

Tribological Advancements in Glass Fabric Epoxy: Effects of Halloysite Nanotubes Additives

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Keywords:

Glass fabric reinforced epoxy
Hnts
SWR
CoF
Scanning electron microscopy

ABSTRACT

In this study, the effects of halloysite nanotubes (Hnts) on the dry sliding wear behavior and coefficient friction (CoF) of E-glass fabric-reinforced epoxy (G/E) composites will be examined. It aims to identify the ideal Hnts weight percentage for improving the wear performance of G/E composites for demanding applications. In the study, G/E composites with varying Hnts weight percentages (2, 4, and 6) were produced and their tribological characteristics were assessed. Under various load and speed conditions (25 N, 3 m/s to 75 N, 5 m/s), the specific wear rate (SWR) and CoF respectively were measured. To identify wear mechanisms, worn surface micrographs were examined by scanning electron microscopy. In line with the study, adding Hnts to G/E composites greatly increases their resistance to wear and lowers their CoF. The composite with 6 wt % Hnts had the lowest SWR ($27.45 \times 10^{-6} \text{ mm}^3/\text{N m}$), which was 26.4 % lower than the unfilled G/E composite. With CoF values of 0.31 at 25 N, 3 m/s and 0.48 at 75 N, 5 m/s, the 6 wt % Hnts composite had the lowest values. Wear mechanisms for unfilled and Hnts-filled composites are different; unfilled G/E exhibits significant matrix damage, whereas Hnts-filled composites exhibit enhanced transfer film formation, fiber thinning, and matrix protection. This study is unique in that it investigates the use of Hnts as filler in G/E composites. By highlighting the promising properties of Hnts for enhancing the friction performance and wear resistance of epoxy-based composites reinforced with E-glass fabric, it offers fresh perspectives on the possible uses of Hnts in high-performance composite materials.

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Received: 12 December 2024

Revised: 18 February 2025

Accepted: 17 March 2025



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1. INTRODUCTION

As modern industries develop, the working conditions of mechanical motion components under dry and lubricated conditions are

becoming harsher due to heavy loads, frequent start-stops, speed variations, and other factors [1,2]. This problem can be addressed by improving the properties of the lubricating medium [3,4] or by substituting high-

performance non-metal for metal-metal friction pairings. Both approaches will guarantee the reliability of the motion tribo-system in this situation.

Over the past few decades, a large number of researchers have studied the tribological behavior of fiber-reinforced polymer composites (FRPCs) [5-7]. Recent years have revealed that the addition of sub-micron and nanoparticles, such as carbon nanotubes [8], graphene [9], titanium dioxide [10], and silicon dioxide [11], further enhances the tribological performance of FRPCs. Because of their self-lubricating characteristics, polymeric composites have actually been widely used in mechanical components to replace metallic materials that are subjected to dry friction conditions [12-14].

The addition of nanofillers to FRPCs enables the design of composites for high-performance, wear-intensive applications in the industrial, marine, automotive, and aerospace sectors. The wear resistance of FRPCs is greatly increased by functional nanofillers, such as nanotubes, which improve load distribution, reduce friction, strengthen the matrix, create protective transfer films, and lessen wear-induced damage [15]. Recent developments have shown that FRPCs containing nanofillers have superior wear resistance and reduced coefficient of friction (CoF) [15-19]. Mohanty and Srivastava Kumar [15] found that adding nano-alumina particles to glass/carbon fiber-reinforced hybrid composites significantly enhanced their tribological properties by strengthening the bond between the epoxy and fiber. Singh et al. [16] developed hemp-sisal natural fiber-reinforced hybrid epoxy composites with varying nano-silica content (0-4 wt %) and conducted dry sliding wear tests using a pin-on-disc machine under different loads, distances, and speeds. Their study revealed that nano-silica had the greatest impact on wear performance, contributing 32.6 %, with 2 wt % nano-silica at a 10 N load, 1.5 m/s sliding speed, and 500 m sliding distance yielding the highest wear resistance. Muralidhara et al. [17] used vacuum bagging combined with hand layup to develop epoxy-based hybrid composites reinforced with carbon fabric and halloysite nanotubes (Hnts), finding that load, abrading distance, and filler content significantly influenced abrasive wear. Naveed et al. [18] investigated the dry sliding wear behavior of

carbon fiber-reinforced epoxy composites and chemically treated sansevieria with and without nano-silicon carbide and nano-calcium carbonate fillers. They observed that both fillers decreased the specific wear rate (SWR). A study by Divya et al. [19] investigated how nano-silica influenced the dry sliding wear and dynamic mechanical behavior of carbon fabric-reinforced epoxy composites. They found that the best conditions for reducing SWR and CoF were 3 wt % filler loading, 0.75 m/s sliding velocity, and 15 N applied load.

Mechanical, tribological, thermal, water-absorption, and vibration characteristics of glass fiber-reinforced polymer composites are highlighted by Sathishkumar et al. [20] in their review. Santoshkumar and Singh [21] carried out a thorough analysis of the basic concepts of tribology, looking at recent studies on the tribo-performance of thermoset polymer composites reinforced with carbon or glass fiber, specifically adhesive wear. They also examined transfer film properties and pinpointed areas that needed more research. Various factors, including the type and amount of filler used, affect the properties of glass fiber-reinforced polymer composites [22-27]. FRPCs with micro/nanofillers have been the subject of extensive research recently. In contrast to unfilled composites, Jeyakumar et al. [22] found that nanoclay addition enhances wear resistance and reduces the SWR by bonding within the matrix, covering the openings of plain woven glass fiber fabric, and increasing strength. James et al. [23] found that because graphite is self-lubricating and glass fibers have a high strength and modulus, adding 10 wt % TiO₂ and 5 wt % graphite to glass fiber-reinforced epoxy (G/E) composites improves wear resistance. Borah and Samanta [24] investigate the effects of natural and ceramic fillers, such as sawdust, fish scale powder, and SiC, on the wear behavior of glass/jute epoxy hybrid composites. They showed that the addition of fillers lowers the wear rate and enhances the mechanical and physical characteristics of the composites. The dry sliding friction and wear characteristics of G/E composites with aluminum particles were investigated by Sarakar et al. [25]. They found that the friction behavior is dependent on the filler content, sliding speed, and load, and that wear loss increases with speed and load. Additionally, they found that a small amount of aluminum filler reduces wear loss in comparison

to unfilled composites. In the study by Jakab et al. [26], silica filler particle size has a major impact on wear rate; coarse particles reduce wear because of their strong bonding at the resin/filler interface. Abdel-Magied et al. [27] observed that adding 10 wt % SiC to G/E composites increased wear resistance by 75 % compared to unfilled composites.

