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Assessing Friction and Wear Behavior of Epoxy Composites Reinforced with Chopped Carbon Fibers

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ABSTRACT

The present study assesses the tribological performance of epoxy composites reinforced with chopped carbon fibers (CCFs). The CCFs having a diameter of ~ 7-8 microns and an average length ranging from ~ 40 to ~ 100 microns were recycled from carbon fiber waste. In the present investigation, epoxy resin was reinforced with CCFs at varying (0.5, 1.0, and 1.5 wt%) to fabricate cylindrical-shaped epoxy composite samples according to ASTM G99 standards. Since friction and wear is an important parameter that governs the tribological behavior of any materials, therefore, the developed epoxy composites were studied under tribometer. It was found that the addition of CCFs in epoxy resin significantly reduces the wear rates and coefficient of friction of the resulting epoxy composites. The addition of 1.5 wt% of CCFs helped lower the coefficient of friction and wear rate by 62% and 29% respectively compared to the control specimen without any reinforcement. The worn surfaces were then characterized under SEM to understand the wear mechanism.

KEYWORDS: **Chopped carbon fibers; Epoxy composites; Wear; Coefficient of friction; Tribology.**

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1. Introduction

The demand for carbon fiber (CF) is increasing rapidly to make lightweight structures for various engineering applications like aerospace, automobile, maritime transportation, civil engineering, porting products, medical equipment, prosthetic devices, etc. [1,2]. The CF is made of polymer precursors, such as polyacrylonitrile, which are spun into yarn and heated to a high temperature during carbonization. By stripping the precursor fibers of their non-carbon components throughout the carbonization process, pure carbon fiber is left behind. Other production techniques, including the pitch method and the plasma approach, have been developed throughout time [3]. While the plasma approach employs a gas plasma to transform a hydrocarbon gas into carbon fibers, the pitch method uses a petroleum-based pitch as the precursor material [4]. The production of CF needs a massive energy supply and hence makes it a costlier solution for high-end applications.

CFs fabrics are mostly introduced in polymer matrices to fabricate carbon fiber-reinforced polymers for the above-said applications. However, during the fabrication process, the trimmings of CF fabrics generate nearly ~ 20 to 30% waste of CF. Similarly, in numerous industries CF leftovers are produced which causes serious environmental problems [5,6]. In addition, CF is an expensive material so the waste and leftovers of CF cause heavy losses to the company which they must bear. Therefore, recycling of waste CF is a preferable solution, particularly chopped carbon fibers (CCF) with significant economic and environmental advantages. Accordingly, the author utilized CCF to develop an epoxy composite (EC) with enhanced thermo-mechanical properties compared to the neat epoxy (NE) without any reinforcement [7,8]. Epoxy resin is a type of thermoset resin that is widely used in many engineering applications today. Its excellent mechanical properties, easy availability, high adhesion properties, good corrosion stability, low shrinkage, and ease of molding make it ideal for use in coating materials, fiber-reinforced composites, sporting goods, and leisure equipment [9–14]. Nevertheless, the cured epoxy resin creates a strongly cross-linked network that reduces wear resistance capabilities and has poor resistance to crack propagation [15]. Since the addition of CCF in epoxy resin improves its strength and toughness without reducing its thermal properties [11,12], therefore it is believed that, if CCF is added to epoxy resin it will help to reduce the wear of the resulting EC.

Therefore, in continuation to the author's earlier work, the present investigation is mainly focused on the tribological behavior of EC reinforced with CCF for the first time.

2. Materials and methods

The waste CF is collected from the leftover unidirectional CF fabrics at Composite Lab, UPES Dehradun. The unidirectional CF fabric shown in **Fig. 1 (a)** was supplied by Composites Tomorrow, Gujrat to the Composite Lab, UPES Dehradun. The single fiber strands were then separated from the fabric as shown in **Fig. 1 (b)** followed by chopping them into ~ 2.5 cm strands as shown in **Fig. 1 (c)**.

