Vol. 48, No. 2 (2026) 309-323, DOI: 10.24874/ti.2125.02.25.03

Tribology in Industry

www.tribology.rs

RESEARCH

Three Body Abrasive Wear Behaviour of Talc-Filled Short Glass Fiber Reinforced Nylon66 Polymer Composites

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Keywords:

Nylon66
Short glass fiber
Three-body abrasive wear
Talc filler
Hybrid composites
Specific wear rate
3D optical profilometer
FESEM

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Received: 2 February 2026
Revised: 10 March 2026
Accepted: 24 March 2026

A B S T R A C T

Fiber reinforced polymer composites (FRPCs) have been widely known for their high strength and better wear resistance in dry sliding condition mainly related to adhesion transfer or fatigue. However, the way FRPCs behaves under abrasion wear situation needs proper investigation. Hence in this study, three-body abrasion wear behaviour of Neat Nylon66 (NN), short-glass fiber (SGF) reinforced Nylon66 (SGF/NN) composites and talc filled SGF/NN (T-SGF/NN) hybrid composites were investigated. Talc fillers were varied from 2 to 8 wt.% at a step of 2 wt.% and designated as 2T-SGF/NN, 4T-SGF/NN, 6T-SGF/NN, and 8T-SGF/NN hybrid composites. These composites were fabricated by melt blending technique using twin screw extrusion and injection molding process. Three body abrasion wear test was performed using rubber wheel abrasion tester in accordance at ASTM G-65 for different loading conditions (10, 15 and 20 N) and abrading distances (500, 750, and 1000 m). Results revealed that wear loss of all the composites increased with increase in the applied load and abrading distance which is attributed to penetration of abrasive particles, micro-cutting and fiber-matrix debonding. However, specific wear rate (SWR) decreased with respect to increase in abrading distance due to the formation of protective tribo-layer that stabilizes wear. In contrast, SWR increased with increasing in applied load because severe contact stress and intensified material removal. Worn surface of the talc filled SGF/NN composites were examined field emission scanning electron microscope (FESEM). Average surface roughness and dept of wear were measured using 3D optical profilometer.

1. INTRODUCTION

Polymeric materials have taken a special place in industries due to their superior physico-mechanical properties and higher durability [1]. Polymers are light weight material with higher specific strength and modulus [2]. Nevertheless, these polymers suffer during tough situations in industrial applications particularly in tribological applications, where damages caused by the abrasive particles. Abrasive wear arises in various forms like wear of the component occurred by the direct the impact of abrasive particles, wear because of the penetration of the abrasives between the components and wear from abrasives entrained in fluids. Generally, abrasive wear is resulted from the hard particles that are mainly forced and moved along the solid surface. Such typical abrasive wear more often witnessed in agricultural and industrial equipment, mainly suffered from the three-body abrasion wear [3]. In industries, situation demands for the development of the new class of polymer composites with good strength and tribological resistance. The wear loss faced by the polymer components due to the three-body abrasion wear is highly significant as it is responsible for 30% of total wear and contributes 60% of the total cost of wear [4]. Several researchers have explored the effect of size of abrasive particles on the three-body abrasion wear of the fiber reinforced polymer composites [5-8]. Besides many studies revealed that three body abrasion wear is unlike the sliding abrasion wear often exhibits opposite trend. The impact of addition of fillers and fibers on abrasive wear performance of the polymer composites is highly complex and unpredictable [9,10]. Suresha et al. [8] evaluated the effect of the short glass fiber on three-body abrasion wear characteristics of the polyurethane (PU) composites. Results showed that increasing of glass fiber content leads to higher wear loss under both increasing load and sliding distance. However, specific wear rate decreases with increasing in normal load. In contrast, Rudresh et al. [11] developed the blends of PA66/PTFE and reinforced with glass fiber and basalt fiber to understand the three-body abrasion wear behavior of the composites. They noticed that fiber filled composite blend exhibited better wear resistance than neat blends of PA66/PTFE. Amongst the composites, hybrid glass-basalt composites showed superior wear behavior under all testing condition. In another study, Rudresh and Ravikumar [12] explored the three-body abrasion wear behaviour of the Polyamide66 and Polytetrafluoroethylene (PTFE) blends of various compositions for different loading and abrading distances. They concluded that wear volume loss in the composites was mainly because of the combine effect of sliding distance and applied load. Presence of 5wt.% of PTFE in PA66 was effectively stabilizes the wear loss and specific wear rate of the composites. Kumar et al. [13] studied the three-body abrasion wear behaviour of the PA66/PP nanocomposites. Results showed that addition of graphite and nanoclay fillers have significantly affected the wear resistance property of the composites. Nanoclay filled PA66/PP exhibited better wear resistance than other composites. Poomali et al. [14] reported on the three-body abrasive wear behaviour of the near poly(methyl methacrlate) (PMMA) and blends of PMMA and thermoplastic polyurethane (TPU). They confirmed that wear loss increased with increase in the abrading distance and PMMA exhibited better wear resistance than blends of PMMA/TPU. Similarly, Syed et al. [15] investigated on the three-body abrasion wear behaviour of the saw palmetto spent (SPS) filled PP composites. They noticed that irrespective of the fiber content, wear loss of the composites increased with increase in the sliding distance and applied load. Interestingly, SPS addition deteriorated the wear resistance ability of the green composite. Mishra et al. [16] proved that addition of the short jute fiber in epoxy matrix beyond the optimum content (36wt.%) leads to deterioration of the tribological properties. At lower velocity and low abrading distance, neat epoxy exhibited better specific wear rate than other laminates. Irrespective of the fiber content, wear loss increased with increase in the sliding velocity and applied load. In another study, bio-flexible composites showed higher wear loss during three body abrasion wear compared to two body wear [17]. However, claim was in contrary to the finding reported by another researcher which clearly confirms the complex mechanisms involved in the abrasion wear behaviour of the composites [18]. Mohan et al. [19] reported that SiC filled glass/epoxy composites showed better abrasion resistance. SWR of the composites was higher at lower abrading distance. As abrading distance increased, SWR decreases and attains steady state and they further stated that tribological properties of the neat and hybrid composites strongly depends on the testing parameters. Suresh et al. [20] reported that addition of boron carbide in the epoxy matrix has significantly improved the abrasion wear resistance of the composites. Arivalagan et al. [21] found that addition of fly ash cenosphere particles into carbo-epoxy composites was useful in enhancing the three-body abrasion wear property of the composites. Wear loss increased with increase in the abrading distance whereas SWR decreased with increase in sliding distance. Incorporation of the talc filler in polymer matrices is widely reported and know to enhance mechanical and tribological properties of the composites. Positive improvements have been reported in the following material system such as talc/polyurethane [22], talc/graphite/epoxy [23], talc/PP [24], and talc/graphite/SU-8 [25].

From the above literature survey, it is confirmed that hybridization of the primary and secondary reinforcements on the three-body abrasion wear behaviour of the polymer composites shows the mixed response. Further, three-body abrasion wear of thermoplastic composites are rarely reported. To the best of author's knowledge, very limited works have been reported on usage of talc filler as a reinforcement member in polymer composites. Thus, present investigation has been undertaken to understand the impact of talc filler on the three-body abrasion wear behaviour of the short glass fiber reinforced Nylon66 composites, which is not reported until now. This study attempts to produce a new class of composites for tribological applications.

2. EXPERIMENTAL DETAILS

2.1 Materials used

Nylon66 pellets were used as a matrix material which was supplied by Grand pacific petrochemical corporation, Taiwan. SGF employed as the primary reinforcement member and was procured from Nippon Electric Glass - Malaysia. Talc particles were used as the secondary reinforcement material for fabricating Nylon-based hybrid composites and were purchased from 20 Microns limited (Tirunelveli, India). The micrograph and EDS spectrum of the talc filler are indicated in the Fig. 1.