Reliable mechanical operation, reduced wear, and increased efficiency all depend on controlling the CoF in machine parts and bearings. Modern materials, like fiber-reinforced polymer composites with lubricating fillers, have revolutionized friction control for a variety of uses. These developments, which were first aimed at enhancing the energy efficiency of major components like engines, compressors, and pumps, are now found in micro- and nano-electromechanical systems. For these applications, low friction coefficients are important. However, the comparatively high CoF of glass fiber reinforced polymer composites [28] restricts their extensive use in mechanical parts.

Additionally, to improve the friction characteristics, woven high strength glass fabric reinforced composites were coated with graphene dispersion that was prepared by combining graphene with polymers [29]. Additionally, graphene oxide has been shown to have self-lubricating characteristics in G/E composites [30]. Demir and coworkers [31] study on the impact of filler type and content on the mechanical and tribological properties of G/E composites found that the MgO-filled composite with a 1.4 % filler ratio had the lowest CoF of 0.45 under a 15 N load. The impact of adding Hnts on the dynamic mechanical and tribological characteristics of carbon/glass hybrid composites was examined by Rajeshkumar and his group [32]. They realized that the minimal wear loss and CoF were 9.6894 μm and 0.5984, respectively.

Previous studies by other researchers have verified that the CoF and SWR of polymers sliding against steel counterface is decreased when thermoset matrices are reinforced with synthetic fibers, micro, and nanofillers. Nonetheless, the type and orientation of the fibers, the amount, shape, size, and composition of the matrix, as well as the testing parameters, such as sliding speed, load, and environment, all have an impact on the

performance [15-32]. Studies on the tribological behaviour of epoxy-based composites reinforced with glass fiber and Hnts are comparatively scarce [33-35].

This study examines the role of Hnts as fillers in G/E composites in a novel way. It systematically investigates the impact of different Hnts loadings (2, 4, and 6 wt %) on the tribological performance of G/E composites, distinguishing it from previous studies. The findings indicate that Hnts enhance wear resistance and reduce CoF in composite materials, making them more suitable for high-performance applications.

The primary objectives are to evaluate the effects of Hnts on the friction and dry sliding wear behavior of G/E composites, determine the optimal Hnts wt % for improved mechanical performance and wear resistance, and analyze wear mechanisms through worn surface micrograph examination. Furthermore, this study highlights the potential of Hnts as promising filler for enhancing the wear resistance and friction performance of high-performance epoxy composites.

2. MATERIALS AND METHODS

2.1 Materials

The resin used in this study was modified diglycidyl ether of bisphenol A-based epoxy (LY556). The curing agent was polyamine amide (HY951, room-temperature cure) from Huntsman, Hindustan Ciba-Geigy Ltd, India. Following the manufacturer's guidelines, the epoxy-to-hardener ratio was maintained at 100:10 by weight. The properties of the epoxy matrix are summarized in Table 1. A woven glass fiber mat, manufactured by Hayael Aerospace India Private Ltd., Chennai, India, was used as the reinforcing agent in this study.

The woven structure enhances mechanical properties by providing balanced strength in both warp and weft directions, improving load distribution and impact resistance. This glass fiber mat was specifically chosen for its high strength-to-weight ratio, thermal stability, and compatibility with the epoxy matrix. The detailed properties of the plain weave glass fiber mat are presented in Table 2.

Table 1. Properties of epoxy matrix material.

Properties	Epoxy (LY556)
Colour	Yellowish
Viscosity ((mPa s)	8000-12000
Density (g cm ⁻³)	1.19
Glass transition temperature °C	67
Hardness (Shore D)	85
Tensile strength (MPa)	52
Tensile modulus (MPa)	2800
Elongation at break (%)	11

Table 2. Properties of plain weave glass fiber mat.

Properties	Glass fiber mat
Aerial density (GSM)	300
Threads count	3×3×6 threads/cm
Density (g cm ⁻³)	2.54
Hardness (Shore D)	85
Breaking strength (N)	3200
Elastic modulus (GPa)	200
Strain at maximum load (%)	1.9
Energy at break (J)	0.47

Halloysite nanotubes (Hnts) are innovative one-dimensional natural nanomaterials characterized by predominantly hollow tubular structures and high aspect ratios.

Their exceptional mechanical strength, thermal stability, biocompatibility, and natural abundance make them highly promising for various applications advanced nanocomposites. Halloysite nanotubes (cylindrical: length range 1–3 μm; mean particle diameter 30–70 nm; surface area 64 m²/g) were sourced from Sigma Aldrich, Bangalore, India, and used as a functional nanofiller. According to supplier specifications, the density of Hnts is 2.53 g/cm³.

2.2 Fabrication of hybrid nanocomposites

The industry uses a lot of Hnts for cement, ceramics, and fertilizer goods. Furthermore, Hnts are a kind of naturally occurring filler that shows promise for enhancing the mechanical, tribological, and thermal properties of different polymers.

Hnts filled hybrid nanocomposites were processed using hand lay-up technique in conjunction with ultrasonication as shown in Figure 1. In order to prevent the formation of aggregates linked to nanofillers, ultrasonication was introduced [36]. More details on fabrication of and its hybrid nanocomposites are given elsewhere [37].

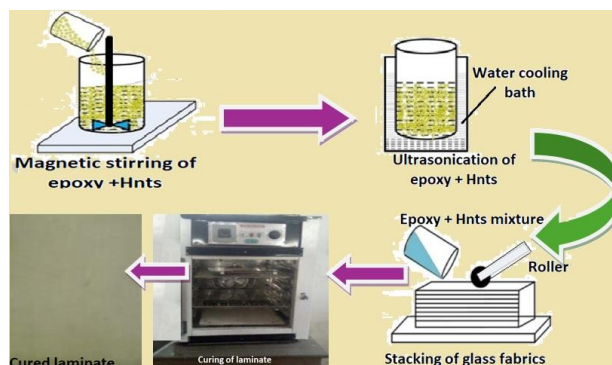


Fig. 1. Diagrammatic representation of the fabrication steps for nanocomposites.

The diagrammatic illustration of the steps involved in fabricating neat G/E and its hybrid nanocomposites are displayed in Figure 1. Table 3 lists the weight percentage of the epoxy matrix, Hnts, and glass mat in the hybrid nanocomposites. Water jet machining was used to create test samples from manufactured laminates following ASTM standards. In our earlier research, we tuned the Hnts loading based on the mechanical characteristics performance [37], and we continue this strategy in this study.

Table 3. Compositions of composites and hardness.

Composite (label)	Epoxy (wt %)	Hnts (wt %)	Glass fiber (wt %)	Hardness (Shore D) [34]
G/E (H0)	50	0	50	29
Hnts-G/E (H1)	48	2	50	36
Hnts-G/E (H2)	46	4	50	43
Hnts-G/E (H3)	44	6	50	55

2.3 Wear testing

A pin-on-disc wear apparatus (manufacturer: Magnum Engineers, Bangalore, India) was used to conduct dry sliding wear tests in compliance with ASTM G-99 standards [38]. This test method evaluates the wear loss of the composite materials under controlled conditions by measuring friction and material loss.