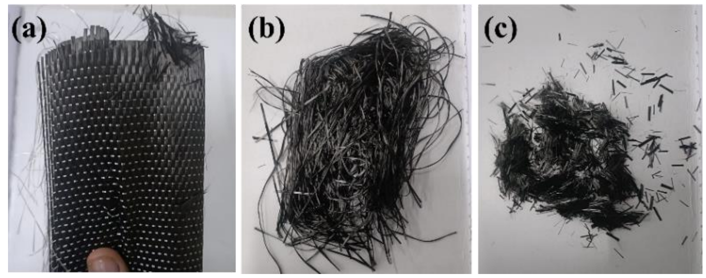

Fig. 1(a) Waste carbon fabric, (b) CF strand separated from the unidirectional fabric, (c) CCF.

The CCF was then cleaned at the soxhlet apparatus **(Fig. 2a)** with ethanol for 48 h to remove the sizing agent present on CF and other impurities. The wet CF is then collected in a petri dish followed by vacuum drying at 80 ºC for overnight as shown in **Fig. 2(b)**. Thereafter, the dried CCF is again crushed in an aged mortar **(Fig. 2c)** to reduce the length of the CCF further.

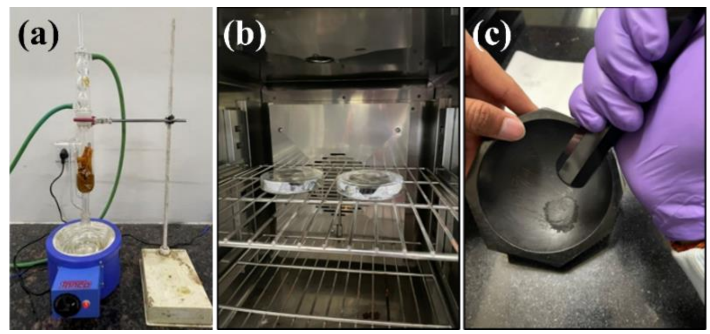

Fig. 2(a) Cleaning of CCF using Soxhlet apparatus, (b) drying of CCF using vacuum oven, and (c) crushing of CCF using aged mortar.

Finally, to examine the impact of CF on the wear behavior of the EC, the CCFs were combined with epoxy resin at wt% of 0.5, 1.0, and 1.5. About 20 g of Lapox L-12 epoxy resin (Make: Atul Ltd, Gujrat) are measured in a plastic beaker to fabricate the EC. After that, the epoxy resin was combined with 0.5 wt% of dried CCF and left overnight. The CCF was evenly distributed throughout the epoxy resin using an overhead stirrer running at 1500 rpm, as seen in **Fig. 3(a)**. As indicated in **Fig. 3(b)**, the mixture was subsequently degassed using a vacuum desiccator to release the trapped air. After that, the epoxy/CCF mixture was mixed with Lapox K-6 hardener in the recommended ratio by the manufacturer followed by further degassing for 5 min to remove the remaining entrapped air. After that, the completed epoxy mixture is put into a silicone mold, as seen in **Fig. 3(c)**, and it is left to cure for 24 h at room temperature. A comparable technique was employed to create EC with 1.0 and 1.5 wt% of CCF. The neat epoxy (NE) sample was similarly prepared without any reinforcement.

Fig. 3(a) Mixing of CCF with epoxy resin using an overhead stirrer, (b) degassing of epoxy resin, and (c) pouring of epoxy resin into silicone mold.

The ASTM G99 standard was followed in the fabrication of the cured cylindrical epoxy composite sample, which has a 50 mm length and a 10 mm diameter, as seen in **Fig. 4(a)**. A wear test was conducted on a pin-on-disc tribometer under dry conditions to evaluate the contribution of CCF to the tribological behavior of EC, as illustrated in **Fig. 4(b)**.

