Jurnal Tribologi 40 (2024) 61-77

MYTRIBOS
Malaysian Tribology Society

Jurnal Tribologi

Website : jurnaltribologi.mytribos.org e-issn: 2289-7232

Friction and wear behavior of short carbon fibers milled polyphenylene sulfide composites

Rupesh Roshan [1*], Avin Ganapathi [2], Suresha Bheemappa [2]

[1] Design and Tribology, AR Design and Technology, Karnataka, INDIA.
[2] Department of Mechanical Engineering, NIE Institute of Technology, Karnataka, INDIA.
*Corresponding author: ruroshan@gmail.com

KEYWORDS

Composite
Polymer
Brake-pad
Polyphenylene sulfide
Short carbon fiber
Wear
Friction
SEM
SRV
Surface roughness
Tribology

ABSTRACT

Metal-based materials can be substituted with composites in various applications due to their favourable strength-to-weight ratio and ease of fabrication. This study aimed to investigate the impact of short carbon fibers as reinforcement in a polyphenylene sulfide matrix on the mechanical and tribological properties of the resulting composites, with the goal of obtaining data relevant to brake-pad applications. The composites were prepared through extrusion followed by injection molding. The tribological properties of the composites were evaluated using an SRV tribometer under dry sliding and oscillating conditions. The effects of load and frequency on the friction and wear behaviour of the composites were analyzed and compared to a reference polyphenylene sulfide material. Polyphenylene sulfide with uniform short carbon fibers exhibited superior mechanical properties and demonstrated better friction and wear resistance, while polyphenylene sulfide with random short carbon fibers showed properties recommended for brake-pad material. The post-test wear scar was analyzed for surface roughness, and the surface morphology of the wear scar on the composites was studied using a scanning electron microscope.

Received 26 July 2023; received in revised form 7 October 2023; accepted 14 November 2023.
To cite this article: Roshan al., (2024). Friction and wear behavior of short carbon fibers milled Polyphenylene Sulfide composites. Jurnal Tribologi 40, pp.61-77.

1.0 INTRODUCTION

In modern times, there has been a significant increase in the adoption of fiber-reinforced polymer composites in tribo-mechanical applications within the automotive and aerospace industries (Newman et al., 2022; Zhang et al., 2020). These composites have emerged as a viable alternative to metals due to their favorable attributes, including cost-effective production, substantial mechanical load-bearing capacity, resistance to chemical degradation, minimal wear rate, lightweight construction, and desired coefficient of friction (Lin and Schlarb, 2018; Palabiyik and Bahadur, 2002).

Recently, there has been an increasing interest in studying the performance of polymer composites to leverage their self-lubricating properties in sliding components, thereby eliminating the need for lubricants and the associated contamination issues. The interaction between polymer composites and metallic counterparts in industrial applications often involves sliding contact (Friedrich, 2018). Numerous researchers have conducted investigations on the friction and wear characteristics of composite materials under both dry and wet sliding conditions. It has been observed that the tribological properties of composites are influenced by various factors, including the type of matrix, fiber content, fiber orientation, and operating conditions (Milosevic et al., 2020). Researchers are currently exploring the tribological performance of polymer composites and the ability of fillers to form transfer films in various applications (Wang and Yan, 2006). By incorporating functional fillers to achieve customized properties, polymer composites have demonstrated significant potential for industrial applications (Maiti et al., 2022). The suitability of polymer composites for such applications depends on the effects of fiber orientation and composite microstructure on their friction and wear behaviour (Luo et al., 2016).

Automotive brake pads are typically composed of composite materials that include thermosetting resins, fibers, fillers, and friction modifiers, as noted by Akıncıoglu et al. (2018). The frictional behavior of a brake pad system significantly impacts its performance. To effectively carry out their function, brake pads must possess a high coefficient of friction and low wear. Conversely, gears or bearings operating under dry sliding conditions require properties of low friction and wear, as highlighted by Friedrich et al. (2005). Meeting the operational requirements of brake pads necessitates fulfilling specific criteria, such as maintaining consistent and high coefficients of friction under various operating conditions and resisting wear across a wide range of working conditions. Additionally, brake pads must exhibit high mechanical and thermal resistance, while also having low hygroscopicity, as emphasized by Szymański (2020).

Polyphenylene sulfide (PPS) is a semi-crystalline engineering thermoplastic material that exhibits significant potential for use in tribological applications within the automotive and aerospace industries (Golchin et al., 2015). PPS has gained widespread utilization in various industries due to its exceptional chemical resistance, superior mechanical and electrical properties, dimensional stability, elevated-temperature resistance, high flame resistance, excellent strength, high modulus, and fatigue resistance. These characteristics make PPS an optimal choice for composite manufacturing (Jin et al., 2013; Khan et al., 2016; Stoeffler et al., 2013; Wang et al., 2014). However, it is important to note that PPS is susceptible to high wear rates under high loads (Ferlic, 2006). Several studies have identified tribo-chemical interactions between PPS and steel equivalents, which can be attributed to the unique molecular structure of PPS. Wang et al. (2014) observed a high friction coefficient for pure PPS, indicating its viability as a tribological material, particularly for high friction applications under dry conditions.

Extensive research has been conducted on the combination of polymer materials, nanofillers, and various types of fibers, such as metallic, glass, ceramic, and carbon fiber composites, for brake applications (Gbadeyan and Kanny, 2017). The incorporation of fillers is a widely used method to enhance the tribological properties of PPS polymer. Yu et al. (1990) reported that the addition of graphite and PTFE fillers significantly improves the wear resistance of PPS, while the inclusion of molybdenum sulfide (MoS_2) filler leads to a notable reduction in wear resistance. This approach modifies the mechanical properties of the PPS polymer and affects both friction and wear performance of the polymer composite, as reported by Chukov et al. (2015) and Jain et al. (2019). The fillers have been found to facilitate the disintegration of PPS, resulting in the formation of compounds that contribute to the wear resistance of the composites.

