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Chopped Carbon Fiber Reinforced Polymer Composites : Effect of Nanoclay on Adhesive and Abrasive Wear Properties

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Abstract*: The present work investigates the wear properties of nanoclay-modified carbon fiber reinforced polymer (CFRP) composites when sliding under adhesive and abrasive wear. The specimens were fabricated using epoxy resin, short carbon fiber, and nanoclay filler of 1.0wt%, 3.0wt%, and 5.0wt% content. The wear tests were conducted using pin-on-disc and abrasion resistance test rig for adhesive and abrasive wear condition, respectively. Operating parameters were fixed at 30N load, 300rpm speed and 10km distance for both tests. Pure CFRP composite exhibited lower wear performance compared to pure epoxy in both test conditions. However, with nanoclay incorporation, the wear properties of CFRP composite have improved up to 56% and 44% under adhesive and abrasive wear, respectively. Therefore, the composite reinforced polymer of carbon fiber and nanoclay filler in epoxy matrix provides a synergistic effect under adhesive and abrasive wear conditions. The experimental findings suggest that the CFRP composite has the potential for tribological components and application such as sliding-contact and rolling-contact bearings.

Keywords*: Carbon fiber; Nanoclay; Adhesion; Abrasion; Wear rate.

I. INTRODUCTION

Polymeric composites have been increasingly used in various industries due to their lightweight properties and high in specific strength and stiffness [1]. They are also popular as sliding materials against metallic counterparts as they possess unique features such as self-lubrication capability, chemical stability and low in weights [2]. Polymer and their composites are increasingly used as bearing materials, rollers, seals, gears, cams, wheels and clutches. Therefore, the need to enhance their tribological properties is in the interest of many researchers nowadays. The traditional concept of improving tribological performance is to enhance their hardness, stiffness and compressive strength and to reduce their adhesion to the counterpart material, which usually related to their reinforcements [3]. Fiber-reinforced polymer (FRP) composites are considered the most effective type of reinforcement due to their high mechanical properties [4]. A good combination of high specific strength and specific modulus, as well as improved wear resistance and friction, make them the fastest growing class of materials [3]. Carbon, glass, and aramid fibers are the most commonly used fiber especially in making tribo-component that operates in harsh operating conditions such as high stresses, speeds, temperature and pressure [5]. Carbon fibers (CFs) show superior properties such as higher Young's modulus, better strength, better thermal conductivity, wear-resistance and more excellent electrical properties than other fibers. It also possesses additional lubricity due to its lattice structure; graphite is responsible for reducing the coefficient of friction and wear rate of the composites [3]–[5]. Short carbon fibers (SCFs) also show superior properties in wear and friction as investigated by [6]- [9]. Other studies were also in the similar interest and important in a tribological application such as fiber content [5], fiber orientation [10]–[12], temperature [6], [10], and wear conditions [6], [13].

Besides fibers, nanoparticles reinforced polymer composites are also well-known to improve mechanical and tribological properties of the polymer [2],[14]. Polymer nanocomposites offer unique properties resulting from the nano-scale structures. The extremely large surface area facilitates an enhanced interaction between the fillers and matrix [15]. A homogeneous dispersion of nanoparticles in the matrix is one of the most important factors affecting the properties and ability of nanoparticle to reduce friction and enhance the wear resistance of the composite polymers [4],[16]. Nanoclay is receiving much intention due to its high aspect ratio and unique interaction/exfoliation characteristics. Studies show that nanoclay incorporation exhibit properties such as gas permeability improved solvent resistance, and superior mechanical properties with specific content (approx. 2%) [14],[17].

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Combination of two types of reinforcement in a polymer opens up a vast area of development. Modification of fiber-reinforced polymers with the addition of filler material has exhibited a positive impact on the mechanical and tribological properties of the composites [3].

Generally, fibers significantly improve the load-bearing capability of the matrix, whereas the fillers act as internal lubricants and promote the formation of a transfer film on the counterface, or provide a rolling effect between counterpart pairs, consequently reduces the friction between the sliding pair.[4],[16]. Studies on the tribological performance of this advanced polymer composites have been investigated by various researchers. Research on the effects of nanofiller content on the FRP composites was studied by [16],[2] and [18]. Kim et.al studied the effect of carbon nanotube (CNT) modifications on flexural and wear behaviors of carbon fiber reinforced polymer (CFRP) composites [19]. Silane-treated CNTs showed superior flexural strength and modulus, and wear properties compared to acid-treated and untreated CNTs. Guo et.al found that grafted nano-SiO_2 gave positive synergistic effect on adhesive wear of SCF/EP composite compared to ungrafted one [9]. Talib et.al investigated the effect of CNT content on glass fiber reinforced polymer (GFRP) composites under abrasive and erosive wear [20]. GFRP composite exhibited better wear performance when incorporated with CNT under both wear types. Suresha et.al also studies the effect of filler on CFRP composites under different wear conditions; i.e dry sliding and two-body abrasive wear [3].