The test setup consisted of a composite sample (6 mm × 6 mm × 3 mm) securely mounted on a pin with a diameter of 6 mm and a length of 25 mm. The pin was brought into contact with a rotating hardened alloy steel disc, which had a surface roughness (Ra) of 0.25 μm and a hardness of 62 HRC (Fig. 2). During testing, a

constant normal load was applied, and the frictional force was recorded in real-time. The coefficient of friction was subsequently calculated based on the measured friction force and applied load. A comprehensive summary of the wear test parameters is provided in Table 4. To ensure correct surface contact with the counterface, the test samples were polished against 1200 grade SiC paper prior to testing.

Table 4. Dry sliding wear test conditions.

Parameter	Values
Applied load (N)	25, 50, 75
Sliding velocity (m/s)	1, 2, 3
Sliding distance (m)	5000

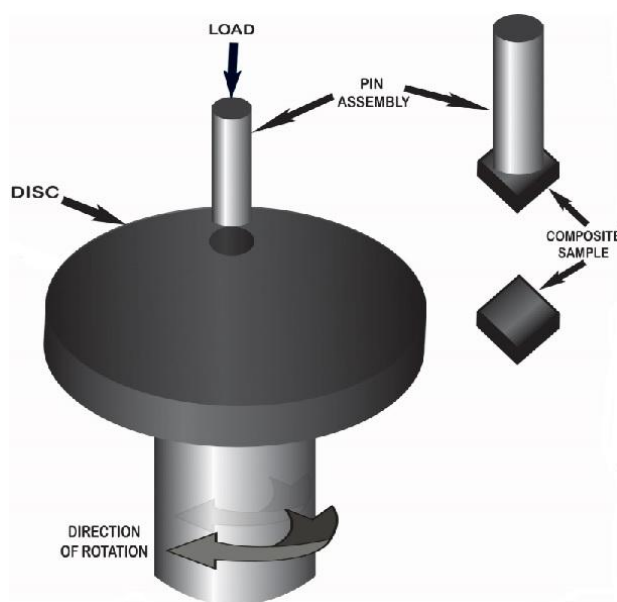


Fig. 2. Pin on Disk wear apparatus.

Before wear testing, the surfaces of the counterface disc and the sample were carefully dried and cleaned with a soft piece of paper soaked in acetone. First, the pin assembly was weighed in an electronic balance (Mettler Toledo) with a precision of 0.1 mg. The weight (wt.) loss is measured as the difference between the starting and final weights. While wear volume (Wv) loss, and SWR were determined with the equations (1), and (2), respectively.

$$Wv \text{ loss} = \frac{wt. \text{ loss} (g)}{\rho \left(\frac{g}{mm^3} \right)} \quad (1)$$

$$SWR = \frac{Wv (mm^3)}{l (N) \times SD (m)} \quad (2)$$

where, ρ : measured density,, l : Applied load, SD : sliding distance. The coefficient of friction was continuously tracked and documented in real-time throughout the wear tests in order to observe changes over the duration of the experiment. For every set of test samples, five samples were run. Hence, the findings shown are the mean of five readings, and the mass loss relative deviation was less than 6 %.

After the wear test, the wear mechanisms were identified by examining the unfilled G/E and Hnts filled G/E worn surfaces under a scanning electron microscope (SEM).

3. RESULTS AND DISCUSSION

When a polymer sample rubs up against a surface, it wears down progressively and releases debris in the form of material. Wear and friction are prejudiced by a number of variables, together with temperature, which is uncontrollable, although surface roughness and distance are. In polymer tribology, friction is essential because it softens the matrix, which causes pieces of the sample to tear off. Because of its cross-linked nature, which results in a high CoF and poor wear resistance, epoxy is often not chosen into consideration for wear-resistant applications, in contrast to thermoplastics [39]. Therefore, the role of Hnts in G/E composite samples to improve the wear resistance and lower CoF is described and addressed in the part that follows.

3.1 Wear loss of hybrid nanocomposites

Demonstrates experimental data for sliding wear loss of G/E hybrid composite with Hnts filler added for different applied loads (25, 50, and 75 N) and sliding velocities (2, 3, and 4 m/s). It is evident from Figure 3a-d that in all situations, wear loss rises as the applied load increases from 25 N to 75 N. Wear loss increases more noticeably at higher loads, suggesting that higher load results in more material removal. All compositions (unfilled G/E (H0) and Hnts-reinforced composites (H1 to H3) exhibit this trend.

Figure 3a-d illustrates how sliding velocity affects wear loss showing that under all load conditions, wear loss similarly increases with sliding velocity. More frictional interaction occurs with

the material as the velocity rises from 3 m/s to 5 m/s, increasing wear loss. At higher loads, particularly 75 N, the rate of increase becomes more pronounced, indicating that wear is exacerbated by both load and velocity.

It is also evident from the figures that the addition of Hnts to H0 composites decreases wear loss. When H0 sample (Fig. 3a) is compared to H1 sample (Fig. 3b), H2 sample (Fig. 3c), and H3 sample (Fig. 3d), the wear loss decreases as the Hnts loading increases. Through an increase in the composite's load-bearing capacity, the reinforcement effect of Hnts improves wear resistance. H3 sample exhibits the best wear resistance, proving that a higher Hnts loading successfully lowers wear loss.

According to Kumar et al. [40], wear loss for unfilled composites is nearly linearly proportional to the increase in applied loads. In contrast to filled composites, the graphite filler also improved mechanical properties and wear resistance, according to Shalwan et al. [41]. Furthermore, Suresha et al. reported a similar trend [42]. Figure 3 is presented for discussion in order to investigate how sliding velocity affects sliding wear loss. In every instance, wear loss rises linearly as applied load and sliding velocity increase. For varying applied loads and sliding velocities as depicted in Figure 3a-d, at a velocity of 3 m/s and a load of 25 N, the composite with 6 wt % Hnts (H3) exhibits the least amount of wear loss. In every instance, for a given load, the wear loss rises linearly as the sliding velocity increases. As load and velocity increase, wear loss also increases, as seen in Figure 3a-d. In comparison to the H2 and H3 samples, the H1 sample is exhibiting comparatively greater wear loss. In Figure 3d, it is evident that wear loss is increasing in tandem with velocity. An increasing wear loss of 0.0073 g to 0.173 g is observed in H3 composite sample at 50 N and 75 N at 5 m/s.