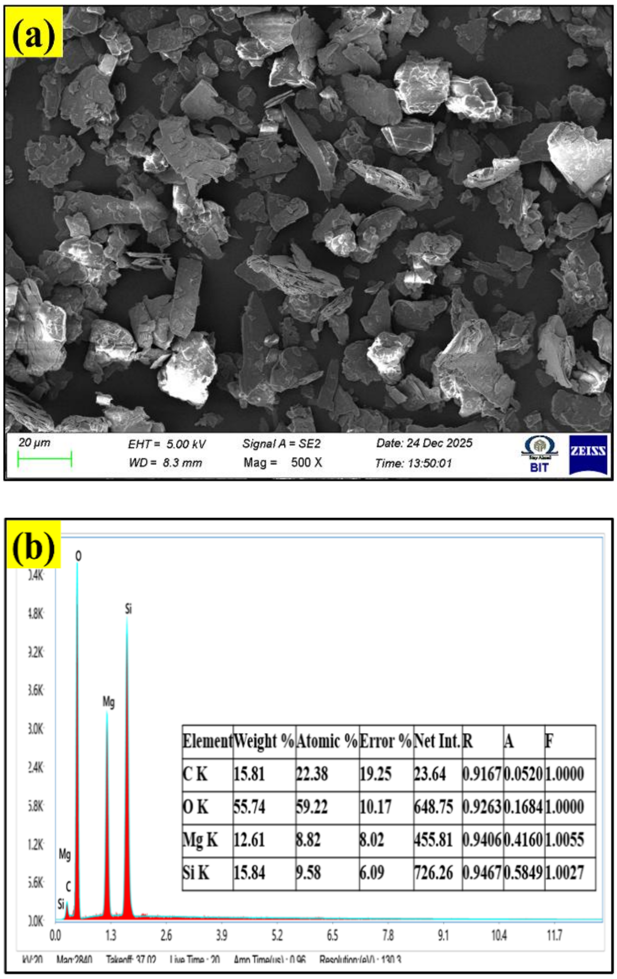


Fig. 1. (a) FESEM micrograph of the talc filler (b) EDS spectrum of the talc filler confirming major elements.

2.2 Fabrication of the composites

Nylon 66 pellets, short glass fibers and talc fillers were dried in the hot air oven at different temperature and time to get rid of the moisture. These constituents were weighed as per the required weight fraction and pre-mixed using mechanical grinder for achieving the uniform distribution.

The mixture was then subjected to compounding process where it was melted in a twin-screw extrusion machine operated at different temperature like feeding zone operated at 80°C, following compression zone and metering zone at 270°C and 290° C, respectively as indicated in the Fig. 2. During melt-compounding process, screw speed around 80-120 rpm was maintained to ensure the effective dispersion of the SGF and talc filler within Nylon66. In the next stage, blended extrudate plastic was cooled in a water bath and subsequently pulled via mechanical puller and converted to granules using mechanical cutter.

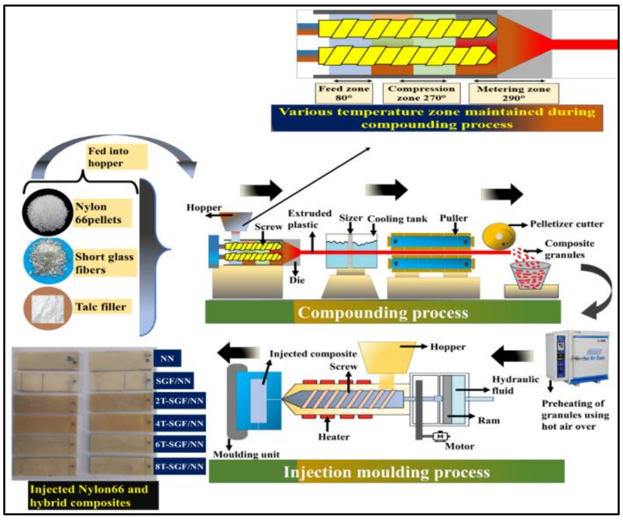


Fig. 2. Procedure adopted for the preparation of talc filled SGF/NN composites.

These granules were dried at 80°C for 4 to 6 hours for smooth injection process. Further these Nylon66 based composite granules were casted to required shape and size using injection moulding machine and its barrel temperature(260-280°C) was maintained during injection time. Fabricated NN, SGF-NN, and tall filled SGF-NN hybrid composites specimens were finally conditioned at room temperature for 48 hours prior to wear investigation. Composition of the composites and their designations are detailed in Table 1.

Incorporation of 40wt.% of SGF in Nylon66 composites is mainly because of its widespread industrial usage range (30-45 wt.%) and provides higher stiffness and strength without compromising processability. Talc is varied between 2 to 8 wt.% to comprehend its incremental impact as a secondary filler. Lower talc content (<2 wt.%) may produce negligible effect whereas higher loading could lead to agglomeration which may deteriorate the interfacial bonding. Therefore, selected formulation range of SGF/NN (40 wt.% /60 wt.%) composites paves the way for systematic evaluation of the talc contribution while maintaining the material stability.

Table 1. Composition of the material system used in this study.

Material	Designation	Nylon66 (wt.%)	Short glass fiber (wt.%)	Talc filler (wt.%)
Neat Nylon66	NN	100	-	-
Short glass fiber reinforced Nylon66	SGF/NN	60	40	-
2% Talc filled SGF/NN	2T-SGF/NN	58	40	2
4% Talc filled SGF/NN	4T-SGF/NN	56	40	4
6% Talc filled SGF/NN	6T-SGF/NN	54	40	6
8% Talc filled SGF/NN	8T-SGF/NN	52	40	8

2.3 Three-body abrasion wear test

Three body abrasion wear test was executed on the talc filled SGF/NN composites using rubber wheel tester as per the ASTM G-65 as illustrated in the Fig. 3.

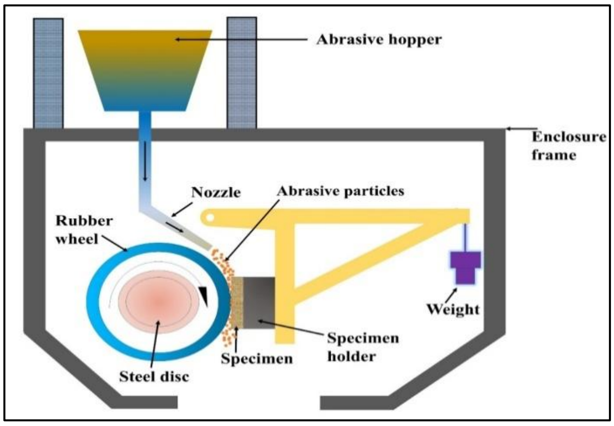


Fig. 3. Experimental setup of three body abrasion wear test [ASTM G-65].

Wear test samples were cut to the required size and fixed on the specimen holder. Rubber wheel of diameter 220 mm, function as a secondary body establishes the firm contact against the specimen. Fine silica sand grains used as abrasive material and act as a third body which was fed between rubber wheel (cholorobutyl rubber) and specimen at a constant feed rate of 255±5 g/min. Because of the application of load, test specimen was pressed against the rotating rubber wheel and gets abraded as a result of control flow of abrasives. Abrasive flow direction was maintained along the rotation of rubber wheel. Specimen weight before and after test was recorded using high precision digital balance (0.1 mg accuracy). At least three tests were performed and their average value was used for further analysis.