Although numerous researchers have studied on the advanced carbon fiber reinforced polymer composites, there is still limited information on the effect of nanoclay filler incorporation on SCF composite, especially when compared between two different wear conditions. In this study, wear properties of nanoclay-filled chopped carbon fiber reinforced polymer composites were investigated under adhesive and abrasive wear conditions.

II. METHODOLOGY

In this experiment, the epoxy resin; Miracast part A/B was used as a matrix. The Miracast 1517 was supplied by Miracon (M) Sdn Bhd and it consists of two parts which are (i) Part A is the epoxy and (ii) Part B is the hardener. The nanoclay material, Nanomer I.30 Montmorillonite clay was used as nanofiller. The nanoclay was supplied by Sigma Aldrich and has a dry size of 8-10 µm and a density of 1.9g/cm3. The fiber reinforcement, carbon fiber (CF) was supplied by Vistec Technologies Sdn Bhd. The carbon fiber was chopped from roving type carbon fiber using SCP Automation Machine; produces short carbon fibers with the average length of between 3-5mm, as shown in Fig. 1.

Fig. 1. Chopped carbon fiber

Nanomodified epoxy resin was prepared using mechanical stirrer and three roll milling machine. Three different amount of nanoclay (1 wt.%, 3 wt.% and 5 wt.%) were prepared. The mechanical stirrer was set at 400rpm speed and 80°C temperature for 30minutes. Meanwhile, the milling process was operated at 14.3 m/s roller speed and 65°C temperature, to ensure uniform dispersion of nanoclay in epoxy resin. In order to produce pure CFRP composites, 10wt% of chopped carbon fiber was added into epoxy resin before hardener is added. The carbon fiber and epoxy was mixed using mechanical stirrer to ensure smooth blending. For nanoclay-modified CFRP composites, similar blending process was adopted but using nanomodified epoxy resin instead of pure epoxy resin. The hardener was then added into the mixture at the ratio of 100:30. The mixture was then stirred manually for 5 minutes before being poured into the silicon mould and cured for 24 hours at room temperature. The summary of composite specimens designation and composition are shown in Table I.

Table-I: Designation and composition of specimens

Composites Designation	Weight fraction (wt%)		
	Epoxy	Carbon fiber	Nanoclay
Pure CFRP	90	10	-
1.0wt% NC CFRP	89	10	1
3.0wt% NC CFRP	87	10	3
5.0wt% NC CFRP	85	10	5

The nanoclay dispersion was observed using Transmission Electron Microscopy (TEM); FEI Tecnai TEM machine at a magnification of 300k. The density of composites was determined using the Archimedes Principle according to ASTM D792. Archimedes Principle state that the buoyant force on an object submerged in a fluid is equal to the weight of the fluid that is displaced by that object. The density of the samples was calculated using Equation (1). Rockwell hardness test scale 'R' was conducted using Series 600 Wilson / Rockwell Hardness Tester according to ASTM D785-08. The scale uses 12.7mm diameter steel ball indenter, 60kg major load, and 10kg minor load. It was chosen in order to cover a large area of epoxy matrix, fiber, and nanoclay. An average of 5 readings on each specimen was taken to get the rationale hardness value.

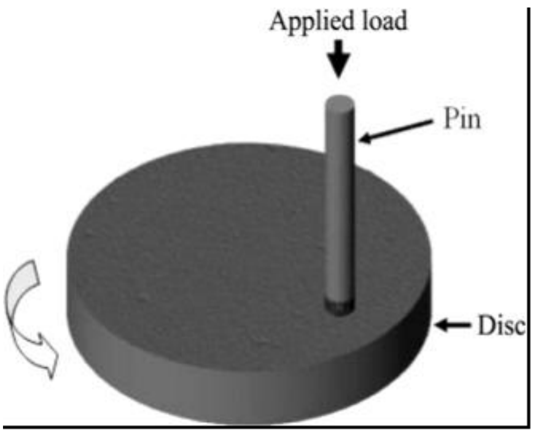
$$\rho = \frac{A}{A-B} \times (\rho_o - d) + d \qquad (1)$$

