International Journal of Surface Science and Engineering

ISSN online: 1749-7868 - ISSN print: 1749-785X
https://www.inderscience.com/ijsurfse

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DOI: 10.1504/IJSURFSE.2023.10061030

Article History:

Received:	30 June 2023
Last revised:	22 August 2023
Accepted:	22 September 2023
Published online:	15 February 2024

Tribological characteristics of carbon fibre reinforced epoxy composite filled with ceramic particles: influence of multi-walled carbon nanotubes

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Abstract: In this experimentation, an endeavour has been taken to develop the short carbon fibre (SCF) reinforced epoxy composites mixed with multi-walled carbon nano-tubes (MWCNT) and silicon carbide particles (SiCp) using a compression moulding machine. The quantity of MWCNT was modified by 0.5%, 1%, and 1.5%, and SiCp quantity has been taken as 15% by weight of the composite. The influence of the ceramic particles on the wear characteristics of SCF stiffened epoxy was explored. The wear testing variables, namely normal load, sliding speed, and sliding distance, were considered for the dry sliding wear test. As per the ASTM standards, the wear test was executed utilising the pin-on-disc apparatus, and the composite's rate of wear and friction coefficient were studied. The worn-out area on the wear test specimen was examined utilising a scanning electron microscope (SEM) to recognise the wear mechanism of the composites.

Keywords: epoxy; carbon fibre; multi-walled carbon nano-tubes; silicon carbide; compression moulding; tribology.

Reference to this paper should be made as follows: Santhanakrishnan, R., Varghese, A.J. and Kamaraj, M. (2024) 'Tribological characteristics of carbon fibre reinforced epoxy composite filled with ceramic particles: influence of multi-walled carbon nanotubes', *Int. J. Surface Science and Engineering*, Vol. 18, No. 1, pp.71–88.

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This paper is a revised and expanded version of a paper entitled 'Tribological characteristics of carbon fiber reinforced epoxy composite filled with ceramic particles' presented at ICRACM-2023, SRM Institute of Science & Technology, Kattankulathur Campus, Chengalpattu District, Tamil Nadu, 603203, India, 22–24 February 2023.

1 Introduction

Brake pads used in automotive braking systems are generally made of composites involving multiple materials consisting of a binder, fibres, friction modifiers, and fillers to control friction and wear performance effectively (Xiao et al., 2016). The brake pads using a non-metallic matrix consists of altered resins and rubber as an adhesive, whereas organic fibres and inorganic minerals are used as reinforcements (Satapathy and Bijwe, 2004). These are usually manufactured by the hot press method after uniformly mixing these composites with other friction additives (Zhu et al., 2011). In the past few decades, using carbon fibre and its products manufactured in various forms has been a major leap in this advancement. Carbon fibres have excellent mechanical properties, attracting applications in various industries like aerospace, automobile, civil, military, and sports equipment (Kumaresan et al., 2011). Short carbon fibre composites are easier and cheaper to produce than continuous fibre composites. Due to their high wear resistance, carbon composites are also used in advanced frictional systems as brake pads (Zhong et al., 2011).

Setting the friction characteristics is conceivably attained by selecting a worthwhile filler and making its quantity optimal in establishing a friction brake pad. Nano-particles are used as fillers to enhance the property of the composite further (Su et al., 2006). Carbon nanotubes (CNTs) also have excellent mechanical properties due to their unique structure and orientation. Due to their outstanding behaviour in stiffness and strength, multi-walled carbon nanotubes (MWCNTs) were chosen as one reinforcement (Thostenson et al., 2001). Xian and Zhang (2005) researched the importance of SCF on the sliding wear of polyetherimide matrix and announced that adding up to 20 vol.% SCF diminishes the wear rate and friction coefficient, particularly at inflated temperatures. Gbadeyan et al. (2017) researched the consequence of the MWCNT and SCF combination on the tribology of epoxy composites and disclosed that the composite had superior performance. Khun et al. (2014) investigated the tribological characteristics of SCF-toughened epoxy and noticed that incorporating SCF effectively enhanced the tribological characteristics.

Gbadeyan and Kanny (2018) examined the consequence of SCF on the tribological characteristics of MWCNT/SCF epoxy composites. They confirmed that 0.1% MWCNT and 10% SCF-filled composite possessed remarkable properties. Shivamurthy et al. (2018) studied the tribology and mechanical characteristics of CF/MWCNT/epoxy composites. They established that the collaborative outcome of adding oxidised MWCNT to the epoxy matrix improved the wear and mechanical properties. Zhong et al. (2022) explored the outcome of hybrids of fluorinated graphite/MoS_2 fillers on the tribological characteristics of CF/epoxy. They reported that the 1.2 wt.% FGr/MoS_2-toughened CFRP exhibited superior friction dependability owing to the high-temperature protection of FGr. Wei et al. (2018) studied the tribological characteristics of CF/epoxy composites toughened by nano-TiO_2 and MWNTs. They observed that when the additional amount of nano-TiO_2 is 3.0%, and MWNTs is 0.4%, the composite attains outstanding wear behaviour. Naidu et al. (2022) reported that specimen with only hemp as a reinforcement component exhibited better physio-mechanical properties along with lower specific wear rate (1.5368×10^{-5} mm^3/Nm) and coefficient of friction (COF) (0.336) at optimum conditions.

The literature survey shows that many works concentrate on adding carbon nano-tubes or SiCp with carbon fibre-reinforced epoxy. Despite sizeable advancements in vehicle brake pads, most current materials utilised quietly come across wear rate and friction. But no one has concentrated on the combined effect of MWCNTs and SiCp for brake pad applications. In this paper, an effort has been made to investigate the influence of MWCNT and SiCp as additional reinforcements in short carbon fibrous epoxy composites' tribological properties.