According to the published findings, unfilled composites experience the greatest wear loss when compared to Hnts-filled composites. Therefore, in this study, H0 composite was hybridized with different Hnts loading, and improved wear loss outcomes were achieved. This is because glass fiber, a synthetic fiber with low density and high strength, enhances the composite's hardness property. Additionally, the addition of Hnts improves fiber-matrix adhesion,

which further enhances the G/E composite's resistance to wear. The formation of a transfer film on the counter surface is aided by the presence of Hnts in the composite matrix, which lowers wear loss.

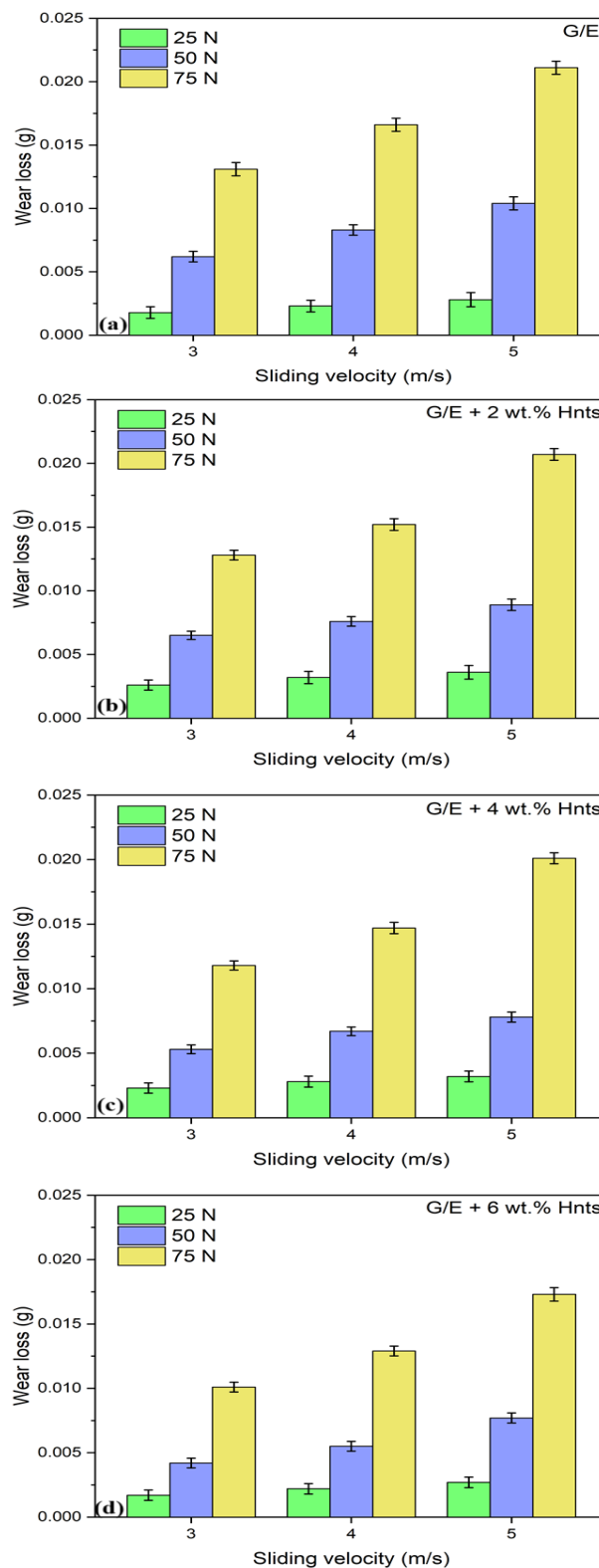


Fig. 3. Wear loss of nanocomposites: (a) H0, (b) H1, (c) H2, (d) H3.

3.2 Specific wear rate of hybrid nanocomposites

Figures 4a, b, c, and d illustrate how the load and sliding velocity influence the specific wear rate (SWR) of Hnts modified composites. In Hnts modified samples, the SWR was measured under dry sliding conditions at velocities of 3, 4, and 5 m/s and normal loads ranging from 25 N to 75 N. It is evident from Figure 4 that when sliding velocities were raised from 3 m/s to 5 m/s, the SWR for all the samples increased normally with the rise in sliding velocities and applied loads. It is obvious from the statistics that an increase in sliding velocity and normal loads outcome in a higher SWR at constant sliding distance (5000 m).

Figure 4a shows the effect of sliding velocity and applied load on the SWR. As applied loads and sliding velocity increased, the SWR of H0 samples obviously increased as well. At 25 N and 75 N, the composite samples exhibit a minimum SWR of $22.57 \times 10^{-6} \text{ mm}^3/\text{N m}$ and a maximum SWR of $34.69 \times 10^{-6} \text{ mm}^3/\text{N m}$. Furthermore, at lower sliding velocities, the SWR clearly drops. Compared to the H0 sample, the H3 sample with 6 wt % Hnts (Fig. 4d) exhibited the lowest SWR of $27.45 \times 10^{-6} \text{ mm}^3/\text{N m}$, representing a 26.4 % reduction compared to unfilled composites. Nayak and Satpathy and Prakash et al. [43,44] both noted an analogous trend in the SWR. Nayak and Satapathy [43] reported a reduction in the SWR of a polyester matrix reinforced with waste marble dust filler. The wear resistance of epoxy composites reinforced with activated carbon fillers was found to be positive by Prakash and colleagues [44]. It has been demonstrated that the durability of epoxy composites against wear was enhanced by 106% when 1 wt % of permeable nano activated carbon was added as reinforcement. Furthermore, the H1 and H2 samples (Fig. 4b and c) showed moderately low SWR values of $33.65 \times 10^{-6} \text{ mm}^3/\text{N m}$ and $32.56 \times 10^{-6} \text{ mm}^3/\text{N m}$, respectively. As a result, micromechanical characteristics and SWR are correlated (Table 1; hardness values). Moreover, the transfer film formed over the steel counter-face is the reason of the drop in SWR in all hybrid nanocomposites. It is a well-known fact that a polymer's capacity to form a thin coating on the counterface has a significant impact on how the polymer behaves while

sliding over a metallic surface. The transfer coating weakens the fiber-reinforced composite's adherence to the metallic counter face during sliding, which hinders the metallic particles' ability to plough through the softer epoxy matrix material.