Where: ρ is the density of the composite specimen, A is weight in the air, B is weight in liquid, ρ_o is the density of the liquid (0.99594 g/cm^3) and d is the density of the air (0.001 g/cm^3). The adhesive wear test was conducted on MAGNUM TE-165-SPOD pin-on-disc tribometer. The pin on disc machine comprised a horizontal rotating disc and a calibrated dead-weight-loaded pin. The contact schematic diagram of sliding bodies is shown in Fig. 2(a). A stainless steel pin of diameter 10mm, length 30mm was used as the counterpart, while the specimen composite was in disc shape of diameter 75mm, thickness 4mm. The sliding movement was performed under the ambient conditions at 30N load, 300rpm speed and 10km distance.

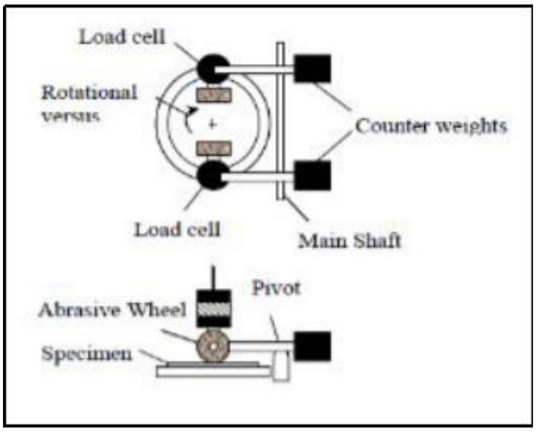
Before each test, the pin surface was polished using SiC abrasive paper to a surface roughness of 0.2µm. The abrasion wear test was conducted on TR-600 abrasion resistance rig tribometer. The abrasion rig comprised of horizontal rotating disc and two rotating abrasive wheel. The contact schematic diagram of sliding bodies is shown in Fig. 2(b). The abrasive wheels are made of vitrified bonded silicon carbide. The specimen composite was in disc shape of diameter 123mm, thickness 4mm. The sliding process was performed under ambient conditions at 30N load, 300rpm speed and 10km distance. At each 2km distance interval, the mass of disc specimen was measured with a precision balance, and then the specific wear rate (W_s) was calculated using Equation (2);

$$W_s = \frac{\Delta V}{L \times F} = \frac{\Delta m}{L \times F \times \rho} \qquad (2)$$

Where; W_s is specific wear rate (mm^3/Nm), ΔV is wear volume (mm^3) ,Δm is mass loss (g), ρ is density (g/mm3) , L is distance travel (m) and F is normal load (N)



(a)

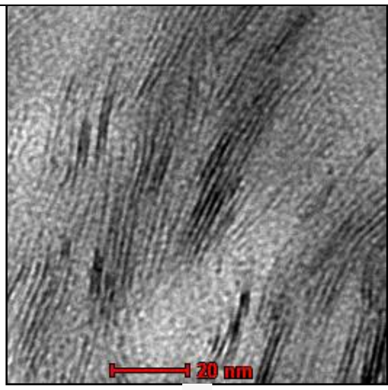


(b)

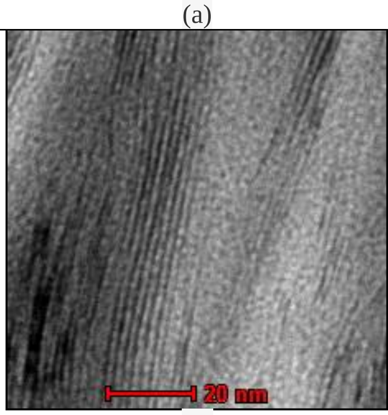
Fig. 2. schematic diagram of a) pin-on-disc and b) abrasion resistance tribometer

III. RESULTS AND DISCUSSION

Fig. 3 shows the nanoclay dispersion images at 300K magnification. The TEM micrographs reveal that the nanoclay filler dispersion in the epoxy resin matrix is almost uniform for all the nanoclay w% of composition. Based on the gap between two adjacent silicate plates, the nanoclay fillers exhibit intercalated and exfoliated structure, with gap between 2.4-8nm and more than 9nm respectively. Therefore, this observed that the combination of mechanical and milling mixing methods are able make epoxy flow uniformly and effectively in between nanoclay platelets, as discussed by [21].