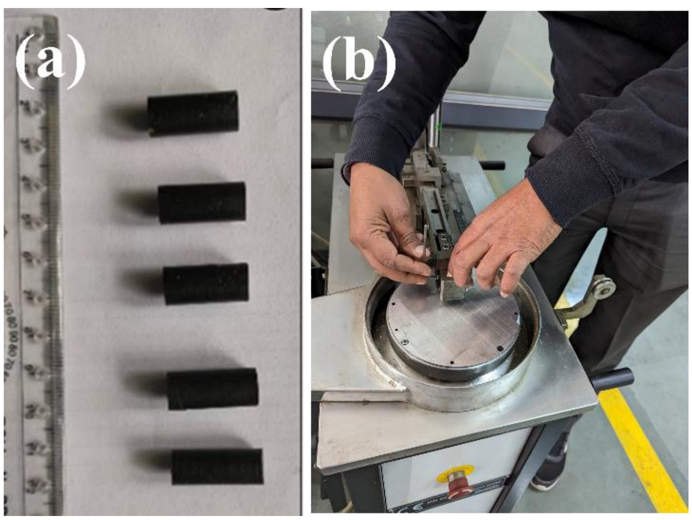

Fig. 4(a) The pin specimens made of cured EC, and (b) mounting of test pin into pin holder of tribometer.

To maintain the track diameter at 60 mm during the test, the composite pin was fixed in the stationary jaw holder. Keeping the load constant at 15 N, the counter disc (hardened ground steel EN-31, hardness 60 HRC, surface roughness 1.6 Ra) was rotated at 300 RMP for 60 min. Eqn. (1) was used to determine the specific rate of the composite samples, and the load sensors were used to estimate the coefficient of friction.

$$W_S = \Delta m \, / \, \rho t V_S F_N \tag{1}$$

In this case, t is the test period (s), V_S is the sliding velocity (m/s), F_N is the average normal load (N), and Δm is the total mass loss during the test (g).

3. Results and Discussion

3.1. Visual and Microscopic Inspection of CCF

It was observed that, when CF was chopped at ~ 2.5 cm length, the fibers tend to agglomerate during mixing with epoxy. The chopped CFs are getting entangled and make a lump of spherical shape as shown in **Fig. 5(a)**. However, when chopped CF was further crushed into smaller spices, these difficulties were overcome. To understand this phenomenon, the crushed CCF was examined under FESEM, and the micrograph is shown in **Fig. 5(b)**. From the FESEM analysis, it is observed that the CF has a diameter of ~ 7.5 µm and a length varying from ~ 40 µm to ~ 100 µm. Therefore, it is concluded that the CCF with a 2.5 cm length and higher length/diameter (l/d) ratio of 3333.33 compared to that of the grounded CCF which has a lesser l/d ratio. The higher l/d ratio for ~ 2.5 cm CCF results in self-entanglements and hence form spherical lumps. Therefore, it is evident that a smaller l/d ratio of CCF is preferable to disperse them into viscous resins.