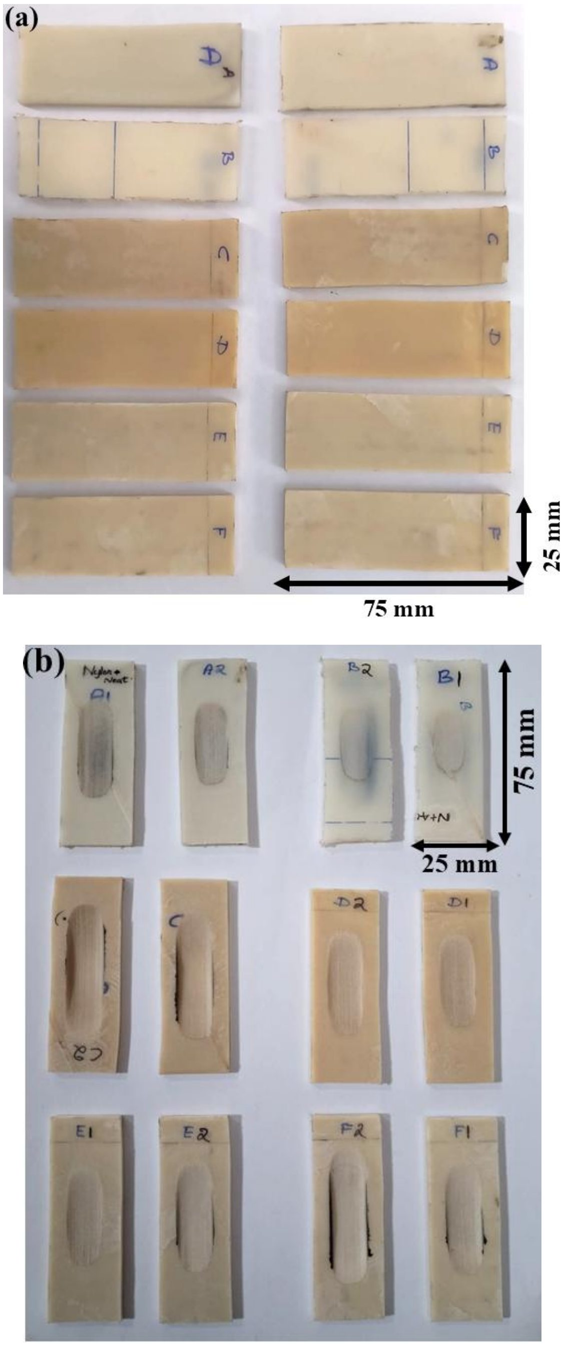


Fig. 4. Talc filled SGF/NN composites (a) before three body abrasion wear (b) after three body abrasion wear.

The specimen wear rate of the composite was determined using Equation (1).

$$K_s = \frac{V}{L \times D} \text{mm}^3 / N - m \quad (1)$$

Where V is the volume loss of the material (mm^3), L is the applied load (N) and D is the sliding distance covered (m). The experimental parameters for conducting three body abrasion wear tests are shown in the Table 2. Worn samples of the Nylon66 composites before and after three body wear test is depicted in the Fig. 4.

Fine silica sand grains used as abrasive material and act as a third body which was fed between rubber wheel (cholorobutyl rubber) and specimen at a constant feed rate of 255±5 g/min. Because of the application of load, test specimen was pressed against the rotating rubber wheel and gets abraded as a result of control flow of abrasives. Abrasive flow direction was maintained along the rotation of rubber wheel. Specimen weight before and after test was recorded using high precision digital balance (0.1 mg accuracy). At least three tests were performed and their average value was used for further analysis. The specimen wear rate of the composite was determined using Equation (1).

Where V is the volume loss of the material (mm^3), L is the applied load (N) and D is the sliding distance covered (m). The experimental parameters for conducting three body abrasion wear tests are shown in the Table 2. Worn samples of the Nylon66 composites after three body wear test is depicted in the Fig. 4.

Table 2. Three body abrasion wear testing condition used in this study.

Sl. No	Experimental testing parameters	
1	Sliding distance (m)	500, 750, and 1000
2	Applied load (N)	10, 15 and 20
3	Rotational speed of the rubber wheel (rpm)	200
4	Feed rate of the abrasive particle (g/min)	255±5

2.4 Surface examination method

Topographies of the worn surface were analysed using 3D optical profilometer. Average surface roughness and wear depth of the composites were measured at the centre region of the specimen. Surface morphologies were examined using FESEM (Model: Sigma 360, Carl Zeiss, Germany).

3. RESULTS AND DISCUSSION

3.1 Abrasive wear volume loss and specific wear rate of the Nylon66 composites

Variation of wear volume loss with the sliding distance under constant applied load (10 N) for NN, SGF/NN and talc filled SGF/NN hybrid composites depicted in the Fig. 5(a). It is evident from the plot that all materials experience increasing of wear loss with abrading distance which is anticipated in three body abrasion wear because prolonged sliding action leads to continuous interaction between abrasive particles and specimen surface resulting in cumulative material removal. Of the tested specimen, NN exhibited highest wear loss at all sliding distances. This clearly shows the poor wear resistance to the three-body abrasion may be attributed to lower hardness and poor load bearing ability of the NN. Inclusion of SGF in NN significantly improved the wear loss of the material under three-body wear condition. Compared to NN, nearly 50.24%, 39.21% and 14.78% reduction of wear loss in SGF/NN composites was noted when abrading with sliding distance of 500 m, 750 m and 1000 m, respectively. Such significant improvement of wear loss in SGF/NN composites may be because of the presence of SGF as enhances the surface hardness property of the composites and thereby offers better resistance to micro-cutting and micro-ploughing by abrasive particles. Moreover, addition of talc filler in SGF/NN composites showed further improvement in wear loss of the hybrid composites. Fig. 5(a) clearly shows that wear loss decreases with increase in the talc content and increases with increase in abrading distance. 8T-SGF/NN composite showed least wear loss among all the fabricated Nylon66 composites. Because talc addition increases the matrix stiffness and hardness thereby limits the plastic flow and significantly reduces the penetration depth of the abrasive particles. Another reason may be due to the better load distribution by the hybrid composite. 2T-SGF/NN composite showed wear loss from 0.227×10^3 mm^3 to 0.397×10^3 mm^{3}for covering the sliding distance from 500 m to 1000 m. For the same testing condition, 8T-SGF/NN composite exhibited wear loss from 0.118×10^3 mm^3 to 0.219×10^3 mm^3, nearly 24.33 % to 46.49 % reduction of wear loss is observed. This significant improvement in wear loss by 8T-SGF/NN composite is mainly due to the presence of talc filler which is harder particle helps against the abrasive penetration and eventually suppress the wear. However, Nylon66 hybrid composites with lower talc content exhibited quite higher wear loss, though better than NN and SGF/NN. This may be because of the micro-cutting and matrix removal by the abrasive particle, which clearly signifies the poor surface interaction among the talc filler, SGF and matrix.

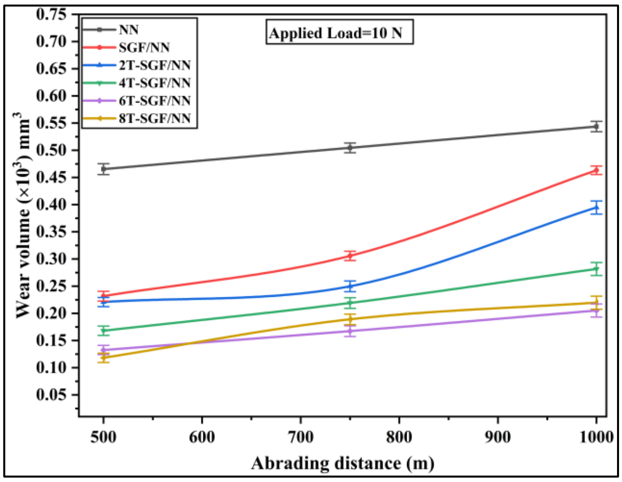


Fig. 5(a). Wear loss versus abrading distance for NN, SGF/NN, and talc filled SGF/NN under 10 N.

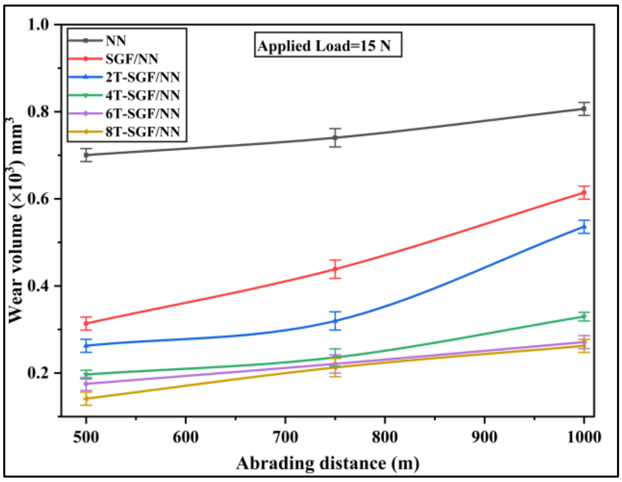


Fig. 5(b). Wear loss versus abrading distance for NN, SGF/NN, and talc filled SGF/NN under 15 N.