(a)



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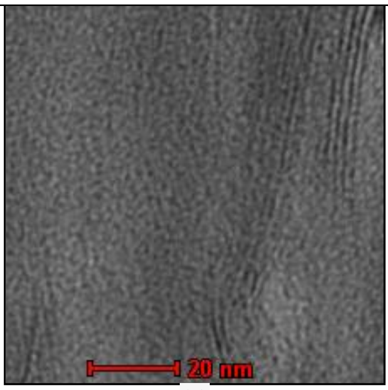

(c)

Fig. 3. TEM micrographs of a) 1.0wt%, b) 3.0wt% and c) 5.0wt% nanoclay at 300000x magnification

Table-II presents the density and hardness of the composites. Study shows that the density increased as the fiber reinforcement and nanoclay filler were incorporated into the epoxy matrix [20]. The increments were mainly due to higher density of carbon fiber and nanoclay filler compared to the plain epoxy resin [15]. However, the density decreased slightly as nanoclay content further increased [1]. On the other hand, hardness measurement also follow similar suit. The hardness (HRR) value increased with fiber reinforcement and incorporation of nanoclay up to 3.0wt% nanoclay content. At 5.0wt% nanoclay content, the HRR decreased tremendously. The higher the nanoclay content might lead to the higher porosity in the composite since the viscosity of nanoclay-modified epoxy matrix has increased, hence the entrapped air remains in the composite system; resulting to voids and porosity condition [17].

Table-II Density and hardness of composites

Composites	Density (g/cm3)	Hardness (HRR)
Pure Epoxy	1.1025	109.8
Pure CFRP	1.1128	112.32
1.0wt% NC CFRP	1.1853	114.8
3.0wt% NC CFRP	1.185	115.44
5.0wt% NC CFRP	1.1805	112.1

The specific wear rate of Pure epoxy, Pure CFRP and its composites are plotted Fig. 4. The graph shows a typical curve of specific wear rate of polymeric materials over time with run-in phase at the beginning of the sliding motion and steady-state phase towards the end of the sliding process. The composites experienced a run-in phase for the first 2km sliding distance where the specific wear rate was high. As distance increased, the specific wear rate eventually decreased. The transition phase between run-in to steady-state phase was closely related to the formation of transfer film where the integrity and development of transfer film affect the specific wear rate and wear mechanism during the sliding event [3], [6], [13].

The highest wear rate was demonstrated by Pure CFRP composite. When nanoclay was added into the Pure CFRP composite, the wear rates improved steadily. And as the nanoclay content increased, the wear rate follows suit. A study by [4], [9], [19] reported that the presence of two types of additives gave the synergistic effect that improved tribological properties of Pure CFRP composite [4], [9], [19]. In Pure CFRP composite, CFs bear the majority of the load. When nanoparticle was dispersed uniformly in the matrix, it homogenized the stress distribution, therefore alleviate stress concentration on the fibers alone [7], [16]. The homogeneous load support of CFs resulting from the good dispersion and interfacial interactions between nanoclays and epoxy matrix, thus improve the wear resistance. The sequence of adhesive wear performance of nanoclay incorporated CFRP composites with their percentage improvement corresponding to Pure CFRP composite are as follows; 1.0w%, 3.0w% and 5.0w% with 18.16%, 34.04%, and 55.68% respectively.

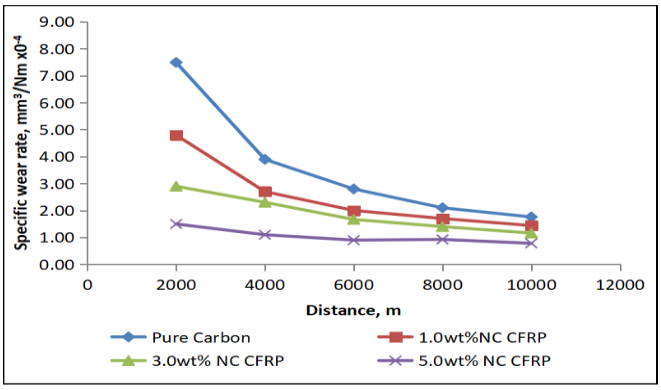

Fig. 4. Specific wear rate of Pure CFRP and its composites against distance under adhesive wear

Fig. 5 shows the specific wear rate of Pure epoxy, Pure CFRP and its composites against distance under the abrasive wear. Typical curves of specific wear rate are displayed by all composites against time; this behaviour is similar to the adhesive wear trend. The specific wear rate was high at first 2km distance due to the freshness of grit in the abrasive roller. However, as abrading distance increased, the specific wear rate was decreased might due to the possibility that some worn particles clog the abrasive grit, reducing its abrasiveness and slows down wear action. As distance increased, the load at the contact region was being shared by more number of worn debris whereby it decreased the stress resulting in reduced wear rate [14].