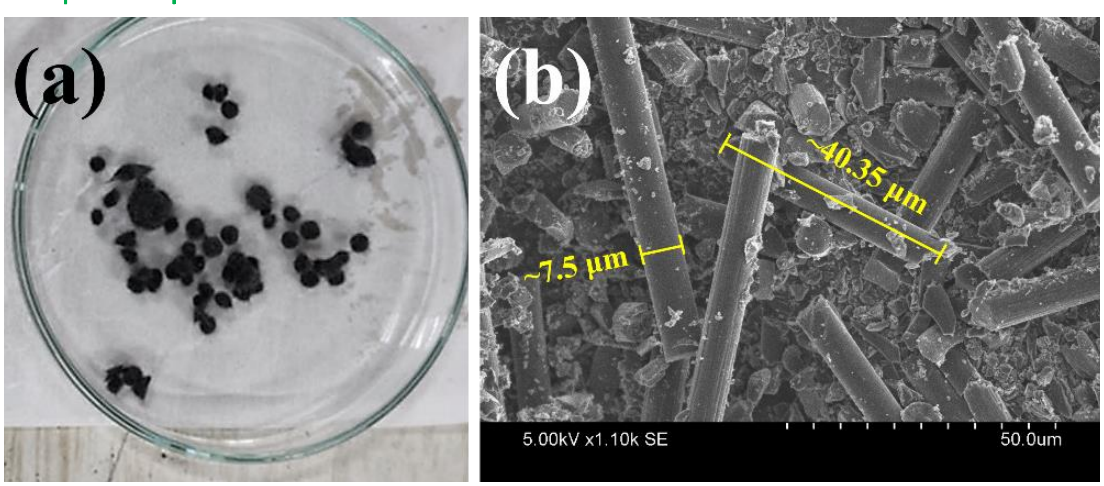

Fig. 5(a) Lump Formation of ~ 2.5 cm CCF during mixing with epoxy resin and (b) FESEM images of crushed CCF.

3.2. Friction and wear

In the present investigation, the wear rate and coefficient of friction (COF) were measured by carrying out the wear test at a pin-on-disc tribometer. The results of wear rate and COF of EC samples containing varying wt% of CCF are exhibited in **Fig. 6(a, b)**. During the wear test, the presence of CCF at the interface of the composite pin and rotating disc helps to reduce the wear rate of the resulting EC. The CCFs are acting as hard particles at the interface and hence lower the wear rate which was reduced by 29% at 1.5 wt% of CCF as revealed by **Fig. 6(a)**. On the other hand, the graphitic nature of CCF acts as a lubricating surface and helps to lower the COF of the resulting EC. At 0.5 wt% of CCF, no significant change was observed in COF, however, at higher wt% the COF started decreasing as clearly observed in **Fig. 6(b)**. A maximum reduction of 62% in COF was observed for 1.5 wt% of CCF owing to the large interaction of CCF at the interface of the pin and rotating disk.

The worn surface was analyzed using a FESEM to comprehend the wear mechanism; the resulting micrographs are shown in **Fig. 7**. The wear rate and friction coefficient of the EC are significantly influenced by the sliding velocity and applied load, and it has been shown that NE wears more than EC [16–18]. The brittleness of the cured epoxy resin is observed to have caused fractures on the friction surface of the NE sample. A brittle fracture [12] that resulted from high pressure and shear stress at the disc's fast sliding speed is indicated by the existence of a distinct imprint in **Fig. 7(a)**, which is indicated by the white arrowhead. However, as demonstrated in **Fig. 7(b)**, the presence of brittle fracture decreased following the addition of 1.5 wt% of CFF in epoxy. Furthermore, it was noted that the worn debris had gathered and compacted around the CCF. Over time, the accumulated debris serves to lower the COF and wear rate by forming a thin coating that acts like a lubrication layer.