According to Gu et al. (2022), carbon fibers (CFs) are widely acknowledged as a critical reinforcement component for high-performance matrix thermoplastic polymers, such as polyamide (PA), polyphenylene sulfide (PPS), polyether ether ketone (PEEK), and polytetrafluoroethylene (PTFE). In addition, these composites are highly desirable due to their ease of manufacturing, cost-effectiveness, and superior mechanical properties. PPS composites containing carbon-reinforced fibers have the potential to serve as suitable materials for mechanical and tribological applications, as highlighted by Jian and Tao (2014). The utilization of carbon fiber-reinforced composites is particularly advantageous in braking systems due to their exceptional tribological behavior, high thermal capacity, high thermal conductivity, good mechanical properties, and high impact resistance to failure (Gadow and Jiménez, 2019).

Extensive research has been conducted in the literature on polymeric composites reinforced with short carbon fibers (SCFs). Previous studies have demonstrated that the incorporation of CFs by 20 wt.% into PPS results in increased strength between the fiber and the matrix, as well as a three-fold decrease in wear during short-duration tests, as reported by Mohamad et al. (2021). Dry sliding experiments have revealed that these composites exhibit lower friction coefficients and wear rates compared to pure PPS coatings. This improvement can be attributed to the superior abrasion resistance of carbon fibers and the formation of a load-carrying tribofilm, as determined by the researchers. The SCF not only acts as a filler, but also as a self-lubricator. Furthermore, Fibers oriented perpendicular to the sliding surface demonstrate low coefficients of friction and wear. However, research on the impact of fiber orientation on wear rate has yielded inconsistent results, and the effects of fiber orientation on the coefficient of friction remain unclear. Quintelier et al. (2005) have observed a high wear rate at both low and high sliding speeds. Interestingly, Luo et al. (2016) have found that SCFs are more effective in enhancing wear resistance and reducing the coefficient of friction compared to their continuous counterparts.

The aim of this research is to identify fiber reinforced PPS composites that demonstrate exceptional wear resistance for potential implementation in brake pad applications, while simultaneously maintaining a consistent frictional performance during sliding-oscillatory motion. Our study extensively examines the tribological properties of a reference PPS composite (PPSR) and SCFs reinforced PPS (PPS1 and PPS2) composites, specifically in sliding motion using a SRV, an oscillating-reciprocating tester. Additionally, the impact of low load (150 N and 300 N) and frequency (5 Hz and 10 Hz) on the friction coefficient and wear loss of PPS was analyzed by incorporating SCF at 25 wt.% and 35 wt.%. The outcomes of this study will offer highly practical recommendations for the optimal utilization of PPS-based composites in brake-pad applications.

2.0 EXPERIMENTAL PROCEDURE

2.1 Materials and Methods

The present study employs PPS and SCF as the primary materials. PPS is a thermoplastic polymer that exhibits inherent brittleness and low impact strength, as reported by Quintelier et al. (2005). It is an organic polymer composed of a phenylene ring linked to sulfur atoms and is known for its thermal and chemical stability, as noted by Zuo et al. (2019). The PPS utilized in this study was obtained from Solvay (Ryton®PPS) and has a density of 1.35 g/cm^3 and a melting point of 285 °C. On the other hand, SCF is a widely used reinforcement material due to its exceptional mechanical properties, electrical conductivity, dispersibility, low coefficient of thermal expansion, and ability to enhance tribological performance, as highlighted by Birleanu et al. (2022). The SCF utilized in this study was obtained from SIGRAFIL®, Sweden, and has an average diameter and length of approximately 7 μm and 80 μm, respectively. Table 1 presents the mechanical properties of the SCF.

Table 1: Mechanical properties of the short carbon fiber (SCF).

Properties	**Unit**	**SCF**
Fiber density	g/cm^3	1.8
Mean fiber length	μm	80
Filament diameter	μm	7.0
Tensile strength	GPa	3.0
Ealstic modulus	GPa	200
Elongation at break	%	1.5

The tribological performance of a system is influenced by a variety of material parameters. Among these parameters, the length and distribution of SCFs, play a significant role in determining the tribological performance. In addition to improving mechanical qualities such as strength, stiffness, and impact resistance, SCF also has a positive impact on tribology. Fei et al. (2014) conducted a study on the tribological characteristics of paper-based carbon-based friction materials based on carbon fiber length. The study revealed that the friction material containing carbon fibers with a length of 100 μm exhibited the best wear resistance, while friction paired with other carbon fibers showed abrasive and fatigue wear. The typical length was chosen to ensure constant thermo-mechanical properties of the composites with respect to SFC addition in the PPS matrix, in line with the results obtained by Rezaei et al. (2009).

2.2 Composite Fabrication

In order to enhance the dispersion and distribution of SCFs, PPS and SCF were blended using a mechanical mixer. The resulting mixture of PPS matrix and SCF reinforcement was subjected to extrusion and injection molding at processing temperatures of 300 °C and 340 °C, respectively. Subsequently, the mixture was extruded using a twin-screw extruder to obtain extrudes that were pelletized and pre-dried prior to injection molding. The injection molding process was carried out at a temperature of 135 °C, as depicted in Figure 1.