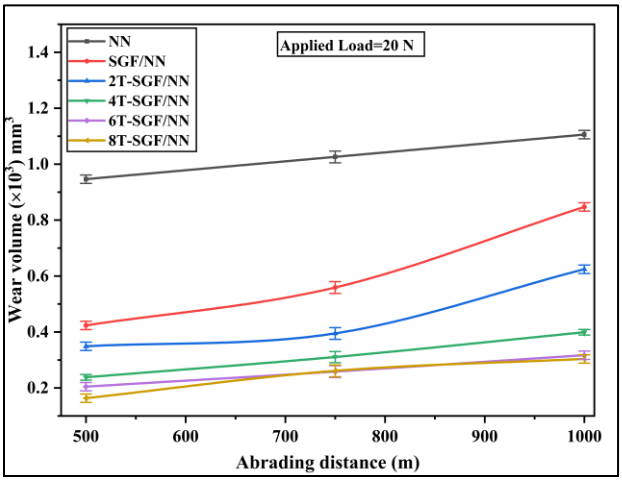


Fig. 5(c). Wear loss versus abrading distance for NN, SGF/NN, and talc filled SGF/NN under 20 N.

Variation of wear volume loss with the sliding distance under constant applied load (15 N) for NN, SGF/NN and talc filled SGF/NN hybrid composites depicted in the Fig. 5(b). Significant increase in wear loss was observed when applied load increased from 10 N to 15 N. Nearly 44-46% increase in wear loss is exhibited by the NN may be suggesting the severe matrix deformation and greater abrasive penetration during the higher normal force. On other hand, SGF/NN exhibited 30-40% higher wear loss at 15 N compared to 10 N loading condition while covering entire abrading distance. This may be attributed to the higher contact stress exerted by the abrasive particles against the Nylon66 composite surface. Apart from this, severe pressure exerted by the rubber wheel along with the sharp abrasive particles against smooth surface of composites may leads to more wear loss. Furthermore, talc filled SGF/NN composites showed relatively lower increase in abrasion wear, ranging between 15-30% when applied load increased from 10 N to 15 N which clearly indicates the superior load bearing ability of the hybrid composites. The higher wear loss at 15 N may be due to the increased contact pressure which facilitates deeper embedment of abrasive particles which further intensifies the micro-cutting and ploughing mechanisms and eventually enlarges the area of contact between the hybrid composite specimen and abrasive particle. However, talc filled SGF/NN hybrid composites lower wear loss than NN and SGF/NN composites. This clearly suggest the effect of the talc filler in the composites along with impact of testing parameter. Presence of talc content significantly mitigates the wear loss by increasing hardness of the composite and uniformly distributing the contact stress and thus promotes the formation of tribo-layer that protects the Nylon66 matrix from direct abrasive action.

As the load increased to 20 N, all Nylon66 based material exhibited higher wear loss compared with 10 N and 15 N while covering the same abrading distance (Fig. 5(c)). This confirms the strong load dependence behavior of the Nylon66 composites under three-body abrasion wear. NN material showed 95-110% and 40-55 % increasing wear loss at 20 N when compared to the 10 N and 15 N, respectively. This indicates the severe matrix softening of NN material with deep embedment of abrasive particles due to high contact pressure. Similarly, at 20 N load, SGF/NN exhibited 70-85% higher wear volume loss than 10 N and 30-46% higher than 15 N. This may be attributed to the increased fiber-matrix interfacial stresses which facilitates the fiber fracture and pull-out at higher loading conditions. Talc filled SGF/NN hybrid composites showed relatively lower wear loss under load escalation. Wear at 20 N load increased in the range of 30-45% compared to 10 N and by 15-30% compared to 15 N clearly shows the superior wear resistance characteristics of the talc filled SGF/NN hybrid composite under severe abrasion testing condition. The pronounced wear loss recorded at 20 N which may owing to the higher normal force which promotes increasing the area of wear contact and paves the way for deeper penetration of the abrasive particles. This mechanism further intensifies the micro-ploughing and micro-cutting action and leads to subsurface damage of the composite specimen. Nevertheless, talc filled SGF/NN hybrid composites, particularly 6T-SGF/NN and 8T-SGF/NN composite showed better lower wear loss even at elevated load 20 N. This may be due to the improved surface hardness and formation of tribo-layer that protects the polymer matrix from direct abrasive action.

From the Fig. 5(a)-(c) it is evident that at all loading conditions, wear loss increases with increase in the abrading distances. At lower sliding distance (500 m), surface asperities of the Nylon66 composites were progressively removed and loose sand particles (abrasive) roll with limited penetration into the composite surface, and thus resulting in smaller material loss and so lower wear volume. However, at abrading distance of 750 m, slight increase in the wear loss is observed and this stage considered as a steady stage regime where steady rolling and sliding of abrasive particles takes place. This stage characterized by the formation of shallow grooves due to aforementioned mechanism caused by abrasive particles. Furthermore, this stage typically promotes for the gradual material removal and consequently exposes the reinforcements, resulting in moderate wear volume loss. At higher abrading distance 1000 m, composite such as NN, SGF/NN and talc filled SGF/NN hybrid composites experiences severe wear characterized by micro-cutting, micro-fatigue and reinforcement damage owing to sustained abrasive embedment and sliding. Moreover, protective tribo-layer formed during the early stage disrupted due to severe action from abrasive particles and contact stress exerted from the abrasion wheel and thus higher wear volume loss is inevitable when material abraded at higher sliding distance. Nevertheless, hybrid composite with increase surface hardness and formation of tribo-layer exhibits lower wear loss, demonstrating the improved wear resistance under three-body abrasion wear conditions.

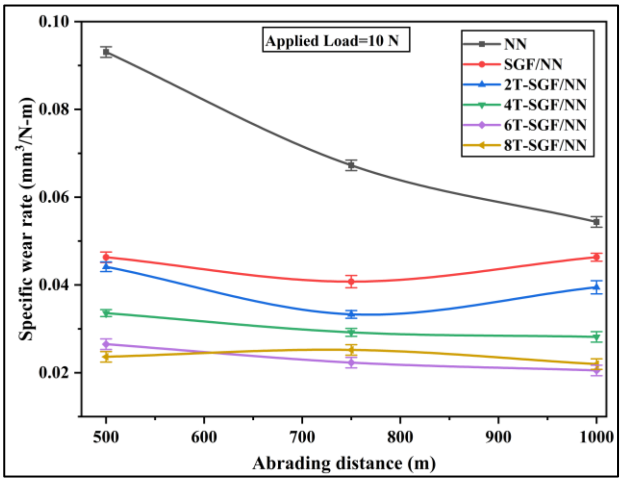


Fig. 6(a). SWR versus abrading distance for NN, SGF/NN, and talc filled SGF/NN under 10 N

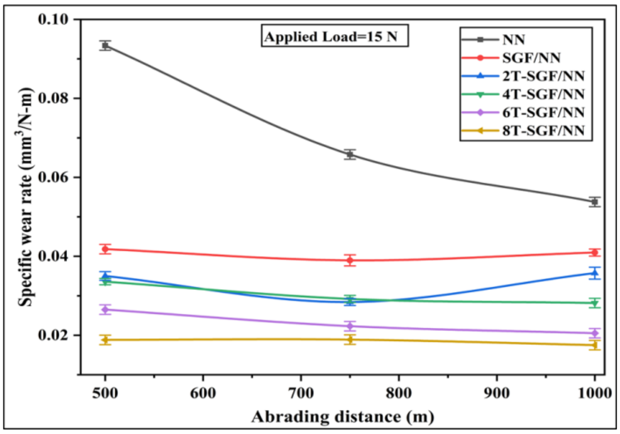


Fig. 6(b). SWR versus abrading distance for NN, SGF/NN, and talc filled SGF/NN under 15