2 Experimental work

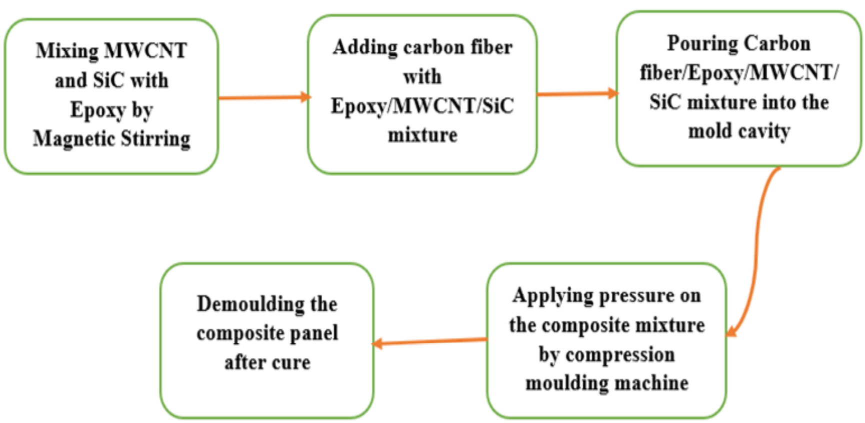
2.1 Materials

All the materials used in manufacturing the hybrid composite panel were sourced from local suppliers in Chennai, India. Short carbon fibres have a filament diameter of 7 µm and 3 mm in length. These carbon fibres' elastic modulus and density are 230 GPa and 1.76 g/cc. MWCNTs have a diameter ranging from 110–170 nm, and their length ranges from 5–9 µm. The MWCNT with the aspect ratio in the range of 45 to 55, and the number of layers in the range of 6 to 8 was used in this research work. The density of selected MWCNTs is 2.1 g/cc, and the SiCp has an average particle size of 50 µm. The structural grade epoxy and readily available hardener selected for this research work are LY556 and HY951, respectively.

2.2 Processing of hybrid composite panels

A mould was developed to make two hybrid composite panels of 200 mm × 150 mm × 4 mm at a time. These composite panels were manufactured in a clean room environment and conformed to best industry practices for quality conformance. The steps followed during the manufacture of the composite panels are illustrated in Figure 1.

Figure 1 Production of hybrid composite panels (see online version for colours)



The composition of MWCNTs was varied as 0.5%, 1%, and 1.5% by weight. Based on the percentage of MWCNTs additive, the epoxy resin and MWCNTs were mixed for 10 minutes using a magnetic stirrer. The composition of SiCp was maintained at 15% by weight (Nassar and Nassar, 2014) and mixed with the existing paste using a magnetic stirrer for about eight minutes until the epoxy was fully formulated with constituent additives of MWCNTs and SiCp. According to the variation of the additives, the viscous black paste was mixed with 50% by weight of short carbon fibres using a mechanical stirrer for 10 minutes to fuse the fibres adequately with the epoxy resin, MWCNTs, and SiCp. This process was executed at room temperature, and the mechanical stirring process was repeated 3 to 4 times until the mixture turned out as a homogenous moulding compound. All the trapped air bubbles due to mixing were fully removed by heating in a thermal oven at 60°C for 3 minutes. The epoxy resin mixture was blended with hardener at a ratio of 10:1 and stirred well.

A mould with 2 rectangular cavities of 5 mm depth was developed for this project. A release film was laid over the mould, and the mixed carbon epoxy composite with additives was poured into the cavity. The charge was evenly distributed and compacted over the entire mould cavity in a controlled manner. The same process was repeated for pouring the second composition, which was already prepared, onto another mould cavity. Another layer of release film was laid over the charge, and the closing tray of the mould was clamped with the base mould. The closed mould was then placed in a compression moulding machine, and a pressure of 5 bar was applied. This compression mould was left for 12 hours to achieve a room-temperature cure. After cure, the panel was removed from the mould cavity using wedges and trimmed by hand. All the trimmed edges were inspected for edge delamination through a close microscopic-based visual inspection to ensure an acceptable level of quality has been demonstrated. The trimmed panel was then placed in a thermal oven for 30 minutes at 50°C to achieve the required post-curing characteristics recommended by the resin and additives suppliers' technical datasheets. The short carbon fibrous epoxy composite test panels were manufactured as per the compositions presented in Table 1.

Table 1 Composition of composite panels

Composite	*Carbon fibre (%)*	*Epoxy (%)*	*SiCp (%)*	*MWCNT (%)*
CW00	50.0	35.0	15.0	0.0
CW11	50.0	34.5	15.0	0.5
CW12	50.0	34.0	15.0	1.0
CW13	50.0	33.5	15.0	1.5

2.3 Characterisation of composite panels

As per the ASTM standards, three specimens were prepared to establish the statistical mean values. The SEM was employed to conduct the microstructural investigation for the composite panels to examine the dispersion of the ceramic particles in SCF-reinforced epoxy. Also, it was employed to examine the worn-out area of the composite panels. The hardness of the composite panels with various compositions of MWNCTs and SiCp was characterised using a Rockwell Ball indenter of 1/16″ diameter and a load of 60 kgf in accordance with ASTM E18-17 (2017) standard. The experimental density (ρ) of all the composite panels was determined by the water immersion method. The wear test was executed utilising the Ducom pin-on-disc wear testing machine (model no: TR20), as shown in Figure 2. The dry sliding wear test was performed at room temperature in accordance with ASTM G99 (2017) standard. The short carbon fibrous composite pin was prepared to have a cross-section of 8 mm × 4 mm with a span of 50 mm. The loaded composite pin was moved against an EN31 steel disc having a hardness of 60 HRC and a track diameter of 70 mm.

The pin specimens were polished with fine sandpaper paper to have a flat contact surface with the disc. The polished test specimen and the disc were wiped with acetone to dispose of if any left-over particles on the surface. The test specimens were weighed using micro-balance (±0.0001 g tolerance), and their dimensions were measured for volume calculations. The specimen was placed inside the pin holder and held against the steel counter face with an applied normal load. The wear-testing machine was operated for a specified speed. From the duration of the test, the sliding distance was calculated using the track diameter. Then the specimen was removed from the holder, wiped with acetone, and weighed again using micro-balance to calculate the weight loss. Based on the weight loss (*W*), normal load (*P*), slide distance (*L*), and density of the pin (ρ), the specific wear rate (*SWR*) was determined adopting equation (1),

$$SWR = \frac{W}{PL\rho} \tag{1}$$

Sliding velocity varies with respect to the space amidst the pin contact and centre of the disc face contact. The sliding distance was calculated based on the sliding velocity (*V*), track diameter (*d*) and duration of the test (*t*) using equation (2),

$$L = \pi dVt \tag{2}$$

The COF was computed by dividing the tangential force by the applied load. The test equipment was fully computerised to control the wear parameters and obtain the results directly. As per the parameters presented in Table 2, the dry sliding wear test was conducted in this research work. The density values of all the composite panels are listed in Table 3.

