (speed) ($p=0.003$) in this order, were significant control factors affecting the wear resistance, but the factor C (orientation) ($p=0.316$) was

insignificant effect. It meant that the speed was the most significant factor and the load had less influence on the performance output. Between the two way possible interactions, the interaction effects showed no remarkable contribution on the wear because p-values changed between 0.163 and 0.569.

Table 3. Analysis of variance for the weight loss of the composites.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	0.019220	0.002136	7.15	0.022
Linear	3	0.014284	0.004761	15.93	0.005
A	1	0.005034	0.005034	16.84	0.009
B	1	0.008878	0.008878	29.71	0.003
C	1	0.000371	0.000371	1.24	0.316
Square	3	0.001211	0.000404	1.35	0.358
A*A	1	0.000239	0.000239	0.80	0.413
B*B	1	0.000797	0.000797	2.67	0.163
C*C	1	0.000196	0.000196	0.66	0.455
2-Way Inter.	3	0.000670	0.000223	0.75	0.569
A*B	1	0.000135	0.000135	0.45	0.532
A*C	1	0.000441	0.000441	1.47	0.279
B*C	1	0.000095	0.000095	0.32	0.597
Error	5	0.001494	0.000299		
Lack-of-Fit	3	0.001470	0.000490	40.49	0.024
Pure Error	2	0.000024	0.000012		
Total	14	0.020715			

3.3. Correlations

The correlations between the main factors A,B,C and the weight loss of the samples were obtained by multiple regressions. The obtained correlations were as follows. The second order model equation for the weight loss prediction in uncoded units for WL was given by

$$\begin{aligned}
 \text{Weight loss (g)} = & 0.0662 + 0.02620 A + 0.03479 B - 0.00606 C \\
 & + 0.00804 A*A + 0.01470 B*B + 0.0083 C*C \\
 & + 0.00580 A*B - 0.00895 A*C - 0.00416 B*C
 \end{aligned}
 \tag{1}$$

where WL is the mean weight loss Eq. (1) indicated that the weight loss increased the load and speed, but C decreased the weight of the samples when testing against SiC abrasive papers. The model had an adjusted R^2 value of 92.7%.

The predicted weight loss was calculated from the regression Eq.(1). The measured and predicted values of parameters for the weight loss testing the composites were tabulated in Table 2. On the other hand, the weight loss was minimal for trial 1 due to using the first level of load, the first level of speed, and the second level of the specimen type (Fig.2). The average value of weight loss was measured about 0.0905 g. The results were combined with some errors of the prediction model for the second order regression. There were some differences between theoretical and experimental values for the second order model. For example, average error was about 2.64 % for the second order model, which was less than 5% for this model. The regression model was found to be better prediction capability, except for trial 5 when considering each experiment separately. It was considered that less than the 5% error was quite reasonable. Therefore, the model constructed in the present work could be used to predict the weight loss of the polymer composite materials. The best tribological properties were obtained when the fibres were parallel and anti-parallel to the sliding direction due to lubricating effect of the carbon fibre. Average COF for G/EP and CA/EP was about 0.63 and 0.41, but EP was about 0.69. However, the COF varied between 0.45 and 0.65 for graphite/epoxy composite and carbon/PEEK composites, respectively (Unal et al.2005).

4. CONCLUSIONS

The following conclusions on the effect of dry wear behaviour of carbon fibre-reinforced epoxy composites were drawn:

- (1) The experimental results showed that the weight loss was highly influenced by the speed and load, but no significant effect was observed for the orientation effect.
- (2) The experimental results indicated that the AP-oriented samples gave the more weight loss than those of the other tested materials due to generating more fracturing fibres in the composites.
- (3) ANOVA indicated that the weight loss was highly influenced by rotational speed and load, respectively. However, the least effect was obtained for the material's type.
- (4) The second regression model was developed to predict their wear behaviour under dry sliding conditions. There were some differences between theoretical and experimental values, but the average error was about 2.64 % for this model.

ACKNOWLEDGEMENTS

This research is financially supported by the Turkish Scientific and Technical Council Foundation of Turkey (Grant No. 1059B191401938).

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