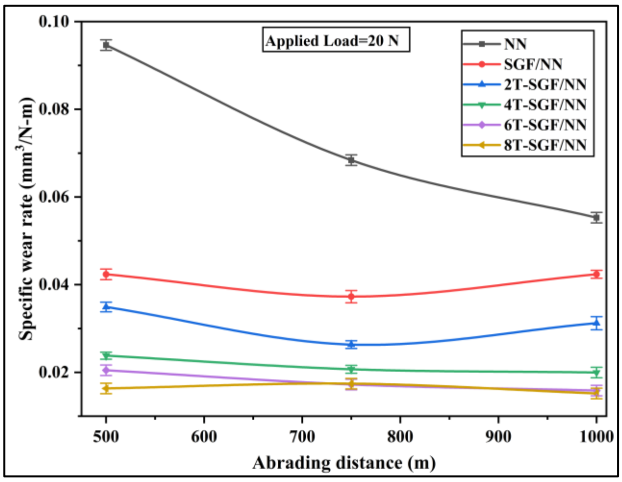


Fig. 6(c). SWR versus abrading distance for NN, SGF/NN, and talc filled SGF/NN under 20 N

Fig. 6(a)-(c) demonstrates the combine effect of material composition and loading severity on the SWR of the neat Nylon66 and its composites under three body abrasion mode at different applied loads of 10, 15 and 20 N. It is clearly evident from the plots that NN material showed highest SWR especially at lower abrading distance suggesting that severe material removal from the composite surface during run-in stage phase may be attributed to lower hardness and highly exposure to abrasive penetration. Inclusion of the SGF in NN significantly reduces the SWR, while further developing of hybrid composite by inclusion of talc fillers results in progressive and pronounced improvement in wear resistance. At 10 N as indicated in the Fig. 6(a), SGF/NN displayed nearly 45-50% reduction of SWR compared to NN, whereas talc showed reduction in the range of 55-75%, particularly 6T-SGF/NN and 8T-SGF/NN exhibited lower SWR among the composites. Similar trend of SWR is observed for 15 N test as shown in the Fig. 6(b), it is clearly seen that SGF/NN showed approximately 40-45% improvement whereas talc filled SGF/NN demonstrates somewhere in the range of 60-75% reduction in SWR when compared with NN, indicating the effectiveness of talc filler in improving the wear resistance of the composites particularly during abrasive actions. Fig. 6(c) shows at 20 N, slightly higher is SWR recorded and values found increases for all the materials, however relative improvement remained substantial, i.e., talc filled SGF/NN composites showed 50-65% improvement of SWR over NN material, whereas SGF/NN attains only 40% reduction. Increasing in SWR with applied load mainly ascribed to higher contact pressure which in turn enhances the penetration of abrasive particles and thus accelerates the micro-cutting and ploughing and further intensifies the subsurface damages of the composites. Nevertheless, talc filled SGF/NN composites exhibited lower SWR with increase of applied load, mainly attributed to enhanced surface hardness and good bonding between filler and matrix material. Also, talc filled composites shows improved stress distribution and helps in formation of tribo-layer that shields the matrix from direct abrasive actions. This synergistic interaction between SGF and talc in neat nylon results in a transition from severe micro-cutting to controlled ploughing and mild material removal under three-body abrasion wear condition.

SWR as a function of abrading distance for Nylon66 and its composites clearly presents that, SWR is higher at lower abrading distance and vice-versa. This may be attributed to the more and more exposure of reinforcements to the abrasion while covering higher abrading distance. These exposed glass fibers due to their higher hardness values helps the composites against the abrasion wear which in turn, abrasive particle needs to spend more energy to cause failure of fibers. Thus, material removal rate with respect to the abrading distance decreases. These findings are in good agreement with the reported literatures [8,11,26].

Furthermore, it is interesting to see that, not much difference of SWR was recorded between 500 m and 1000 m abrading distance which may be due to the transition phase from run in stage to steady state wear regime particularly during three body abrasion wear. When specimen abrading at lower sliding distance, fresh abrasive particles entrained by the rubber wheel control the contact area resulting in removal of higher volume of material. However, as abrading distance increased, rubber wheel conditions the abrasive particles for rolling and sliding actions rather than cutting. This stable and sustained sliding causes abrasive fragmentation and rounding, collectively responsible for reducing the effectiveness of abrasive tracks. Moreover, tribo-film layer mainly formed from filler fragments, fine abrasive particles and debris further shields abrasive track from further wear and so SWR decreases at higher abrading distance

3.2 Surface morphology

FESEM micrographs of the worn surface of the Nylon66 composites under three body abrasive wear abraded at different sliding distance and applied load depicted in the Fig. 7-8. FESEM clearly discloses the progressive damage evolution of the composites with increasing abrading distance. At lower abrading distance, composite's major damage occurred by means of micro-ploughing owing to which formation of shallow grooves with limited matrix deformation as shown in the Fig. 7(a)-(g). EDS spectra of the NN, SGF/NN and talc filled SGF/NN composites are shown in the Fig. 7(b), Fig. 7(d), and Fig. 7(f), respectively, which confirm their elemental composition and also corroborate the impact of silica sand on the worn samples as its traces are evident in the plot. Further increasing of abrading distance, and due to the continuous rolling and sliding of sand particles, wear intensifies and leads to accumulation of subsurface stresses and steady material removal as shown in the micrographs (Fig. 8(a)-(d)). From the FESEM image (Fig. 7(a)) it is evident that, when NN material abraded progressed from shallow scratches at lower abrading distance to grooves, severe plastic deformation, and matrix tearing at higher abrading distance which clearly shows the sign of shifting from micro-ploughing to micro-cutting mechanism. Though such mechanisms are obvious in the SGF/NN and talc filled SGF/NN hybrid composites, intensity of damage is lower compared to that observed in NN. Fiber pullouts, voids and surface damage was significant and clearly observed in the FESEM image for the composites tested at different loading conditions. Furthermore, continuous abrasive interaction with Nylon66 specimen further escalates the damage to micro-cracking. Some of the important observations such as crack initiation and propagation are shown in the FESEM images clearly implies that composites undergo a micro-cracking mechanism under different loading conditions (Fig. 8). Such mechanisms eventually lead to fiber pullouts and debonding as shows in the micrographs. The rubber wheel supports for repeated engagement of the abrasive particles with the specimen thereby causing deeper abrasive penetration of the particles and subsequently crack growth forms with increasing abrading distance. Talc filled SGF/NN hybrid composites showed different damage evolution. Fig. 7(e)-(g), shows the FESEM image of the worn surface of the hybrid composite abrades at lower abrading distance. Micro-pictures show the controlled micro-ploughing at lower abrading distance however shallow discontinuous grooves and tribo-layer characterized at higher abrading distance (Fig. 8(a)-(e)). Furthermore, tribo-layer which formed from the filler fragments, wear abrasive entrapped helps to suppresses the micro-cutting and inhibits the micro-crack initiation by reducing direct abrasive impact (Fig. 8(e)). At higher abrading distance, only 8T-SGF/NN composites showed minimal damage of fiber fracture, fiber pullouts and poor bonding though matrix deformation and third body interaction is inevitable and which further conforms the effective load transfer and interfacial stability as indicated in the Fig. 8 (c)-(e).

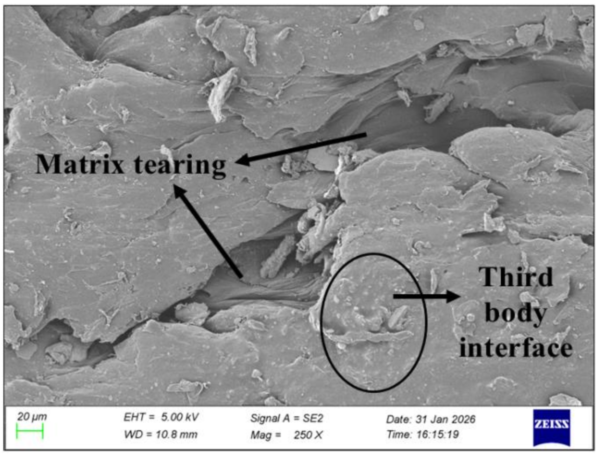
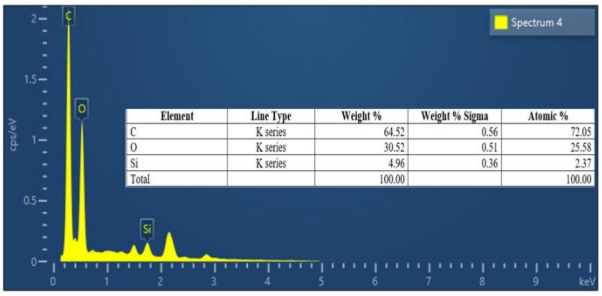


Fig. 7(a). FESEM image of worn surface of the NN composite abraded at sliding distance 1000 m at 10 N.