Figure 2 Pin on disc tribometer setup (see online version for colours)

Table 2 Wear testing parameters

Parameter	*Unit*	*Level 1*	*Level 2*	*Level 3*
Load (P)	N	10	20	30
Sliding velocity (V)	m/s	1.1	1.7	2.2
Sliding distance (L)	m	1,500	2,000	2,500

Table 3 Density of the composite panels

Composite panels	*Density ρ (g/cm³)*
CW00	1.38
CW11	1.40
CW12	1.43
CW13	1.45

The specimens were prepared to carry out the water absorption test in accordance with the ASTM D570 standard. In this test, the specimens were submerged in distilled water for seven days at room temperature. The samples were subsequently taken from the water at regular intervals and the surface of the samples was cleaned with a dry cloth to measure the weight. The water absorption percentage in the composites was calculated by equation (3).

$$W = \frac{W_t - W_i}{W_i} * 100 \tag{3}$$

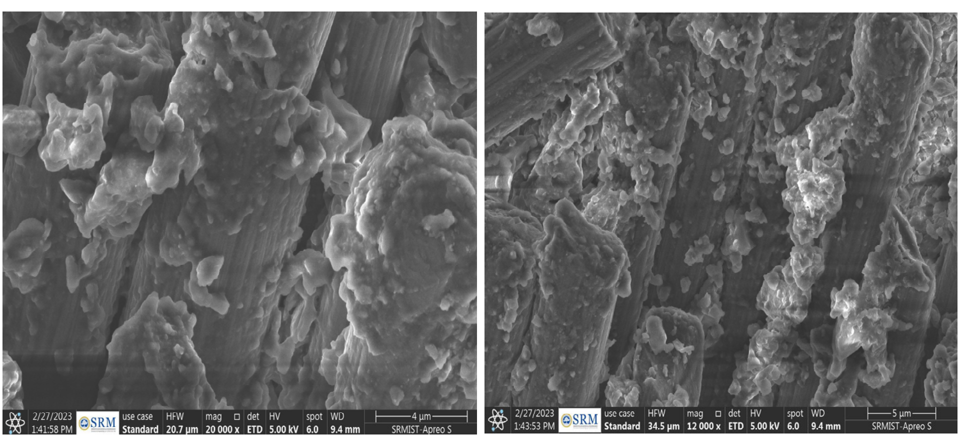
where W is the % of water absorption, W_t is the final weight and W_i is the initial weight.

3 Results and discussion

3.1 Morphology of composites

The SEM micrograph of the 1.0 wt.% MWCNT particles filled SiCp/SCF epoxy composite is shown in Figure 3(a), which shows the homogeneous dispersion of SiCp in the composite and agglomeration in a few locations on the composite. The micrograph also showed the randomly oriented short carbon fibres on the epoxy. The SEM micrographs of the 1.5 wt.% MWCNT particles filled SiCp/SCF epoxy composite is shown in Figure 3(b). The micrograph showed a uniform dispersion of SiCp and MWCNT particles in the SCF epoxy composites while increasing the quantity of MWCNT. The micrographs showed that a perfect bonding is established among the constituent materials of the composites.

Figure 3 FESEM micrographs of the composite panels, (a) CW12 (b) CW13 (see online version for colours)

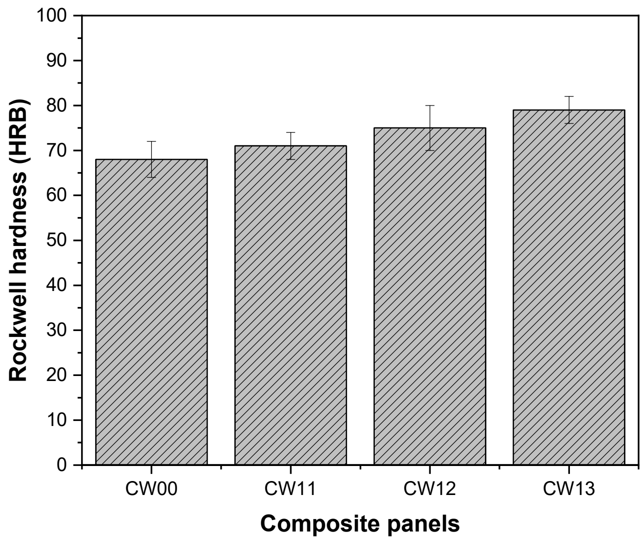


(a) (b)

3.2 Hardness

Figure 4 depicts the average hardness number of composite panels in terms of the variations in the weight fractions of MWCNTs. The hardness of SiCp/SCF is 68 HRB, which is increased to 71 HRB when the composite is filled with 0.5 wt.% MWCNT. The Figure shows that the hardness number increases with increasing the content of MWCNT from 0.5 to 1.5 wt.%. The maximum hardness number of 79 HRB is reported for the SiCp/SCF composite filled with 1.5% MWCNT. This is 16% greater than the hardness number of SiCp/SCF composite. The reason is due to the exceptional performance of MWCNT, which improved the hardness number.