From the figure, Pure CFRP composite exhibited worse wear properties. When nanoclay was incorporated in Pure CFRP composite, the wear rate reduced steadily. It continued to reduce as nanoclay content increased. The enhanced wear-resistant was attributed to great polymer-filler interaction between nanoclay particle and epoxy matrix that leads to better adhesion between reinforcements in the composites [3]. The sequence of percentage improvements corresponding to Pure CFRP composite are; 1.0w%, 3.0w% and 5.0w% with 26.65%, 35.44% and 44.03%, respectively.

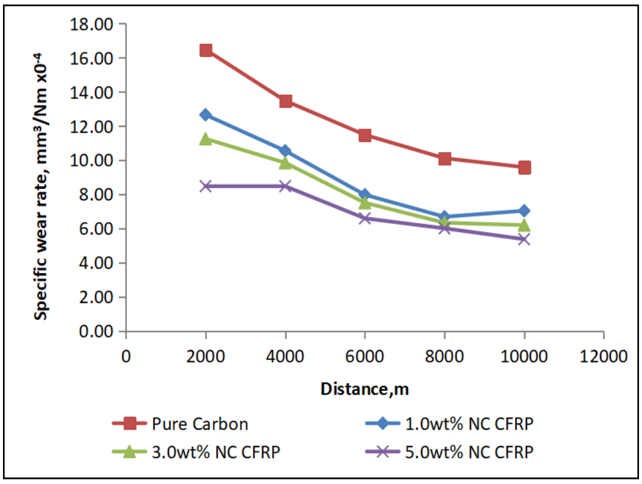

Fig. 5. Specific wear rate of Pure CFRP and its composites against distance under abrasive wear

The effect of nanoclay incorporation in CFRP composite is compared between adhesive wear and abrasive wear, as shown in Figure 6. The abrasive wear exhibit a higher wear rate than adhesive wear, due to different wear mechanisms that occurred during sliding. In the abrasive wear, the abrasive/harder roller cuts and plows the composite surface [6], while adhesive wear involved transfer of material from low cohesive energy density to one of the higher cohesive energy density due to the interfacial adhesion property [22]. Besides that, the figure also shows that nanoclay incorporation gave positive impact in improving the wear rate of the CFRP composites in both wear conditions, especially at 5.0wt% nanoclay content.

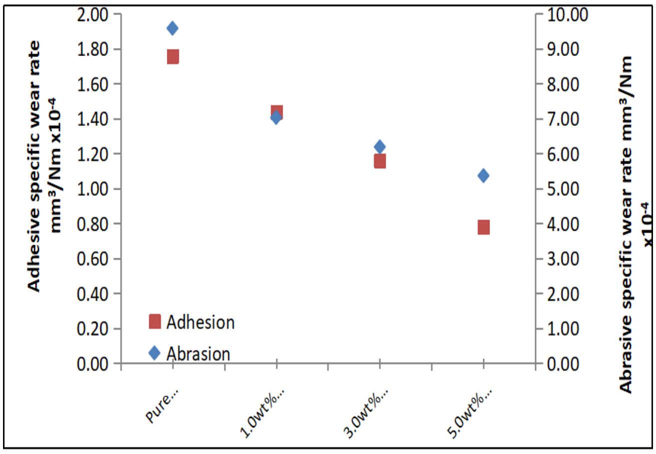

Fig. 6. Comparison of specific wear rate of CFRP composites at adhesive and abrasive sliding of 10km distance

IV. CONCLUSION

This paper reported the specific wear rate of nanoclay-filled CFRP composite under adhesive and abrasive wear conditions. Nanoclay-filled CFRP composite with 1.0wt%, 3.0wt% and 5.0wt% nanoclay content were fabricated using mechanical mixing and three roll mill. The density and hardness of CFRP composites showed increasing value as nanoclay content increased up to 3.0wt%, then decreased slightly. Under adhesive and abrasive sliding test conditions, it was found that the presence of nanoclay particles and carbon fiber gave a synergistic effect on wear resistance of pure epoxy. 5.0wt% nanoclay content exhibit highest wear resistance with improvement up to 55.68% and 44.03% corresponding to Pure CFRP composite under adhesive and abrasive wear, respectively. In conclusion, nanoclay incorporation gave promising result in improving adhesive and abrasive wear properties of CFRP composite. The nature of both testings suggests that the nanoclay-filled CFRP composite has the potential to be exploited in the tribological area, such as the component for sliding-contact and rolling-contact bearing.

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