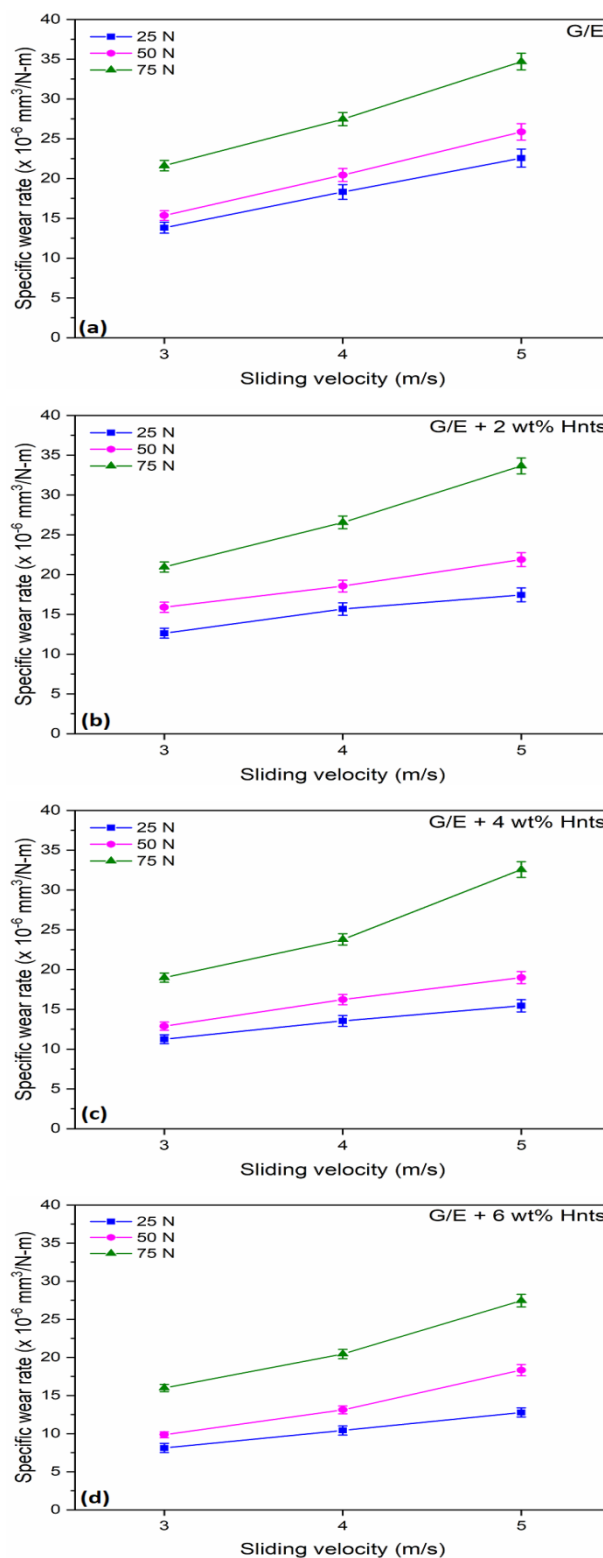


Fig. 4. SWR of nanocomposites: (a) H0, (b) H1, (c) H2, (d) H3.

The H0 sample wears out more quickly ($34.69 \times 10^{-6} \text{ mm}^3/\text{N m}$) than its hybrid nanocomposites because of the brittle fracture the surface experiences when shear loads are applied. The hybrid nanocomposite sample H3 had the lowest SWR ($27.45 \times 10^{-6} \text{ mm}^3/\text{N m}$) of all the samples.

Chavhan and Wankhade [39] reported the similar behavior of sliding distance and load over the SWR of steel embedded G/E composites. Researchers Chauhan et al. [45] looked into how hybridizing TiO_2 filler affected the mechanical properties and adhesive wear behavior of epoxy-based composites reinforced with fibers of hairy cotton grass. To analyze the SWR, the Taguchi technique was employed. The results showed that a significant sliding velocity of 1 m s^{-1} TiO_2 loading of 6 wt % $>$ normal load of 30 N combined with an optimal value of SWR. The increase in SWR with increasing sliding velocity and load is typically caused by a combination of mechanical and thermal factors that influence wear behavior in polymeric composites. As the sliding velocity and load increase, so does the frictional heat at the contact surface. The generated heat builds up because polymers typically have low thermal conductivity, raising the surface temperature. The polymer matrix softens at high temperatures, decreasing its mechanical strength and increasing its vulnerability to wear.

Compare to metals and ceramics, the polymeric tribology is more difficult to examine due to the epoxy matrix's lower glass transition temperature. It is well known that pores, voids, and free volume form in epoxy during the curing method. Moreover to potentially impairing the covalent bond between the horizontal polymer layers, these gaps and pores may cause a reduction in shear resistance during extended periods of continuous cyclic shear loading, ultimately resulting in sample failure [46]. Improved shear resistance can be achieved by reducing gaps and free volume through improved fiber and filler-matrix interaction [47].

In the current study, wear is mild and characterized by processes such as adhesive wear or micro-plowing at low sliding velocities and loads. Wear in H0 sample can change into more severe forms, like abrasive wear, as load and velocity increase (Fig. 4(a)). Tribo-layers developed in Hnts-filled composites at high loads and velocities. As a result, hybrid composites have

a lower SWR (Figs. 4(b) to (d)). Strong filler-matrix contact that can withstand shearing during the counter surface's cyclic movement against the sample is responsible for this. However, in the case of H0 sample, this improved mechanism is absent, resulting in the highest SWR.

3.3 Coefficient of friction of hybrid nanocomposites

Figure 5a and Figure 5b show how the coefficient of friction (CoF) changes with sliding distance for unfilled (H0) and 6 wt % Hnts filled glass fabric reinforced epoxy (H3) composites at 3 m/s under 25 N, 50 N, and 75 N loads. As can be seen from Figure 5a, the CoF first drops for the H0 composite before stabilizing over the course of the 5 km sliding distance. At 25 N, the CoF begins at about 0.45, decreases a little in the beginning, and then levels off at about 0.38. While the applied load is increased to 50 N, the CoF begins at 0.5, fluctuates slightly, and then stabilizes at 0.45. In contrast, the maximum CoF (0.55) stays comparatively constant at a higher load of 75 N. Figure 5b shows the CoF trend for H3 composite at 3 m/s. The effect of Hnts in lowering friction is demonstrated by a decrease in CoF when compared to the unfilled composite (H0). The CoF begins at about 0.35 and reaches a stable value of 0.32 at 25 N. CoF starts at 0.42 and progressively drops to 0.36 when the load is increased to 50 N. Nevertheless, CoF begins at 0.45 and steadies out over time at a higher load of 75 N.

When comparing Figure 5b to Figure 5a, the addition of 6 wt % Hnts causes the CoF to decrease overall for all loads. One possible explanation is that Hnts reduce direct fiber-matrix contact by functioning as solid lubricants. In both situations, a higher CoF is typically maintained at higher loads. There is less fluctuation in Hnts-filled composites (Fig. 5b), which suggests better wear resistance.

Halloysite nanotubes play a key role in altering the tribological behavior of the composite material, which explains the lower CoF in the H3 sample when compared to the H0 sample. The lower CoF in H3 samples can be attributed to the solid lubricating properties of Hnts, which lessen direct contact between the sliding surfaces' asperities. Reduced friction can result from their tubular nanostructure's ability to create a protective layer by reducing shear stresses at the interface.