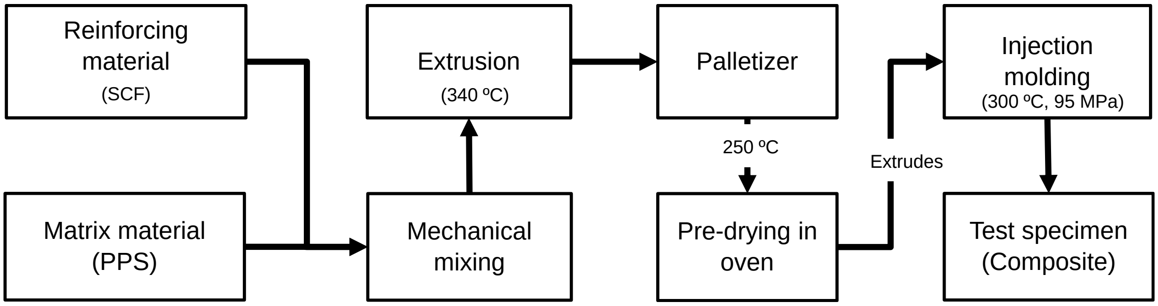
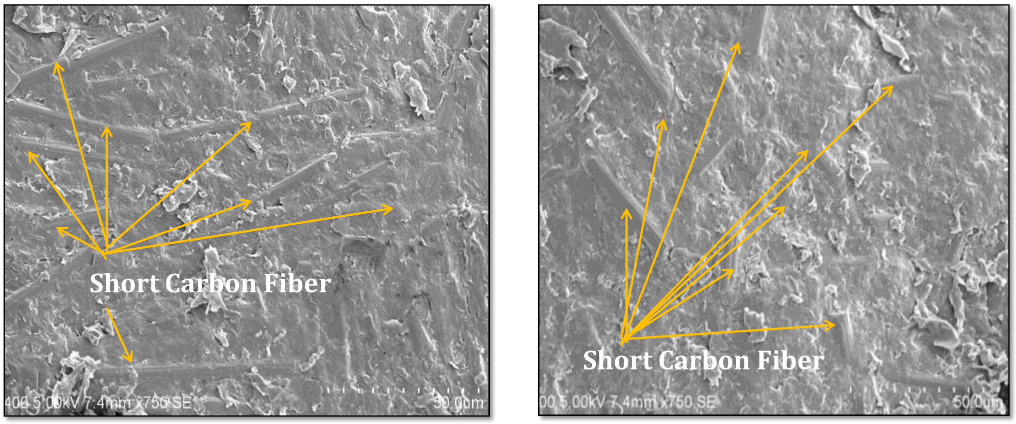


Figure 1: Schematic representation of fabrication process of SFC reinforced PPS composite.

Table 2: Composition of the specimen composites.

Specimen composites	Composite constituents	Matrix material [PPS] wt.%	Reinforcement [SCF] wt.%	Fiber Distribution
PPSR	PPS	100	-	-
PPS1	PPS+SCF	75	25	Aligned
PPS2	PPS+SCF	65	35	Random

Table 2 presents the composition of the composite samples. Although SCF reinforced polymer composites are generally known to exhibit weak mechanical properties, a higher SCF loading beyond 20 wt. % was chosen based on the promising results reported in Jain et al. (2019) to ensure that the brake-pad material meets the desired mechanical properties.



(a) PPS1 at 750X

(b) PPS2 at 750X

Figure 2: SEM images of the PPS1 and PPS2 composites showing the SCF distribution.

Figure 2 displays the scanning electron microscope (SEM) images of the PPS1 and PPS2 composites, illustrating the orientation and distribution of the SCF within the PPS matrix. It is evident that PPS1 contains reinforced SCF that are aligned in the matrix, whereas PPS2 contains reinforced SCF's that are randomly oriented within the matrix. Notably, the agglomeration of fibers is significantly higher in PPS2 composites with a 35 wt.% SCF content compared to the PPS1 composite with a 25 wt.% SCF content. Furthermore, the agglomeration of fibers increases with the increase in wt.% of SCF filler in the PPS composite. It is worth mentioning that existing literature suggests that SCF-reinforced polymer composites offer moderate strength and the lowest coefficient of friction when compared to composites with continuous fibers and unreinforced polymers (Sudhagar and Kumar, 2020).

2.3 Reciprocating Piston Tribometer

The friction and wear tests were conducted using an SRV, an oscillating-reciprocating tester manufactured by Optimal Instruments. The acronym "SRV" stands for "Schwingung Reibung Verschleiß" in German, which translates to oscillation, friction, wear. The testing equipment comprised a testing chamber with upper and lower test specimens securely placed in their respective holders. The tests were performed under dry conditions, adhering to the DIN 51834 standards. A 10 mm diameter steel ball was reciprocated on the stationary test disk, as shown in Figure 3.

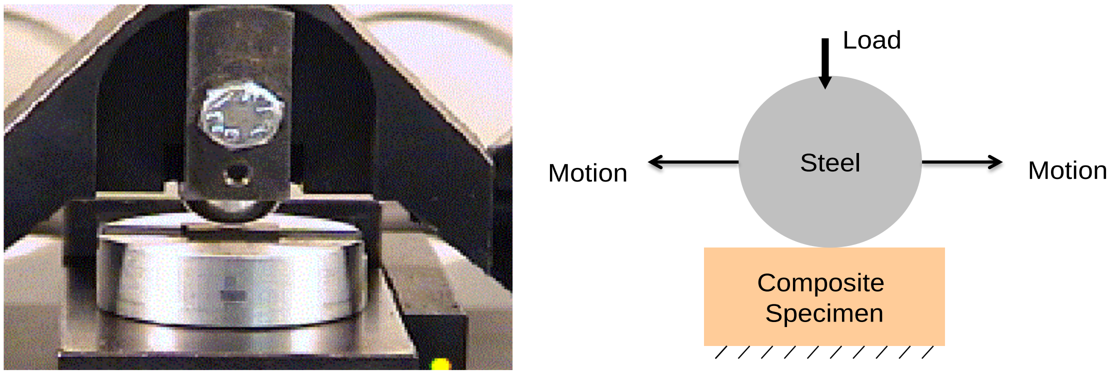


Figure 3: Pin-on-plate setup in a SRV machine.