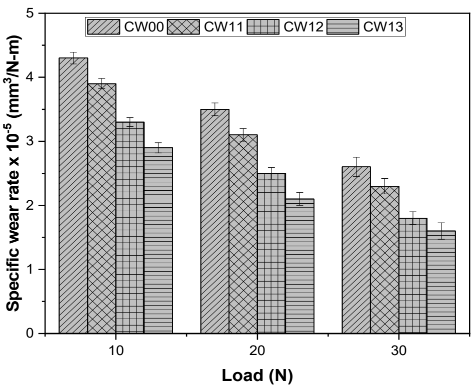
Figure 4 Hardness of composite panels



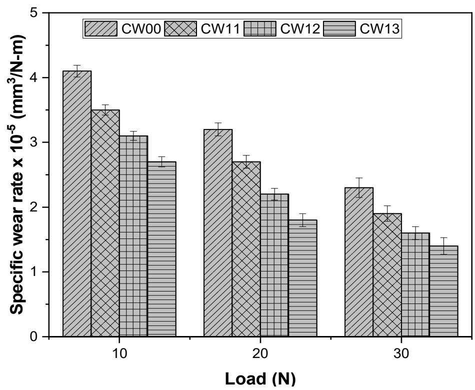
3.3 Effect of normal load on specific wear rate and friction coefficient

To study the impact of loads, the SWR of composites with loads is illustrated in Figure 5 for different sliding velocities and 2,500 m sliding distance. The SWR decreases drastically with increasing the loads for all the composites and sliding velocities. Figure 5(a) shows the maximum wear rate for all the composites at 10 N load and 1.1 m/s sliding velocity. It is noted that the SWR decreases for all the composites while increasing the loads. At 10 N load, the SiCp/SCF composite showed a maximum SWR of 4.3×10^{-5} mm^3/N – m, reduced to 2.6×10^{-5} mm^3/N – m when the load increases to 30 N. This is 65% lower than the SWR at 10 N load. The same results trend is observed for MWCNT filled SiCp/SCF composite. A higher wear rate (4.3×10^{-5} mm^3/N – m) is noticed for SiCp/SCF composite compared to MWCNT filled SiCp/SCF composite. Increasing the MWCNT quantity up to 1.5 wt.% decreases the SWR of SiCp/SCF composite from 4.3×10^{-5} mm^3/N – m to 1.6×10^{-5} mm^3/N – m. This is 169% lower than the SWR of SiCp/SCF composite. The minimum SWR is observed for SiCp/SCF composite with 1.5 wt.% MWCNT. The results reveal that adding MWCNTs into SiCp/SCF composite significantly decreases the wear rate. Namdev et al. (2023) found that incorporating a considerable amount up to 0.5 wt.% of GNP significantly improved the wear performance of carbon fibre reinforced epoxy composites. The SWR of composites as a function of normal loads at 1.7 m/s and 2.2 m/s sliding velocities are illustrated in Figures 5(b) and 5(c). The trend of the SWR plot is similar to those of Figure 5(a).

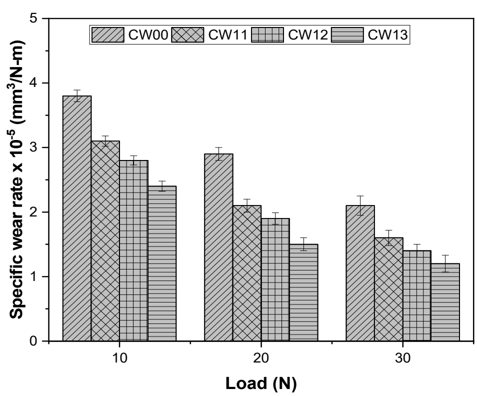
Figure 5 Specific wear rate of composites with normal load at, (a) 1.1 m/s (b) 1.7 m/s, and 2.2 m/s sliding velocities for 2,500 m sliding distance



(a)



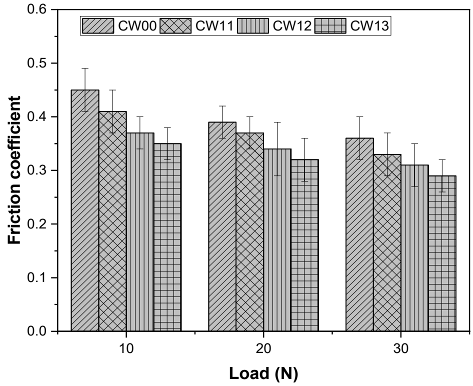
(b)



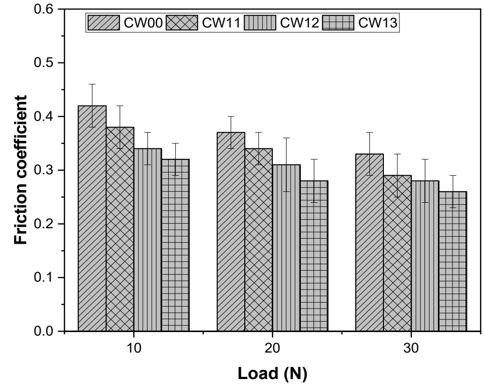
(c)

To study the impact of loads, the COF of composites as a function of load is illustrated in Figure 6 for different sliding velocities and 2,500 m sliding distance. The COF of composites decreases with an increase in load for all the sliding velocities. The Figures show that the minimum friction coefficient is observed for all the composites at 30 N normal load and 2.2 m/s sliding velocity. The variation in the friction coefficient of composites with loads at 1.1 m/s sliding velocity is illustrated in Figure 6(a). The friction coefficient of SiCp/SCF composite decreases from 0.45 to 0.36 when the load increases from 10 N to 30 N. The same results trend is observed for MWCNT filled SiCp/SCF composite. The COF of composites as a function of loads at 1.7 m/s and 2.2 m/s sliding velocities are illustrated in Figures 6(b) and 6(c). The tendency of the friction coefficient plot is identical to those of Figure 6(a).

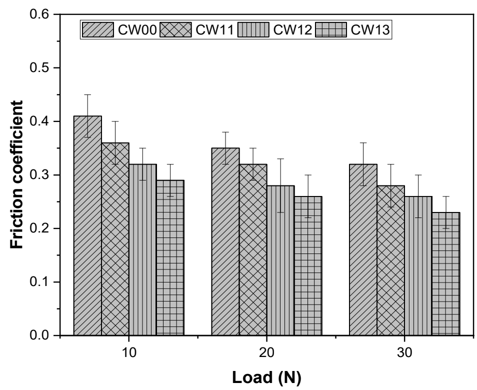
Figure 6 Friction coefficient of composites with normal load at, (a) 1.1 m/s (b) 1.7 m/s, and 2.2 m/s sliding velocities for 2,500 m sliding distance



(a)



(b)



(c)

This is because of the lubricating action of MWCNT filler and abrading nature of carbon fibres.