Element	Line Type	Weight %	Weight % Sigma	Atomic %
C	K series	64.52	0.56	72.05
O	K series	30.52	0.51	25.58
Si	K series	4.96	0.36	2.37
Total		100.00		100.00

Fig. 7(b). EDS spectrum of the worn surface of the NN material.

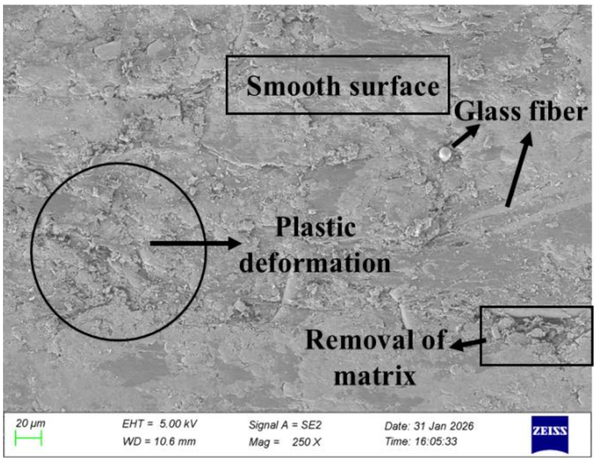
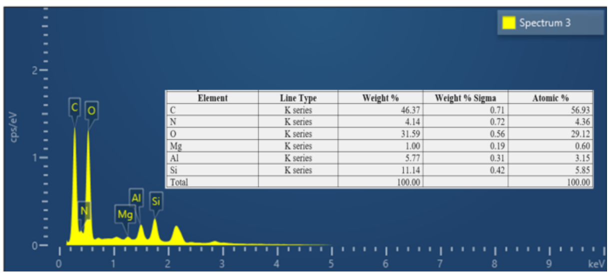


Fig. 7(c). FESEM image of the worn surface of the SGF/NN composite abraded at sliding distance 1000 m at 10 N.



Element	Line Type	Weight %	Weight % Sigma	Atomic %
C	K series	46.37	0.71	56.93
N	K series	4.14	0.72	4.36
O	K series	31.59	0.56	29.12
Mg	K series	1.00	0.19	0.60
Al	K series	5.77	0.31	3.15
Si	K series	11.14	0.42	5.85
Total		100.00		100.00

Fig. 7(d). EDS spectrum of the worn surface of the SGF/NN composite.

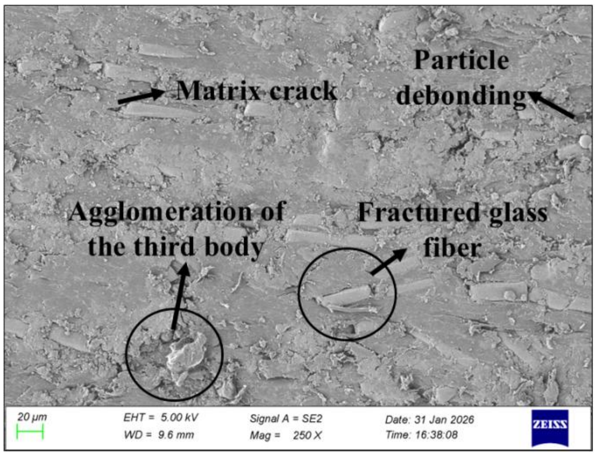
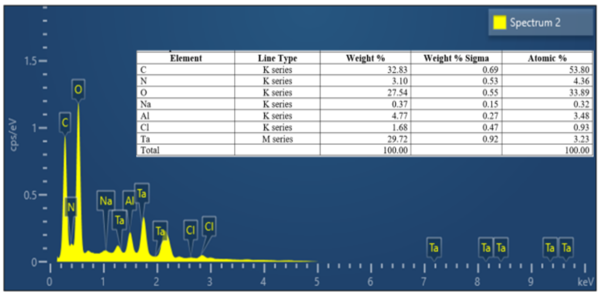


Fig. 7(e). FESEM image of the worn surface of the 8T-SGF/NN composite abraded at sliding distance 500 m at 10 N.



Element	Line Type	Weight %	Weight % Sigma	Atomic %
C	K series	32.83	0.69	53.80
N	K series	3.10	0.53	4.36
O	K series	27.54	0.55	33.89
Na	K series	0.37	0.15	0.32
Al	K series	4.77	0.27	3.48
Cl	K series	1.68	0.47	0.93
Ta	M series	29.72	0.92	3.23
Total		100.00		100.00

Fig. 7(f). EDS spectrum of the worn surface of the 8T-SGF/NN composite.

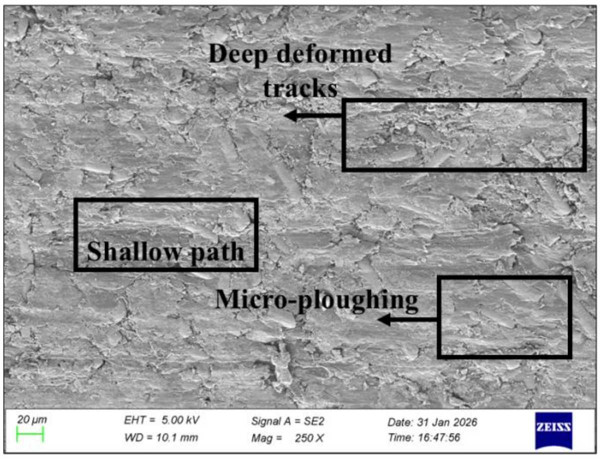


Fig. 7(g). FESEM image of the worn surface of the 8T-SGF/NN composite abraded at sliding distance 1000 m at 10 N.

Inclusion of talc particles results in surface hardening and promotes the formation of tribo-film which further function as a protective barrier against the material removal. Besides, synergetic impact of SGF and talc limits the plastic flow of matrix and reduces the crack propagation along the fiber-matrix interface. The worn surfaces of the 8T-SGF/NN hybrid composites also show the reduced delamination and fewer deep furrows implying transition phase of wear loosing intensity as abrading distance increased.

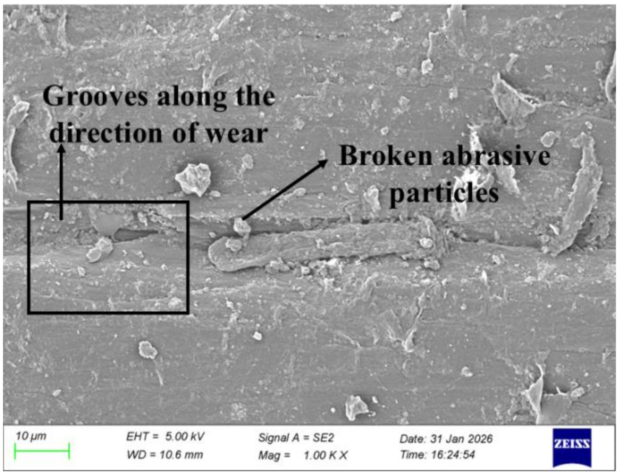


Fig. 8(a). FESEM image of the worn surface of the NN composite abraded at sliding distance 1000 m at 20 N.