Table 3: Test conditions.

Parameters	Unit	Levels
Amplitude (Stroke length)	mm	3
Frequency (Sliding speed)	Hz (m/s)	5,10 (0.27, 0.55)
Ball diameter	mm	10
Load	N	150, 300
Temperature	°C	50
Test duration	min	10

Crăciun et al. (2017) have emphasized the importance of selecting appropriate materials for brake pads that exhibit stable and reliable frictional and wear properties, even under varying conditions of load, velocity, temperature, and high durability. The study involved conducting tests with fixed parameters of stroke length, temperature, load, and test time, while varying frequency and load for different tests, as presented in Table 3. The friction-wear tests were performed in accordance with the modified ASTM G99 standard, as described by Akıncıoglu et al. (2018). The specimen was secured in a fixture measuring 24 mm × 8 mm, and a stainless-steel ball with a diameter of 10 mm was placed on the polymer composite, which was clamped onto the machine bed. Each composite sample underwent a friction-wear test under specific conditions for a short test duration of 10 minutes, which was repeated three times. It is noteworthy that PPS polymers, typically combined with carbon fibers, exhibit a short cycle duration and are used in service having temperatures ranging from 45 to 70 °C. Therefore, the load was maintained at a constant level during the test, with an operating temperature of 50 °C. Prior to the test, each specimen was cleaned in an ultrasonic bath, dried, weighed using a precision electronic balance (SHIMADZU AUX 220), and measured with a surface roughness meter. At the end of the test, the specimen was removed and weighed to determine the weight loss. The software automatically recorded the coefficient of friction (COF), and the wear volume was calculated using the following equations:

$$W_v\ (mm^3) = \frac{\pi\, d_4^2\, (d_3 - s)^2}{64} . \frac{1}{R'} + s\ .\ W_q \qquad (1)$$

$$R^{'}\ (mm) = \frac{d_4^2}{12\ \mathrm{W}_q} \qquad (2)$$

$$W_q\ (\mathrm{mm}^2) = \frac{\mathrm{d}_3\ .\ \mathrm{W}_d}{2} \qquad (3)$$

Where, μ is coefficient of friction, d_4 is width of the wear track in mm, d_3 is length of the wear track in mm, s is the amplitude in mm, R' is the mean radius of the wear marks in mm, W_q is the wear mark transverse to the sliding direction in mm^2, W_d is the wear depth in mm. Furthermore, the results of the friction-wear tests were correlated with the surface roughness of the traces formed on the composite surface. Additionally, microstructure analysis was conducted via. SEM images on the post-test samples.

3.0 RESULTS AND DISCUSSION

3.1 Hardness

The hardness of the polymer composite was evaluated following the guidelines of the ASTM D2583 standard, employing a Barcol hardness tester. The findings demonstrate that the incorporation of short carbon fibers (SCFs) significantly improves the hardness of the PPS polymer. Among the samples tested, PPS1, containing 25 wt.% SCF, exhibits the highest level of hardness due to the uniform dispersion of SCF throughout the composite. Conversely, PPS2, with an uneven distribution of SCF, displays an intermediate level of hardness, as shown in Table 4.

Table 4: Specimen composite hardness.

Specimen composites	**Hardness (HBa)**
PPSR	70
PPS1	80
PPS2	75

3.2 Coefficient of Friction

The results shown in Figure 4 illustrate a friction plot obtained for all samples at a constant frequency of 10 Hz and a load of 300 N, in accordance with the parameters outlined in Table 3. The coefficient of friction (COF) displayed an upward trend during the run-in phase, which lasted less than 5 minutes, before stabilizing at a constant value after approximately 10 minutes of testing. Notably, the reference material PPSR exhibited a high COF beyond the 10-minute run. The findings suggest that the implementation of SCF resulted in a reduction in friction for PPS1 and PPS2. However, PPS2, which had a higher concentration of SCF, exhibited increased COF values compared to PPS1.