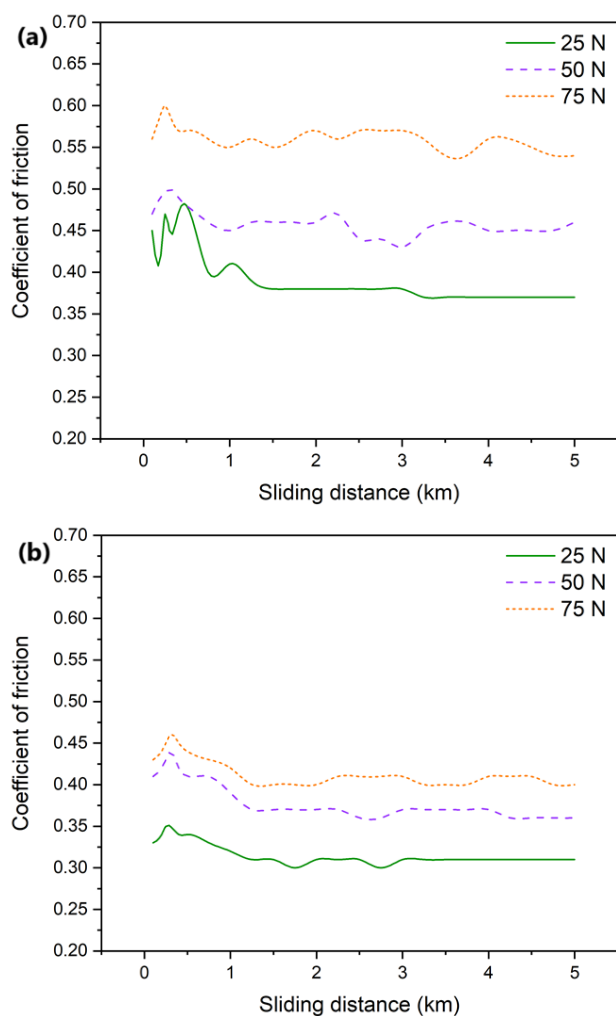


Fig. 5. CoF of nanocomposites: (a) H0, (b) H3.

The addition of Hnts decreased CoF and improved the wear resistance of polymer composites, according to several studies [48–50]. According to Chang et al. [48], Hnts-filled polymer composites have a lower CoF because of their inherent lubricity and capacity to create a transfer film on the sliding surface, which decreases adhesion wear. During long-term sliding wear, Chan et al. [49] found that Hnts-reinforced composites show less accumulation of wear debris, resulting in a stable and lower CoF. In composite materials under tribological conditions, Sinha & Briscoe [50] showed that nanofillers, such as Hnts, improve hardness and load-bearing capacity, lowering friction. The Hnts-filled composites (H1 to H3) in this work have lower CoF (Figs. 5a, and b; Table 5) because of their improved load-bearing capacity, reduced material transfer, and self-lubricating properties. These results are consistent with earlier research on composites made of Hnts-filled composites which highlights their contribution to enhanced tribological performance.

The friction coefficient (CoF) and tribological behaviour of polymeric composites can generally be significantly improved by carefully choosing the type, concentration, and dispersion method of nanofillers [51]. In addition to the typical friction coefficient curves elaborated, the steady state CoF values of the H0 and Hnts-filled composites (H1 to H3) samples were affected in this work was discussed in the following paragraph. After five minutes of the experiment, the CoF values reach their steady states.

Table 5 provides a summary of the CoF results that were obtained. The mean CoF values for unfilled and its hybrid nanocomposites increases with load and sliding velocity, as summarized in the Table 5. While the load and sliding velocity increases, the CoF usually rises as well, with H0 sample achieving the highest value.

The values of CoF shown in Table 5 differ by a very little amount. Table 5 also shows that the H0 sample CoF ranges from 0.36 to 0.59, and that these values dropped as the Hnts loading (H1 to H3 samples) increased. Among all composite samples tested, composite sample H3 had the lowest CoF of 0.31 at 25 N, 3 m/s, and 0.48 at 75 N, 5 m/s. Because of their nano-size and nearly unique structure, nanofillers are generally well recognized for exhibiting self-lubrication when integrated into the polymer matrix, which can significantly lower CoF.

The wear and friction of rare earth oxide (La_2O_3) reinforced polyimide composites have been studied by Pan and team [52]. The addition of 1.5 wt % La_2O_3 microparticles to polyimide at high preloads of 3–5 N led to a 70 % reduction in CoF and frictional forces, based on friction properties. Song and colleagues [53], who investigated the impact of carbon fiber, graphite, and nano- Si_3N_4 on the tribological characteristics of PI composites, reported similar findings. Their experimental results demonstrated that the separate addition of graphite and carbon fiber significantly enhanced wear resistance and decreased the PI composites' coefficient of friction. In this work, because of the excellent adherence and greater dispersion of particulates in the epoxy material, the Hnts-

filled composites may perhaps have a lower CoF. Moreover, it has been found that a major factor in lowering the CoF of hybrid nanocomposite samples is wear debris produced by rubbing between the contact surfaces. The self lubricity was observed in Hnts-filled G/E composites, where transfer film produced resulted in a reduction in the CoF. Moreover, by filling in surface voids and irregularities in the epoxy matrix, these Hnts create a smoother surface that lowers friction. They lessen the energy required to resist sample movement through friction. Low CoF and low SWR values in the H3 hybrid nanocomposite demonstrated controlled wear and prevented the interior polymer layers from being exposed to the counter surface.

3.4 Micrographs of cryo-fractured samples

The scanning electron micrographs of the cryo-fractured microstructure of unfilled G/E (H0) and 6 wt % Hnts-filled G/E (H3) samples at high magnification are displayed in Figure 6a and b.

The microstructure depicted in Figure 6a exhibits fiber pull-out and considerable matrix cracking on smooth, clean fiber surfaces. Weak adhesion between the epoxy matrix and the glass fibers is indicated by the small number of voids at the fiber-matrix interface. The fracture appears brittle, with debris surrounding the fiber surfaces and sharp edges. This implies that the composite is vulnerable to interfacial failure due to inadequate load transfer from the matrix to the fibers.

Table 5. Coefficient of friction data of unfilled G/E and its hybrid nanocomposites.