The presence of MWCNT in SiCp/SCF composite improves the interfacial bonding and mechanical properties. The MWCNT, SiCp, and epoxy take part in rubbing at the time of the wear test. In such cases, MWCNT assists the epoxy from being removed by shearing owing to the applied load. An effective interface suggests that the applied load in the course of sliding would be effortlessly handled by the MWCNT, increasing the wear resistance of the composite surface. Adding MWCNT reduced the interface temperature between the sliding surfaces due to their intrinsic self-lubricating nature and better mechanical property. Moreover, the higher conductivity of MWCNTs increases heat dissipation and avoids the accumulation of heat energy. Similar findings were reported by Shinde et al. (2023) for CNTs filled with silicon rubber composites. However, during the sliding of the composite pin with a steel disc, the carbon fibre eliminates the deformation of the composite pin due to its low thermal expansion coefficient and transfers the heat generated at the interface quickly due to its high thermal conductivity. Similar results are announced by Rezzoug et al. (2019) and Ozsarikaya et al. (2019) for CF-epoxy composite strengthened by metallic filler and CF/MWCNT reinforced polyamide composites.

At lower loads, the temperature rise at the interface is low and insufficient to form a lubricating layer, leading to a maximum wear rate. Further increase in loads enhances the temperature at the junction, forming a lubricating layer that reduces the wear rate. At higher loads, the friction at the mating surfaces increases, leading to exorbitant heat generation (Rao et al., 2021). The sliding friction under a higher load generates a dense sophisticated friction film peeled off throughout the test. The transmission and peeling-off phenomena by the composites exhibited a smaller frictional behaviour and wear rate. At the beginning of the sliding, the distorted rubbish of epoxy resin, SiCp, and MWCNT encloses the CF bundles. The tangling of rubbish amidst the sliding surfaces created a friction layer. This layer is extremely influencing the tribological characteristics of the sliding wear system, which is related to the deterioration of the friction properties of the mating surfaces. Similar results are reported by Sudhagar and Kumar (2020) for carbon fibre-epoxy composite.

3.4 Effect of sliding distance on specific wear rate and friction coefficient

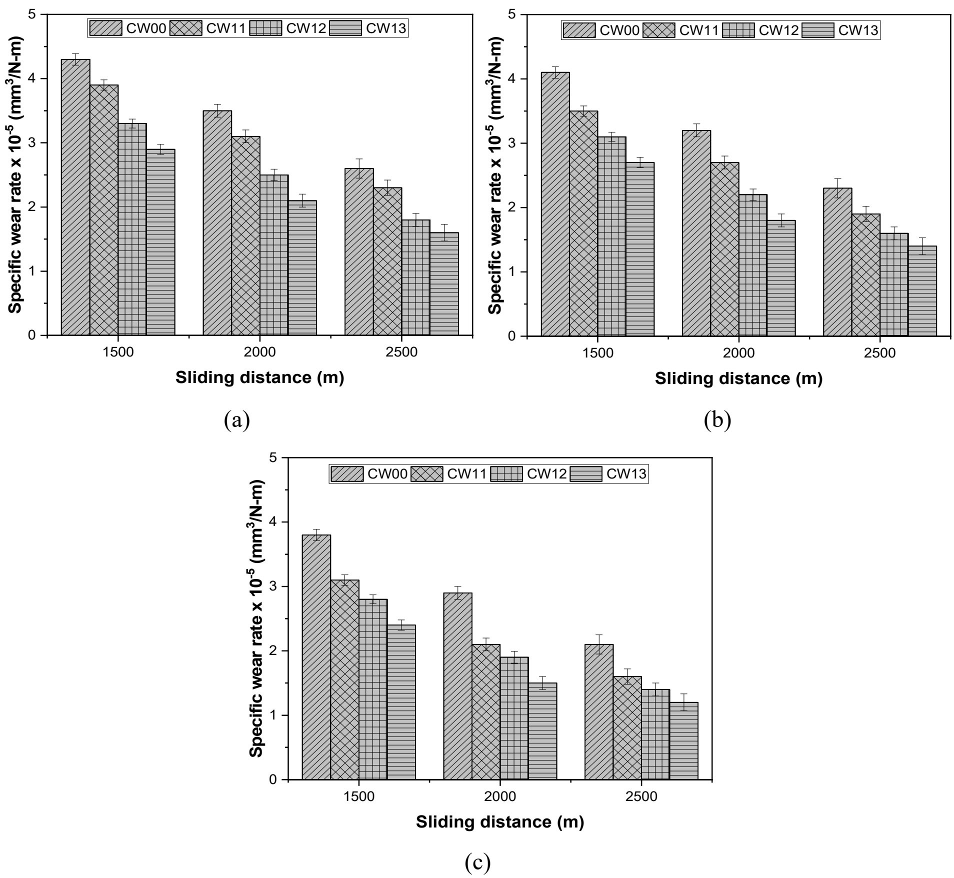
The variation in the SWR of MWCNT filled SiCp/SCF composite with sliding distance is shown in Figure 7 for different sliding velocities and 30 N load. The SWR decreases drastically with an increment in the sliding distance for all the samples and sliding velocities. From Figure 7(a), it is exciting to note that the maximum SWR is observed for all the samples at 1,500 m sliding distance and 1.1 m/s sliding velocity. The Figure shows that the SWR decreases for all the samples with increased sliding distance. At 1,500 m sliding distance, the SiCp/SCF composite showed a maximum wear rate of 4.4×10^{-5} $mm^3/N - m$, reduced to 2.5×10^{-5} $mm^3/N - m$ when the sliding distance increased to 2,500 m. This is 76% lower than the wear rate at a 1,500 m sliding distance. The same results trend is observed for MWCNT filled SiCp/SCF composite.