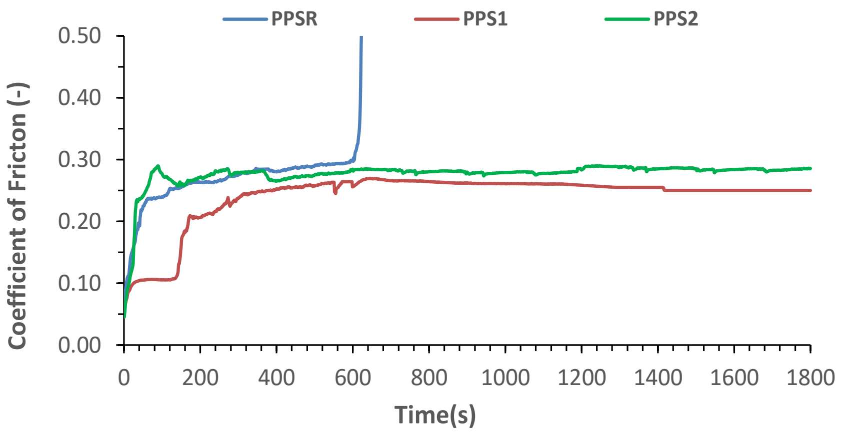
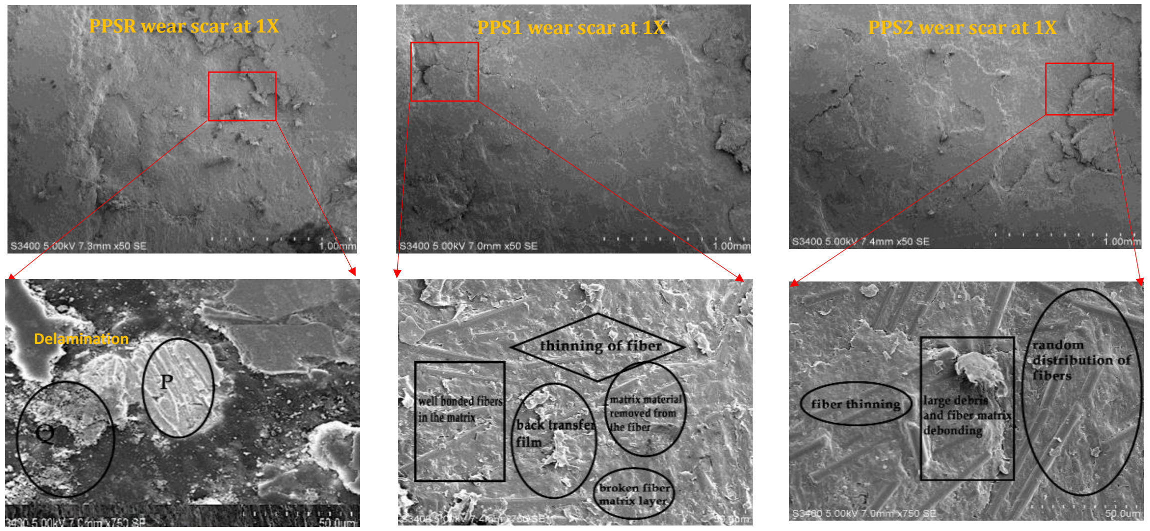


Figure 4: A typical example of change of the coefficient of friction with time.



(a) PPSR wear scar at 750X

(b) PPS1 wear scar at 750X

(c) PPS2 wear scar at 750X

Figure 5: SEM images of (a) PPSR, (b) PPS1 and (c) PPS2 wear scar post test at 300 N and 10 Hz.

The experiments were conducted three times for each sample under consistent operating conditions, with a limited run duration due to observed delamination issues in PPSR samples, as illustrated in Figure 5a. The wear scar post-test of PPSR, PPS1, and PPS2 was examined using a scanning electron microscope (SEM). Upon lower magnification, the wear scar surface was found to be uneven and inconsistent, displaying grooves, fractures, and regions of plastic deformation. The wear scar area labeled P exhibited adhesive wear characteristics, while area Q displayed peeling or delamination of the surface. Additionally, SEM images of PPS1 and PPS2 composites wear scar post-test at 300 N and 10 Hz are shown in Figures 5b and 5c. The PPS1 wear scar displayed well-embedded carbon fibers in the matrix, fiber thinning, a few broken fibers, and debris lying in between the gaps of fibers. In contrast, the PPS2 composite wear scar showed fiber thinning, broken carbon fibers, and fiber/matrix de-bonding.

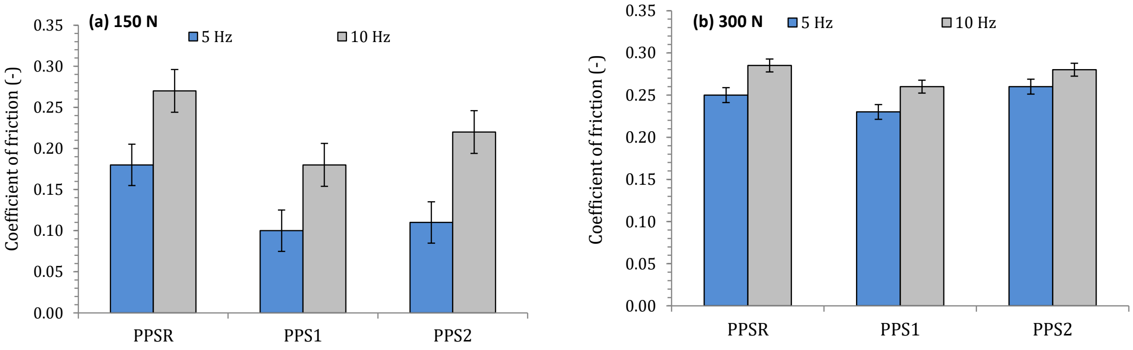
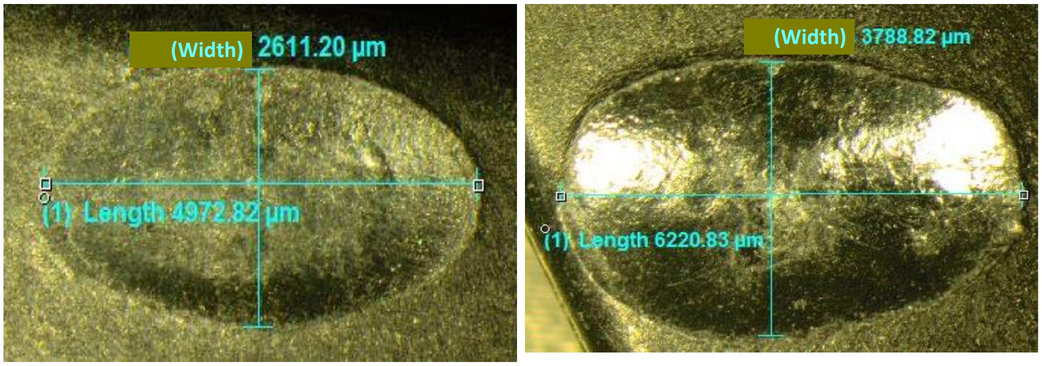


Figure 6: Effect of load on the coefficient of friction at (a) 150 N and (b) 300 N.