Load (N)	Sliding velocity 3 m/s				Sliding velocity 4 m/s				Sliding velocity 5 m/s			
	H0	H1	H2	H3	H0	H1	H2	H3	H0	H1	H2	H3
25	0.38	0.37	0.35	0.31	0.41	0.39	0.36	0.32	0.43	0.40	0.38	0.34
50	0.45	0.44	0.40	0.37	0.48	0.45	0.42	0.39	0.50	0.47	0.45	0.42
75	0.55	0.52	0.48	0.41	0.57	0.54	0.51	0.45	0.59	0.56	0.55	0.48

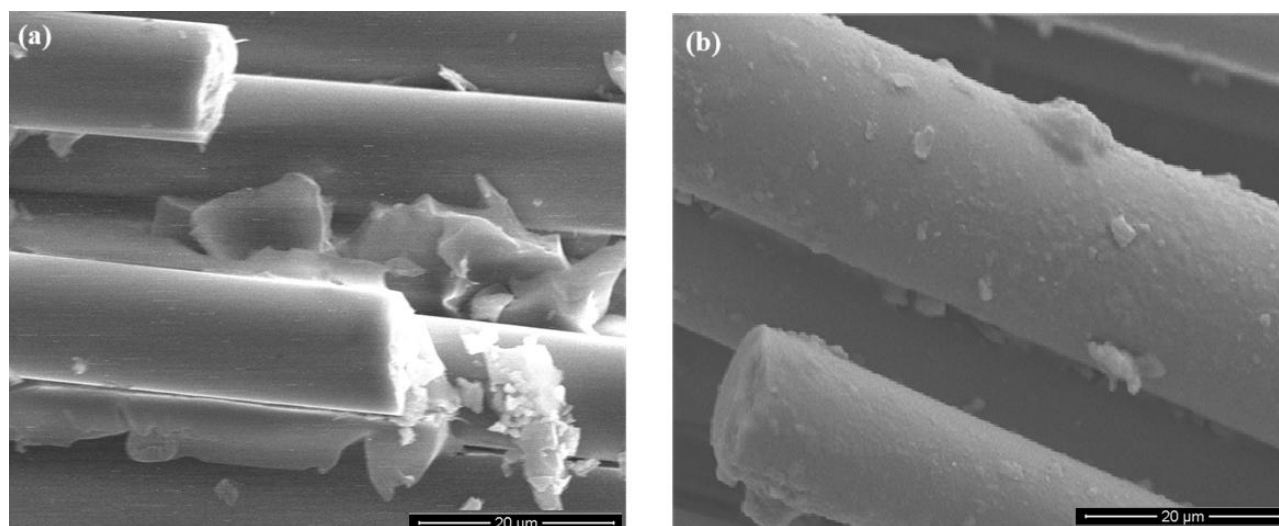


Fig. 6. Micrographs of as-received composite samples: (a) H0, (b) H3.

In contrast, the fibers in H3 hybrid nanocomposites appear coated and rough, most likely as a result of Hnts enhancing interfacial adhesion, as shown in Figure 6b. Stronger fiber-matrix bonding is indicated by less fiber pull-out. Better load transfer, which improves mechanical properties is suggested by the presence of scattered particles on the fibers.

3.5 Worn surface morphology

Worn surface morphology is analyzed to understand wear mechanisms, material degradation, and the impact of friction on surface integrity. Figure 7a-d displays the micrographs of the unfilled composites (H0) and its hybrid

nanocomposite samples (H1, H2, and H3), showing wear on their surfaces.

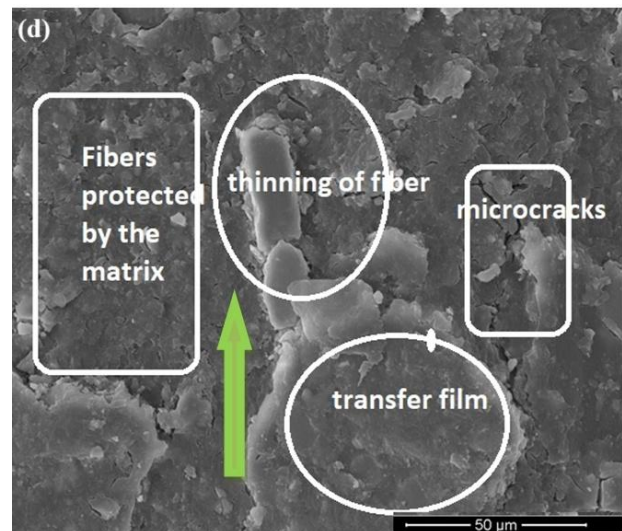
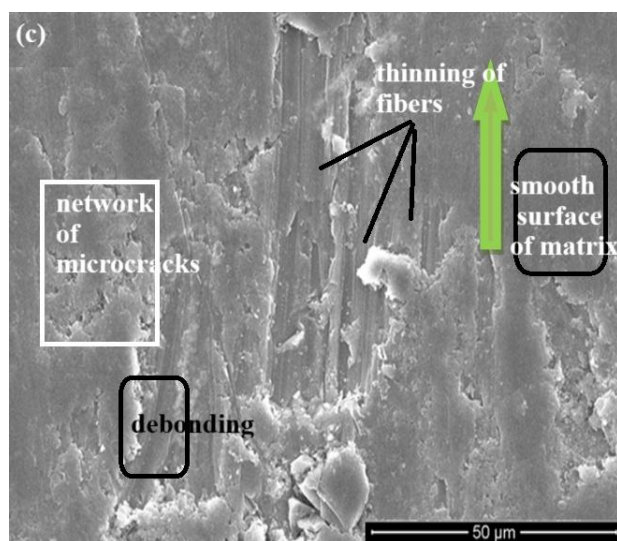
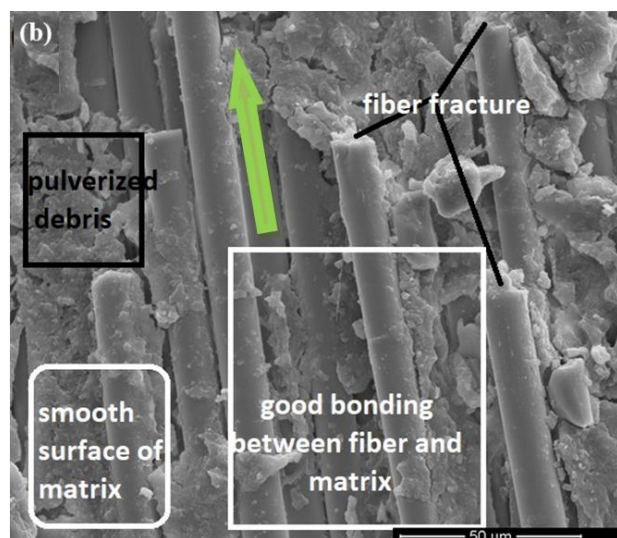
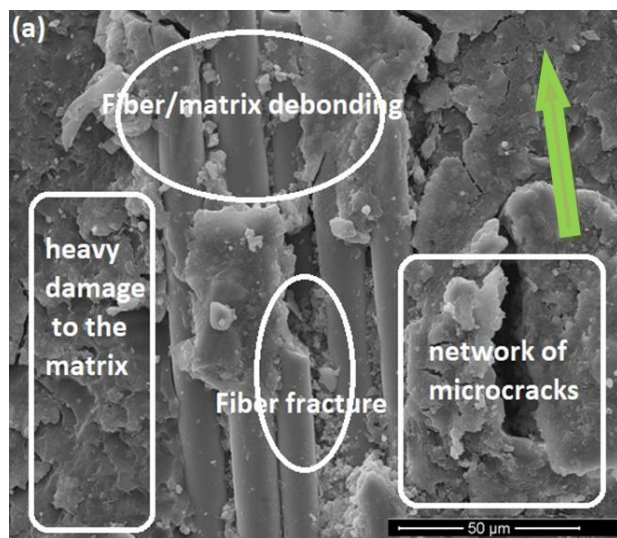


Fig. 7. Micrographs of worn surfaces: (a) H0, (b) H1, (c) H2, (d) H3.