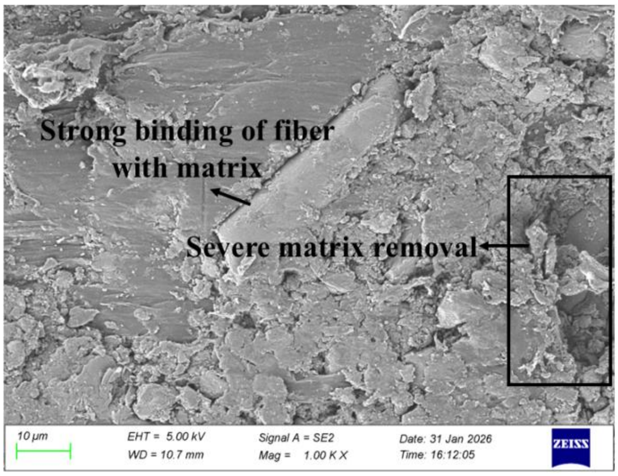


Fig. 8(b). FESEM image of the worn surface of the SGF/NN composite abraded at sliding distance 1000 m at 20 N.

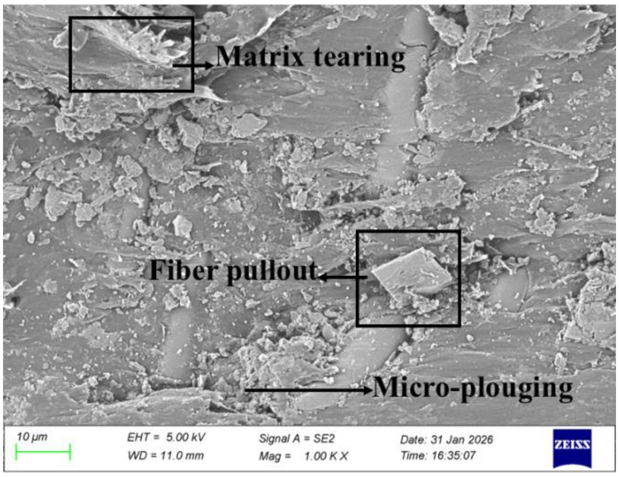


Fig. 8(c). FESEM image of the worn surface of the 8T-SGF/NN composite abraded at sliding distance 500 m at 20 N.

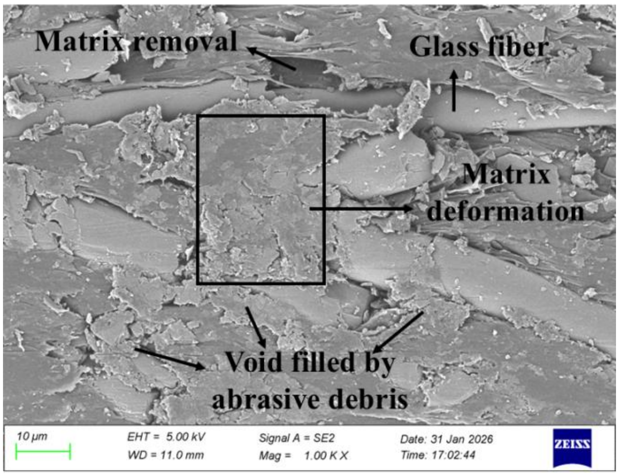


Fig. 8(d). FESEM image of the worn surface of the 8T-SGF/NN composite abraded at sliding distance 1000 m at 20 N.

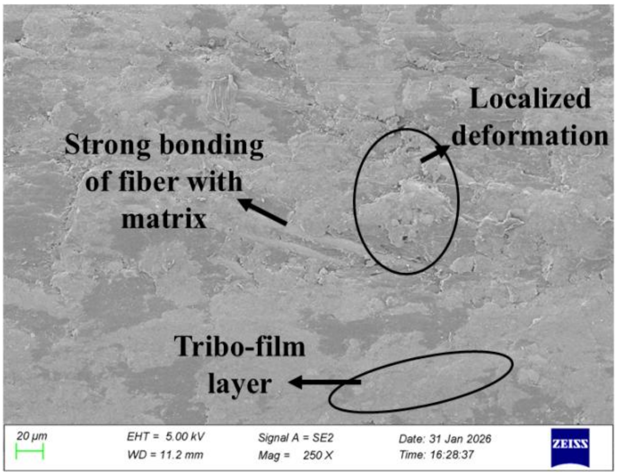


Fig. 8(e). FESEM image of the worn surface of the 8T-SGF/NN composite abraded at sliding distance 2000 m at 20 N.

3.3 Topography analysis

Surface roughness of the three-body abrasive worn samples of the Nylon66 composites were examined using 3D optical profilometer. Fig. 9 and Fig. 10 shows the average roughness and dept of the wear of the Nylon66 composites abraded at a sliding distance of 1000 m and 20 N loading condition, respectively. Hybridized composites showed higher surface roughness than other composites as depicted in the plots. Interestingly, surface roughness shows reverse trend with respect to wear loss, where composite samples with lower mass loss exhibited higher surface roughness value and vice-versa. This may be attributed to the formation of debris accumulation. Since samples abraded at higher loading (20 N), protrusion of SGF and talc filler along with debris accumulation possibly increased the surface height variation without causing significant amount of material removal. In contrast, Nylon66 during abrasion undergo plastic deformation, resulting smooth surface accompanied with severe wear loss.

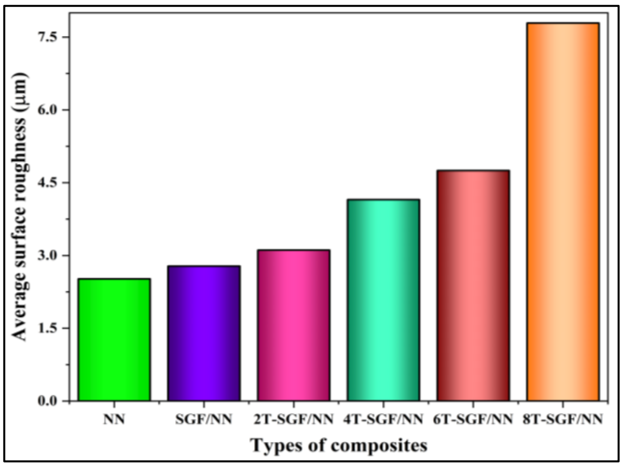


Fig. 9. Average surface roughness of the worn-out composite samples (abrading distance of 1000 m and 20 N loading).

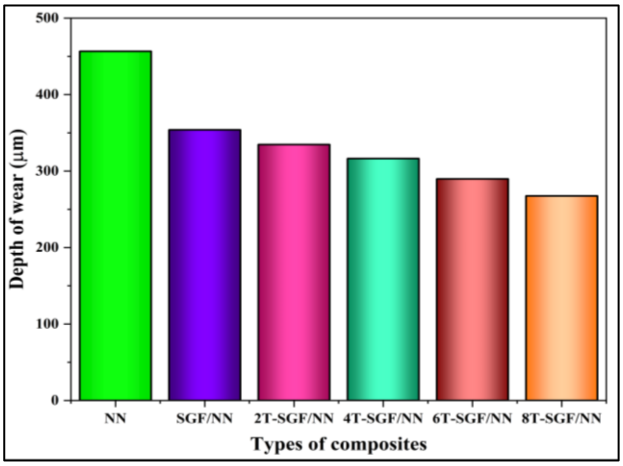


Fig. 10. Depth of the wear measured in the worn-out composite samples (abrading distance of 1000 m and 20 N loading).

Furthermore, dept of the wear was measured for all the Nylon66 composites abraded at sliding distance 1000 m under a normal applied load of 20 N. From the Fig. it is evident that NN exhibits highest wear depth. NN showed severe wear loss due to its relatively lower hardness and poor load absorbing capacity during abrasive action. However, incorporation of SGF and talc filler into Nylon66 significantly increases the wear resistance property and so wear depth this may be attributed to enhanced stiffness and resistance to abrasive penetration. Further reduction in wear depth in the talc filled SGF/NN composite is noted which clearly indicate the role of talc in enhancing the surface hardness property of the material and thereby restricts the material removal. Among the composites, 8T-SGF/NN exhibited lower wear depth demonstrating superior wear resistance under three-body abrasion testing conditions.

Fig. 11-15 depicts the 2D surface profile and 3D optical profilometer height maps of Nylon66 composites abraded at sliding distance of 1000 m under the applied load of 20 N. As discussed earlier, wear loss increased with increase in the abrading distance owing to the cumulative abrasive interactions. NN exhibited higher wear loss indicating its poor resistance to prolonged three-body abrasion wear. Despite higher wear loss, NN showed lower surface roughness compared to the SGF and talc filled SGF/NN hybrid composites. 2D worn surface profile of NN was characterized by relatively smoother profile however deeper wear tracks by plastic deformation and matrix tearing was inevitable as shown in 3D optical profilometer false-color height map (Fig. 11).