In Figure 6, the average COF for the last two minutes of data is presented. The data indicates that an increase in load and sliding speed leads to a rise in COF. The results suggest that the introduction of SCF resulted in a reduction in friction for PPS1 and PPS2 at a low load of 150 N and 5 Hz. However, at a high load of 300 N and 10 Hz, PPS1 and PPS2 exhibited an elevated and similar COF, similar to the reference material PPSR. The COF of PPSR and reinforced PPS increased with an increase in sliding speed, with a final COF of approximately 0.33, consistent with previous studies (Quintelier et al., 2005). The difference in COF was significant at a low load of 150 N, which can be attributed to the carbon fiber being a hard phase in the soft PPS polymer matrix, reducing the actual contact area with the mating surface under a certain load, resulting in a reduction in the adhesion force (Suresha et al., 2010). The composite material exhibited minimal differences in COF under the high load of 300 N. The results confirm that the uniformity of SCF in the PPS composite affects the friction coefficient for PPS1 under both loads and operating frequencies. When the carbon fiber content reaches a high value (35 wt.%), the COF tends to increase, which could be due to the activation of the fracture at the interface between reinforcing fibers and PPS2 matrix during the sliding process.

3.3 Wear Scar

The wear performance of composite materials requires careful consideration of key factors such as load, composite hardness, and speed (frequency). Figure 7 illustrates that load has a significant impact on the wear scar, while other parameters such as 5 Hz, 3 mm stroke, and 50 °C remain constant. The wear scar was analyzed using an Olympus SZX10 microscope. The softer composite material produced an elliptical wear scar that was easily distinguishable due to its lower hardness compared to the steel mating surface. Additionally, the wear particles from the composite material acted as a third body, accelerating the wear. It is evident that the wear scar increases proportionally with increasing load.



Load = 150 N

Load = 300 N

Figure 7: Influence of load on wear scar of PPS1 at load of 150 N and 300N.

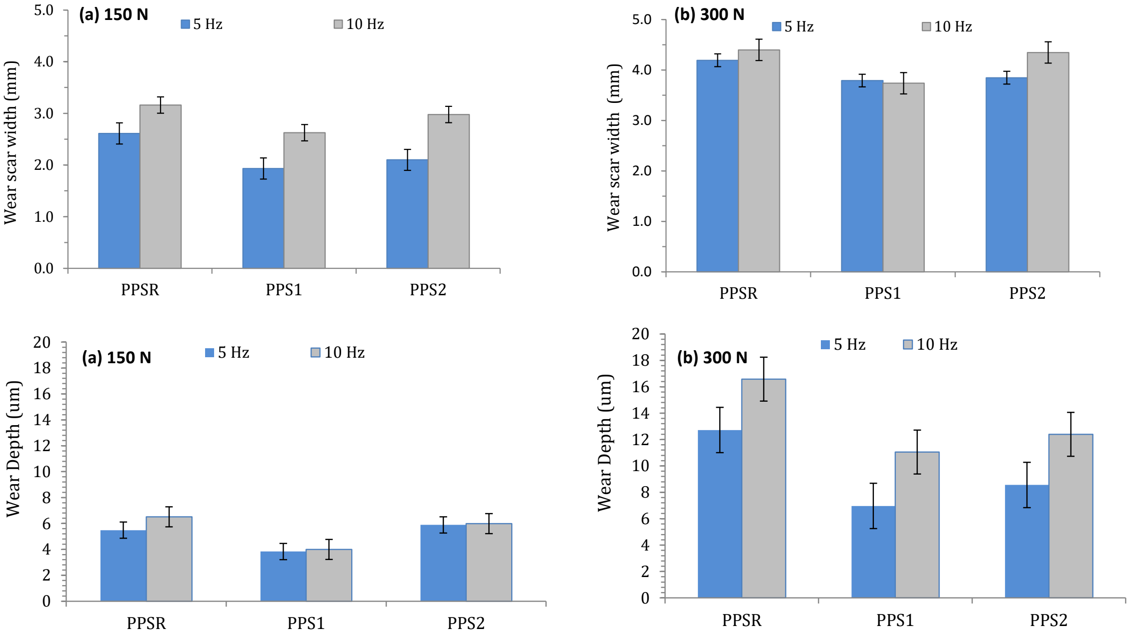


Figure 8: Effect of load on the wear scar width and the wear depth at (a) 150 N and (b) 300 N.

The results shown in Figure 8 illustrate the impact of load and frequency on the wear scar of the specimens. In order to assess the effect of these variables on the composite, measurements of wear scar width and wear depth were taken after each test. The maximum wear length, wear width, and wear depth of the wear scar were determined using a contact area profilometer (Mitutoyo SJ-310). It was observed that the wear scar width is influenced by the applied load and remains consistent for both PPS1 and PPS2. At a low load of 150 N, the wear scar width remains constant despite variations in frequency and non-uniformity of SCF in the composite matrix. However, the wear depth is found to vary with frequency at a load of 300 N.