A higher wear rate (4.4×10^{-5} $mm^3/N - m$) is noticed for SiCp/SCF composite compared to MWCNT filled SiCp/SCF composite. Adding the MWCNT quantity up to 1.5 wt.% decreased the SWR of SiCp/SCF composite from 4.4×10^{-5} $mm^3/N - m$ to 1.4×10^{-5} $mm^3/N - m$. This is 114% lower than SiCp/SCF composite. The minimum SWR is observed for SiCp/SCF composite with 1.5 wt.% MWCNT. The results reveal that adding MWCNTs into SiCp/SCF composite significantly decreases the SWR. The specific wear rate of composites as a function of normal loads at 1.7 m/s and 2.2 m/s sliding velocities are illustrated in Figures 7(b) and 7(c). The tendency of the SWR plot is identical to those of Figure 7(a).

The COF of MWCNT filled SiCp/SCF composite with sliding distance is shown in Figure 8 for different sliding velocities and 30 N load. The COF decreases drastically while increasing the sliding distance for all the composites and sliding velocities. The figures show that the minimum friction coefficient is observed for all the composites at 2,500 m sliding distance and 2.2 sliding velocity. Figure 8(a) shows that the maximum friction coefficient is observed for all the composites at 1,500 m sliding distance and 1.1 m/s sliding velocity. The figure shows that the COF decreases for all the composites with increased sliding distance. At 1,500 m sliding distance, the SiCp/SCF composite showed a maximum friction coefficient of 0.46, which is reduced to 0.34 when the sliding distance increased to 2,500 m. This is 35% lower than the friction coefficient at

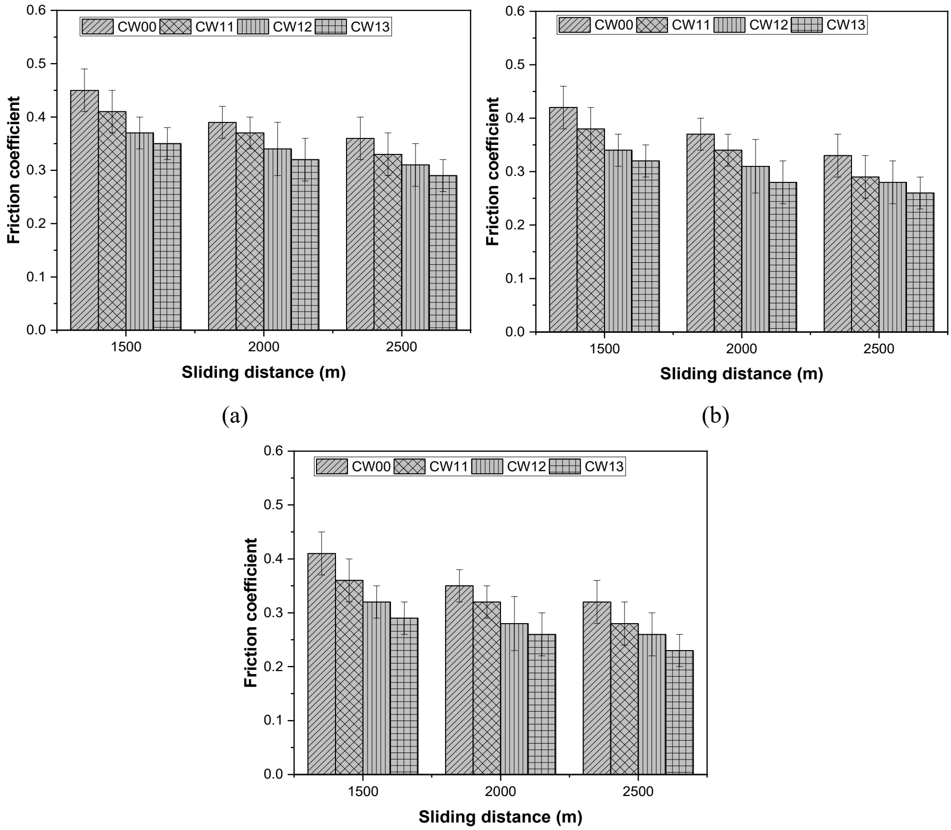
1,500 m sliding distance. The same results trend is observed for MWCNT filled SiCp/SCF composite. Similar results are reported by Fouly et al. (2021) for corn cob-reinforced epoxy-based composites. The COF of composites as a function of sliding distance at 1.7 m/s and 2.2 m/s sliding velocities are illustrated in Figures 8(b) and 8(c). The tendency of the COF plot is identical to those of Figure 8(a).

Figure 7 Specific wear rate of composites with sliding distance at, (a) 1.1 m/s (b) 1.7 m/s, and 2.2 m/s sliding velocities and 30 N load



The wear rate is more at a smaller sliding distance and decreases with increasing the sliding distance. This is because of the oxide film formed on the pin's surface. The film acts as a protective layer, reducing the contact area between the two surfaces. The lubricating behaviour of MWCNT minimises the COF of the SiCp/SCF composite. Moreover, the development of the lubricating film encloses the pin surface, and this film performs as a solid lubricant amidst the tribo pair, and consequently, the COF declines in composites. The friction coefficient of the composite reveals a high value at the start owing to more frictional force. The COF declines as the sliding distance increases because of less friction.

Figure 8 Friction coefficient of composites with sliding distance at, (a) 1.1 m/s (b) 1.7 m/s, and 2.2 m/s sliding velocities and 30 N load



(a) (b)

(c)

Table 4 Water absorption percentage of composite panels

Composite panels	*Initial weight (g)*	*Final weight (g)*	*Weight gain (%)*
CW00	1.4279	1.4320	0.28
CW11	1.5311	1.5347	0.24
CW12	1.2287	1.2314	0.22
CW13	1.3006	1.3034	0.21