These worn surfaces match the composite samples H0, H1, H2, and H3 at 75 N, 5 m/s, and a fixed sliding distance of 5 km. The impact of Hnts loading (2, 4, and 6 wt %) on the SWR and CoF of the composites is evident in these photomicrographs.

The H0 sample worn surface (Fig. 7a) displays several morphological patterns, including fiber breaking, an epoxy matrix plastic network, extensive matrix damage, lengthy fiber exposure, and wear debris adhered to the sample surface. The severe breakage of fibers and the weak adherence of the fiber to the matrix point to the neat composites lower the wear performance.

Figure 7b shows the photomicrograph of the H1 nanocomposite sample, which shows very little damage to the epoxy and merely a few broken fibers. Furthermore, it can be seen the impressions that remain after the fiber is removed because of the extreme sliding velocity. Additionally, there are fewer cases of fiber breakage, strong fiber-matrix bonding, and long fiber retention, all of which point to the benefits of adding Hnts in enhancing the resistance to wear of composite.

The worn surface morphology of a 4 wt % Hnts-filled G/E composite (H2) that underwent a dry sliding wear test is depicted in Figure 7c. The presence of microcracks in the image indicates matrix degradation brought on by repeated stress and thermal effects during sliding, which are the main features identified and their implications for wear mechanisms. The

formation of wear debris and surface delamination can result from the spread of these microcracks and material loss. The fiber-matrix debonding indicates a breakdown in interfacial adhesion. This results in fiber pull-out and composite weakening because of high frictional forces at the contact surface. A smooth, compacted layer may be a sign of tribo-film formation, which could offer short-term resistance to wear before disintegrating. Based on the SEM micrograph, it appears that the composite experiences fatigue wear from repeated sliding as well as abrasive and adhesive wear. Although Hnts strengthen the matrix and increase wear resistance, failure happens at high stress levels due to interfacial debonding, matrix cracking, and fiber thinning.

The 6 wt % Hnts-filled G/E sample (H3, Fig. 7d) worn feature shows a rather smooth worn surface without any instances of fiber loss or damage. It may be stated, with reference to Figure 7d, that the transfer film, which is composed of fine debris on both the sample and the counter surface, is the primary cause of the drop in the CoF and SWR. In comparison to the H1 and H0 samples, the worn surface of the H3 sample shows less discernible fibers. This suggests that Hnts were able to absorb a fraction of the applied normal load in the H3 samples. The worn surface photomicrographs showed that adhesive abrasion had replaced fatigue abrasion as the primary wear mechanism in the H0 samples.

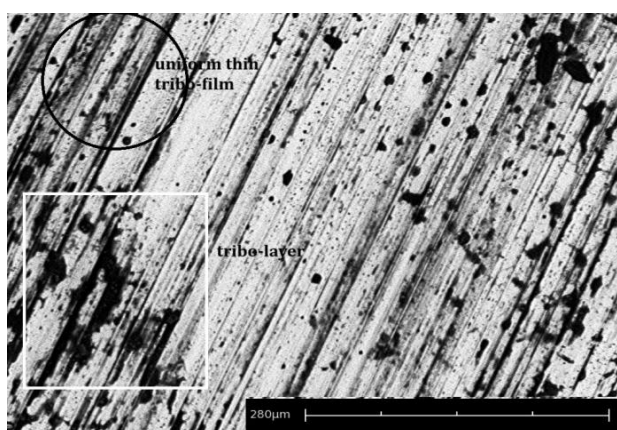


Fig. 8. SEM of the counter surface successive to its sliding against H3 sample.

Figure 8 displays the counter-disk surface successive to its sliding against H3 sample. The visible characteristics, like the consistent thin

tribo-film and tribo-layer, are essential for improving the composite's resistance to wear. During sliding, the polymer debris spreads and sticks to the counter-disk surface to form the tribo-film. Hnts serve as reinforcing particles in the composite, helping to create a thin, uniform tribo-film. As a protective layer, this tribo-film lessens wear by minimizing direct metal-to-composite contact. Additionally, by smoothing the sliding surface, it acts as a solid lubricant, lowering wear as well as friction. These characteristics demonstrate how important Hnts are in improving the H0 composite's wear performance under dry sliding conditions.

4. CONCLUSION

This study used lay-up technique to produce G/E composites with Hnts, then hot pressing to cure them. The research work yielded the following results.

- Hnts loading results in better wear resistance. It is confirmed that increased Hnts loading significantly reduces wear loss because the H3 sample shows the best wear resistance.
- The composite samples demonstrated SWR values ranging from a minimum of $22.57 \times 10^{-6} \text{ mm}^3/\text{N m}$ at 25 N to a maximum of $34.69 \times 10^{-6} \text{ mm}^3/\text{N m}$ at 75 N, with a noticeable decrease at lower sliding velocities. Notably, the H3 sample with 6 wt % HNTs achieved the lowest SWR of $27.45 \times 10^{-6} \text{ mm}^3/\text{N m}$, reflecting a 26.4 % reduction compared to unfilled composites.
- Among all composite samples tested, composite sample H3 had the lowest CoF of 0.31 at 25 N, 3 m/s, and 0.48 at 75 N, 5 m/s. A higher Hnts loading resulted in better adhesion, a better filler-matrix interaction, the formation of transfer films, and a rapid decrease in CoF.
- The sample H3 worn feature showed a smooth worn surface without any instances of fiber loss or damage. An amalgamation of adhesive and abrasive mechanisms was seen in all hybrid nanocomposites.
- By acting as reinforcing particles in the composite, Hnts contribute to the formation of a thin, homogeneous tribo-film, which lowers both wear as well as friction.

- Practical suggestions for creating sophisticated wear-resistant composite materials include the development of lightweight, wear-resistant parts for gears, sliding surfaces in machinery, brake pads, bushings, and bearings in cars, provided that Hnts are properly loaded into G/E.
- Future research can further explore the potential of Hnts in epoxy-based composites by optimizing Hnts functionalization, incorporating hybrid reinforcement strategies, conducting extended tribological testing, and performing application-specific performance studies.

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