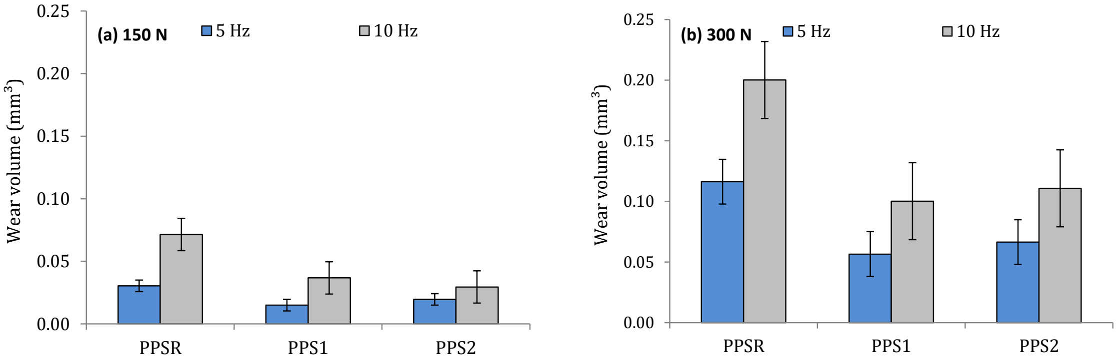


Figure 9: Effect of load on the wear volume at (a) 150 N and (b) 300 N.

Based on the findings presented in Figure 9, it can be observed that the wear of composites is directly proportional to the applied load and shows a positive correlation with its hardness. The data indicates that both the load and frequency have an impact on the increase in wear volume. When comparing PPS1 and PPS2 to PPSR, it is evident that PPS1 and PPS2 exhibit superior load capacity. Pure PPS, on the other hand, demonstrates an increase in steady state wear rate at both 5 Hz and 10 Hz frequencies, with thermal softening observed at 10 Hz resulting in a higher wear volume (Quintelier et al., 2005). Both sample PPS1 and PPS2 display better wear resistance compared to the reference PPS material (PPSR). This can be attributed to the presence of SCF, which acts as a hard phase in the soft polymer matrix. Furthermore, PPS1 exhibits a slight improvement in wear resistance compared to PPS2 due to the uniform distribution of SCF in the matrix. The aligned orientation of short carbon fibers in sample PPS1, as opposed to the random orientation in sample PPS2, contributes to its enhanced wear resistance (Kukureka et al., 1999).

3.4 Surface Roughness and Morphology

The surface roughness of both the fresh and post-test samples of PPS composites was evaluated using a contact area profilometer (Mitutoyo SJ-310), as depicted in Figure 10. The results indicate that the PPS1 and PPS2 composites are rougher than the PPSR sample due to the presence of SCF in the PPS matrix. Among all the samples, the PPS1 wear scar obtained after the 5 Hz and 150 N test exhibited the smoothest surface, while delamination during the test resulted in a rougher surface. Additionally, the surface morphology of the PPS composite wear scar was analyzed using scanning electron microscopy (SEM) to establish its correlation with the friction and wear behavior of PPS1, PPS2, and PPSR fresh composites. The findings suggest that the worn scar surfaces of all composites exhibit smoothness without any apparent plastic deformation at normal magnification. However, significant differences were observed in the magnified images of the worn scars at 750X.

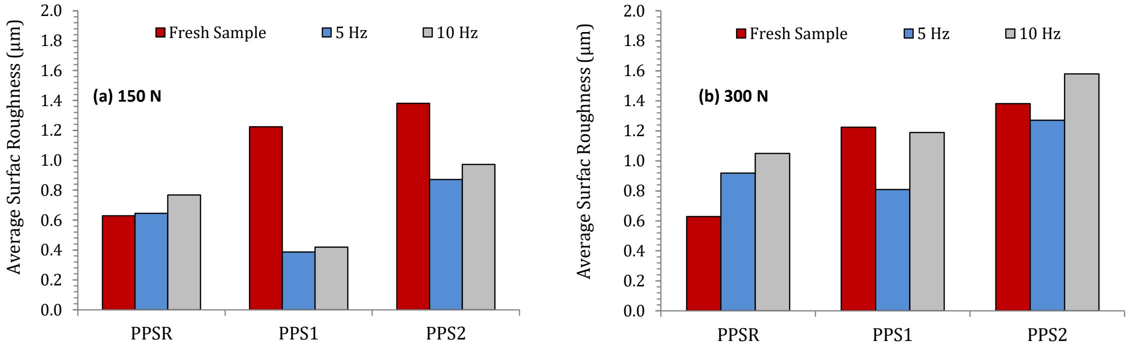
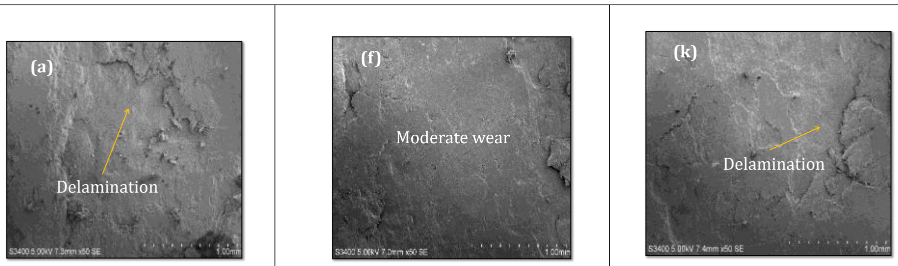
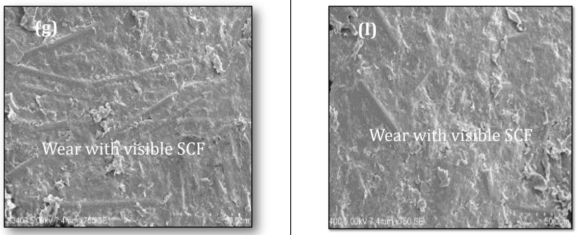


Figure 10: Surface roughness of the PPS1, PPS2, and PPSR fresh samples and its comparison to the post-test wear scar obtained at (a) 150 N and (b) 300 N.