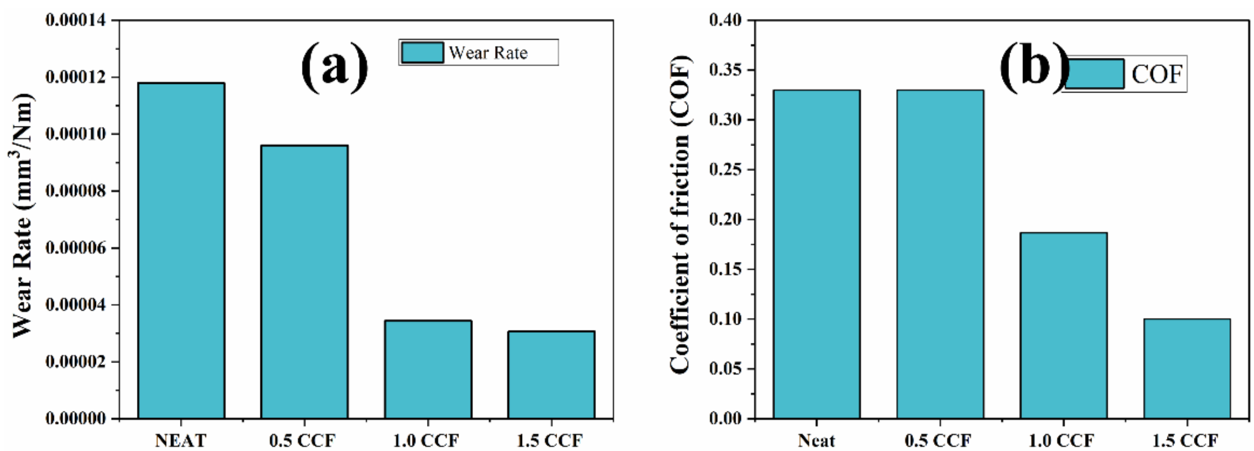

Fig. 6(a) Wear rate and (b) COF of the EC containing different wt% of CCF at a constant load of 15 N.

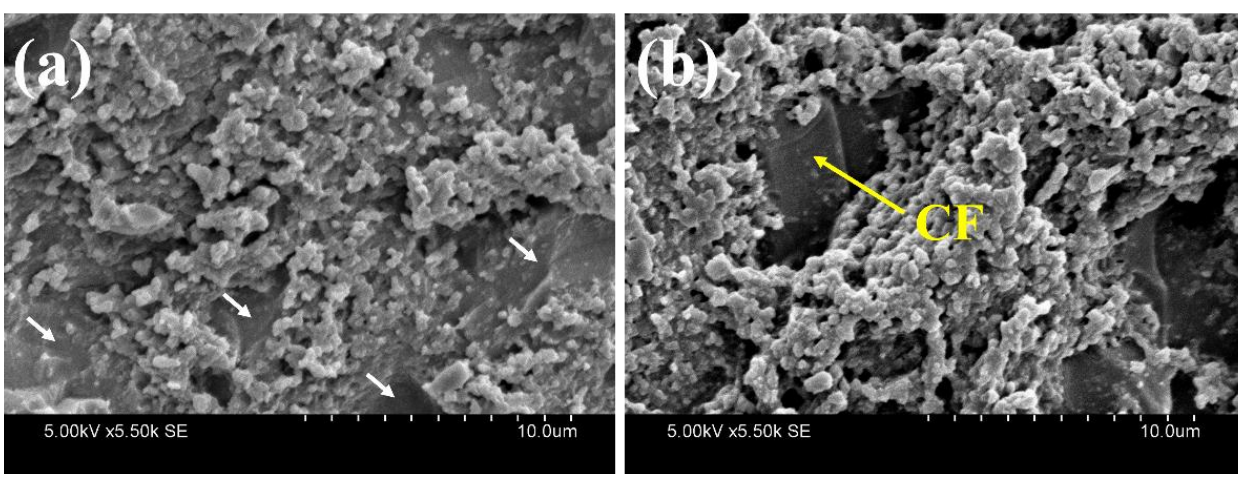

Fig. 7. Worn surfaces of (a) NE sample and (b) epoxy composite filled with 1.5 wt% of CCF.

4. Conclusions

The involvement of CCF in the tribological characteristics of EC is the primary focus of the current investigation. When the EC samples were dry, the wear and COF were measured using a pin-on-disc tribometer. The calculated values of the COF of NE and wear rate are around 0.00012 mm^3/Nm and ~ 0.32, respectively. While 0.5 wt% of CCF added to epoxy resin does not significantly lower the friction coefficient, it does aid to minimize the wear rate. The wear rate and friction coefficient are dramatically reduced by 29% and 62%, respectively, with the addition of 1.5 wt% of CCF. The NE was undergoing brittle fracture to impart shear force during the test in the absence of CCF. However, the presence of CCF helps to lower the wear rate by minimizing the brittle fracture. In addition, the accumulation of debris around the CCF also helps to reduce the wear rate and COF. Thus, it is concluded that recycling waste CF to CCF will open a new pathway to reinforce epoxy and other polymers for developing polymer composites for tribological applications.

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Disclosure statement

The authors declare no relevant financial or non-financial interests.

Data availability

Raw data of the research article is available with the authors and will be provided as per a request from the journal.

Ethical approval

Not applicable.

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