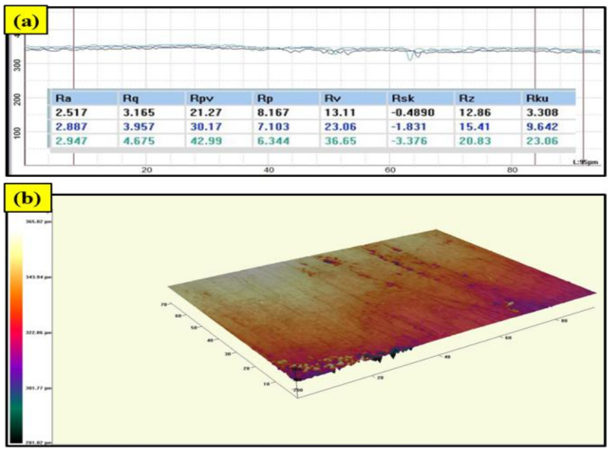


Fig. 11. (a) 2D surface profile and (b) 3D optical profilometer false-color height map of the NN material worn-out while covering sliding distance of 1000 m under 20 N loading condition.

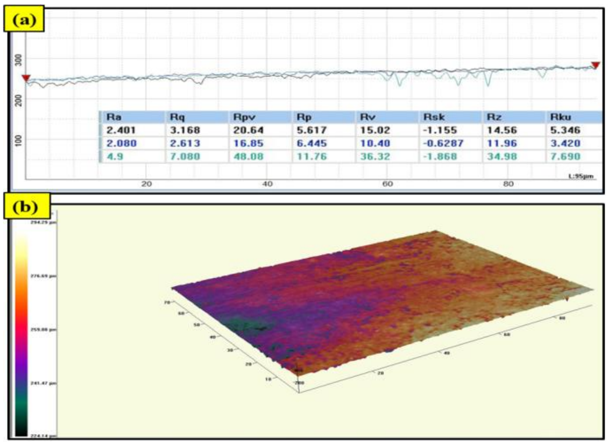


Fig. 12. (a) 2D surface profile and (b) 3D optical profilometer false-color height map of the SGF/NN composite worn-out while covering sliding distance of 1000 m under 20 N loading condition.

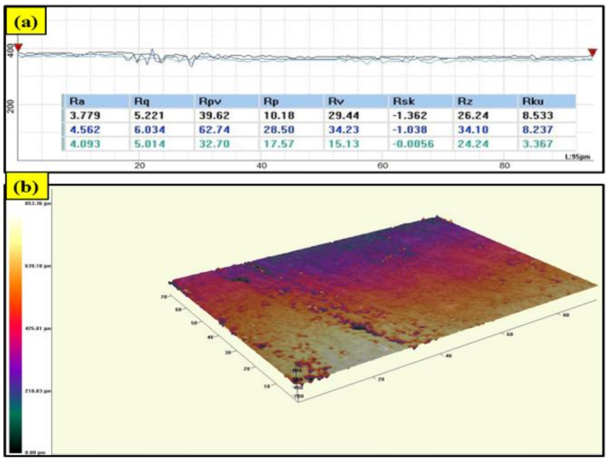


Fig. 13. (a) 2D surface profile and (b) 3D optical profilometer false-color height map of the 2T-SGF/NN composite worn-out while covering sliding distance of 1000 m under 20 N loading condition.

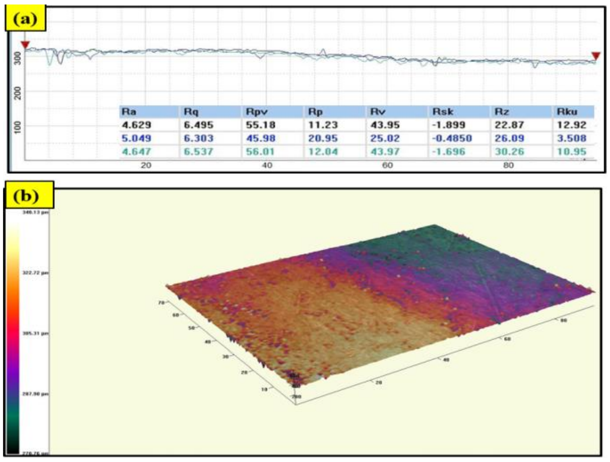


Fig. 14. (a) 2D surface profile and (b) 3D optical profilometer false-color height map of the 4T-SGF/NN composite worn-out while covering sliding distance of 1000 m under 20 N loading condition .

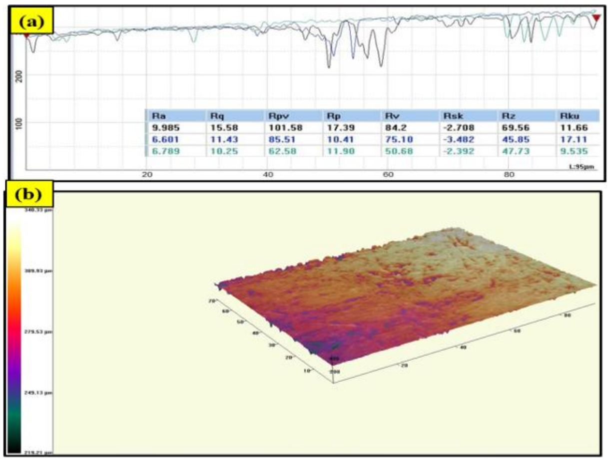


Fig. 15. (a) 2D surface profile and (b) 3D optical profilometer false-color height map of the 8T-SGF/NN composite worn-out while covering sliding distance of 1000 m under 20 N loading condition.

In contrast SGF/NN and talc filled SGF/NN hybrid composites shows abrupt profile variations with higher peak-valley heights and localized pits as indicated in the 2D profiles and 3D height maps (Fig. 12-15). Such behaviour is mainly owing to the presence of SGF and talc particles, which limits the bulk material removal but encourages localized micro-cutting, micro-cracking and particle pull-outs. Worn detached fragments further act as secondary abrasives thereby increases the surface roughness without increasing wear loss.

4. CONCLUSIONS

The following conclusions were made after successfully conducting the investigation on three-body abrasion behaviour of SGF/NN and talc filled SGF/NN hybrid composites.

Three body wear performance of the talc filled SGF/NN hybrid composites was found superior than SGF/NN and NN materials. Particularly, 8T-SGF/NN exhibited better specific resistance. Wear loss of the composites increased with increasing abrading distance whereas SWR decreased with increasing abrading distance regardless of the composition of the material.

Applied load significantly influenced the wear resistance property of the talc filled SGF/NN composites. Wear loss and SWR of the material increased with increasing applied load. 8T-SGF/NN exhibited superior abrasion wear resistance even at elevated loading condition may be owing to their effective load transfer and interfacial stability.

FESEM examination on the worn surface disclosed the maximum damages endured by the composite samples. Fiber breakage, micro-cutting, micro-tearing, and micro-ploughing were clearly identified from the micrographs. Moreover, such failure mechanisms are strongly influenced by applied load, and abrading distance. EDS spectra revealed the material composition and the presence of the abrasive particle in the worn sample which clearly support formation of tribo-film resulting from filler fragments, fine abrasive particles and wear debris. Topography analysis demonstrated that average surface roughness of the composites increased with increasing talc content whereas wear depth decreased.

This study has been restricted to dry-three body abrasion wear and test was performed under controlled parameters and limited to reinforcement proportions which may strongly restrict the direct industrial implementation. Therefore, investigations needed to be carried out under varied environmental conditions for the broader compositional ranges of composites. Real-component validation is highly recommended to establish the composite's wear performance and application potential.

Enhanced three-body abrasion wear resistance is exhibited by talc filled SGF/NN composites than NN and SGF/NN indicates the suitability of the composites for making components exposed to abrasive environment. Possible applications include bushing, conveyor belt components, agricultural machinery parts and sliding components used in dusty environment.

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