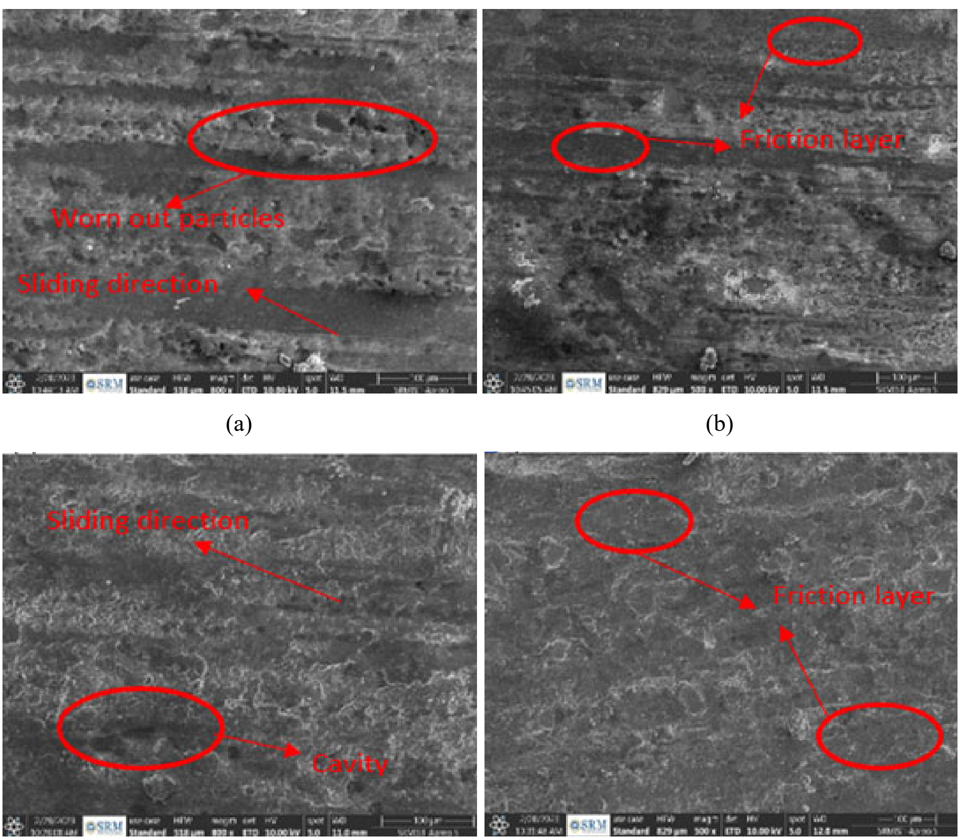
3.5 Water absorption test

Table 4 provides the percentage of water absorption for the MWCNT/ SiCp/SCF epoxy composite. The increase in MWCNT content reduces the percentage of water absorption of the SiCp/SCF epoxy composites. The MWCNT is an efficient barrier to water intake that reduces water absorption in SiCp/SCF epoxy composite. The nanosized MWCNT particles limit the intermolecular motion of the surrounding epoxy, which delays the relaxation of polymer chains, thus reducing the diffusion of tiny molecules through the composites. MWCNT acts as a barrier to water being transported through the epoxy owing to enhanced tortuosity for water molecules spreading through the epoxy.

3.6 Worn surface analysis

Figures 9(a) and 9(b) illustrates the worn-out area of the SiCp filled SCF epoxy composite. Figure 9(a) shows that the SiCp filled SCF epoxy composite at 10 N load, 1.1 m/s sliding velocity reveals a comparatively rough worn-out area with many ploughed furrows. While increasing the load and speed (30 N and 2.2 m/s sliding velocity), the number of ploughed furrows of the composite surface emerges to marginally decreases, evidenced by Figure 9(b). This is due to the formation of lubricating film at the interface at a higher load and speed.

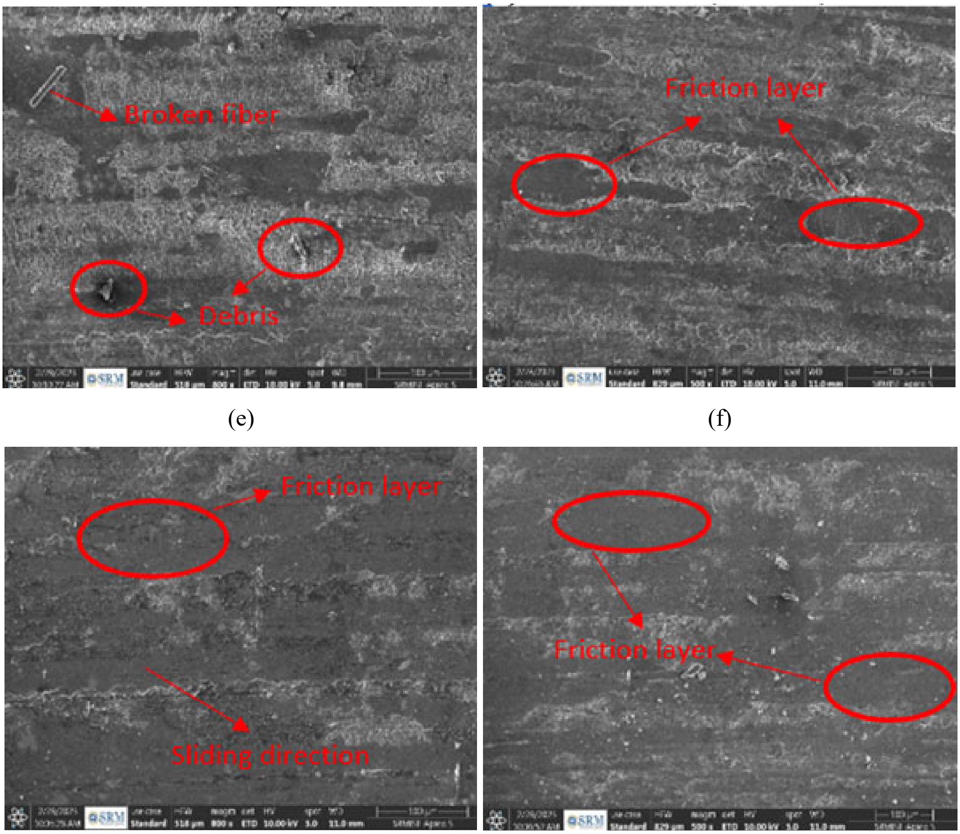
Figure 9 SEM images of the worn-out surface of composites at different loads and velocities, (a) CW00 at 10 N, 1.1 m/s, 1,500 m (b) CW00 at 30 N, 2.2 m/s, 25,00 m (c) CW11 at 10 N, 1.1 m/s, 1,500 m (d) CW11 at 30 N, 2.2 m/s, 2,500 m (e) CW12 at 10 N, 1.1 m/s, 1,500 m (f) CW12 at 30 N, 2.2 m/s, 2,500 m (g) CW13 at 10 N, 1.1 m/s, 1,500 m (h) CW13 at 30 N, 2.2 m/s, 2,500 m (see online version for colours)



(a) (b)

(c) (d)

Figure 9 SEM images of the worn-out surface of composites at different loads and velocities, (a) CW00 at 10 N, 1.1 m/s, 1,500 m (b) CW00 at 30 N, 2.2 m/s, 25,00 m (c) CW11 at 10 N, 1.1 m/s, 1,500 m (d) CW11 at 30 N, 2.2 m/s, 2,500 m (e) CW12 at 10 N, 1.1 m/s, 1,500 m (f) CW12 at 30 N, 2.2 m/s, 2,500 m (g) CW13 at 10 N, 1.1 m/s, 1,500 m (h) CW13 at 30 N, 2.2 m/s, 2,500 m (continued) (see online version for colours)



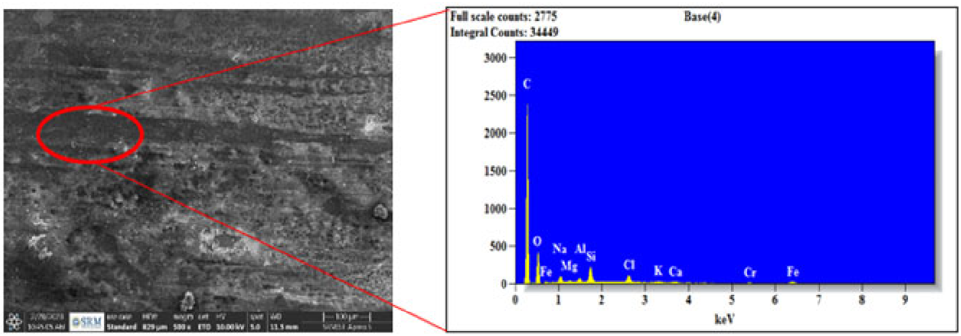
(e) (f)

(g) (h)

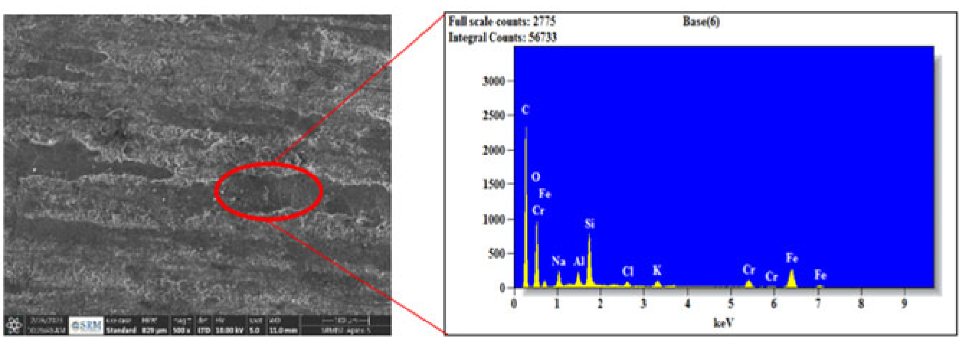
After the incorporation of 0.5% MWCNT into the SiCp/SCF epoxy composite, the number of ploughed furrows of the composite surface decreased, evidenced by Figures 9(c) and 9(d). At a higher load and speed, the damage on the worn surface is reduced compared to a low load and speed [Figure 9(d)]. When the weight fraction of MWCNT rises to 1%, the worn-out area of the nanocomposite changes into even-textured with a few scratching marks, and the ploughed furrows have almost vanished, as indicated by Figures 9(e) and 9(f). At the same time, several small-sized rubbishes are bonded to the worn-out area of the nanocomposite. Figures 9(e) and 9(f) depict more spots containing smooth surfaces due to the lubrication effect compared to Figures 9(a)–9(d). When the weight fraction of MWCNT increases to 1.5%, the worn surface of the nanocomposite becomes smoother than that of the 1% MWCNT filled SiCp/SCF epoxy composite.

Figure 9 shows a nominally meagre transfer film developed in sliding for SiCp/SCF epoxy composite. Consequently, SWR and the COF are larger in the tests at distinct loads and sliding speeds. Adding MWCNT to SiCp/SCF epoxy composite, the capability of a composite to develop a transfer film is perfectly beneficial and generates reliable and persistent transfer film on the pin surface. Eventually, it can be assured from the results that MWCNT filler exhibits an outstanding synergistic development on the tribological performance of SiCp/SCF epoxy composite. Figure 10 shows the EDS spectrum with and without MWCNT filled SiCp/SCF epoxy composite. The EDS spectrum of SiCp/SCF epoxy composite is shown in Figure 10(a), which indicates the elements C, O, Si, Cr, and Fe worn out from both pin and disc surfaces. This is because of the thin layer of the lubricating film formed at the interface. Figure 10(b) shows the EDS spectrum of MWCNT filled SiCp/SCF epoxy composite. The intensity of the elements C, O, Si, Cr, and Fe from the EDS spectrum is more, evidenced by the thick lubricating layer formation at the interface that reduced wear and friction.

Figure 10 EDS spectrum of the composites, (a) CW00 (b) CW12 (see online version for colours)



(a)



(b)

4 Conclusions

The consequences of the MWCNT particles on the tribological characteristics of SiCp/ SCF composite were investigated. The ensuing remarkable conclusions were drawn from the findings:

1 It was observed from the microstructure that the MWCNT dispersed homogeneously in the SiCp/carbon short fibrous composite.

2 There was an 18% enhancement in the hardness number of SiCp/SCF composite filled with 1.5 wt.% MWCNT.

3 The SWR and COF decrease while increasing the loads, sliding velocities, and sliding distance for all the composites.

4 The SWR and COF were found to be minimum at 30 N load, 2.2 m/s sliding velocity, and 2,500 m sliding distance.

From the results of this research work, it is concluded that the CW13 composite panels show higher hardness and superior wear resistance. The COF of the composite is within the range of standard commercial brake pad material's COF of 0.25 to 0.5, Hence this material can be a substitute for the existing commercial pads based on its application.

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