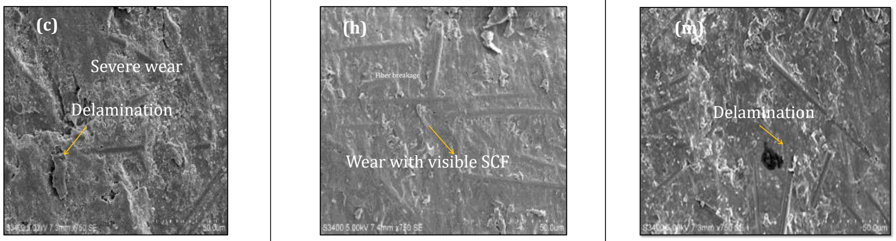
Figure 11 (f-o) illustrates that the surfaces of PPS1 and PPS2 remain intact at a low load of 150 N and a low frequency of 5 Hz. However, with increasing load, the composite surface deteriorates, resulting in fiber breakage for PPS1 and delamination for PPS2. The composite exhibits the lowest friction and wear when the short carbon fibers are uniform and well-aligned in the PPS composite matrix. Conversely, uneven alignment of the SCF fibers in the PPS composite matrix results in a slight increase in friction and wear. Therefore, fiber alignment is a critical factor for polymer composites when sliding against a steel surface. Furthermore, Figure 11 (a-e) demonstrates a significant correlation between the images and the PPSR friction and wear data. The high coefficient of friction observed in PPSR is attributed to severe wear and delamination at a load of 300 N. Conversely, at a load of 150 N and a frequency of 5 Hz, the coefficient of friction is low, and the surface exhibits the onset of delamination. PPSR displays the lowest wear resistance when subjected to oscillation, as delamination is observed at frequencies of 5 Hz and 10 Hz. Morphological analysis reveals a delamination on the worn surface that is specific to thermoplastic polymers, as previously reported by the authors (Suresha et al., 2010).



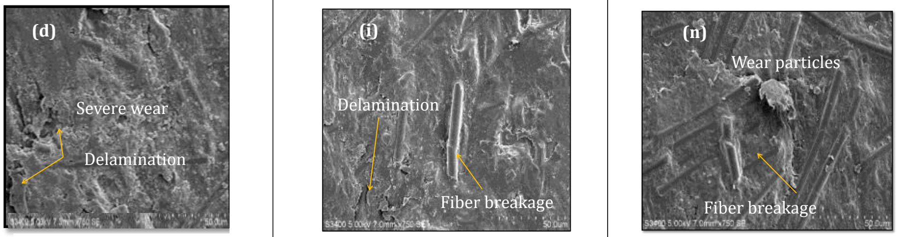
PPSR wear scar at 1X **PPS1 wear scar at 1X** **PPS2 wear scar at 1X**



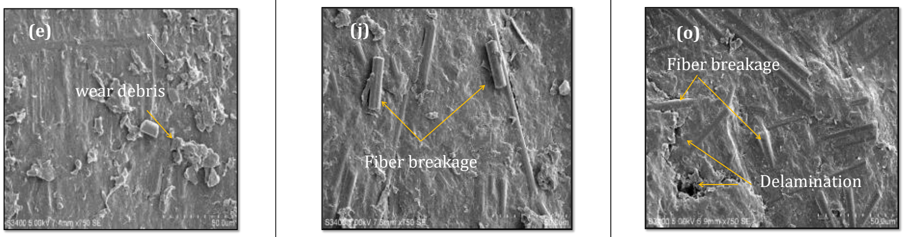
PPSR after 150 N, 5 Hz **PPS1 after 150 N, 5 Hz** **PPS2 after 150 N, 5 Hz test**



PPSR after 150 N, 10 Hz **PPS1 after 150 N, 10 Hz** **PPS2 after 150 N, 10 Hz**



PPSR after 300 N, 5 Hz **PPS1 after 300 N, 5 Hz** **PPS2 after 300 N, 5 Hz**



PPSR after 300 N, 10 Hz **PPS1 after 300 N, 10 Hz** **PPS2 after 300 N, 10 Hz test**

Figure 11: SEM images of the worn surfaces of (a-e) PPSR, (f-j) PPS1 and (k-o) PPS2 composites.

CONCLUSIONS

The objective of this study was to examine the friction and wear characteristics of PPS reinforced with SCFs under low-frequency reciprocating motion in a dry state. The tribological analysis revealed that the arrangement of fibers in the polymer material plays a critical role in determining the friction and wear properties of PPS composites. The wear performance of the SCF reinforced composite was found to be superior to the reference material (PPSR). Additionally, the study observed that the wear volume of the composite PPS2 is similar to PPS1, but lower than that of PPSR. Furthermore, PPS1 exhibited a lower coefficient of friction at loads of 150 N and 300 N, as well as at frequencies of 5 Hz and 10 Hz, making it suitable for applications within the specified range. Finally, the study identified that the composite PPS2 (65% PPS and 35 wt% SCF) is better suited for high friction and low wear applications such as brake pads and clutches. Conversely, the composite PPS1 (75% PPS and 25 wt% SCF) demonstrated high hardness and exhibited good wear resistance with a low coefficient of friction compared to the other two samples.

NOMENCLATURE

μ	coefficient of friction
°C	degree Celsius
cm	centimeter
d_3	length of the wear track (mm)
d_4	width of the wear track (mm)
HBa	Barcol hardness value
Hz	Hertz
g	gram
GPa	gigapascal
m	meter
mm	millimeter
N	newton
MoS_2	molybdenum sulfide
PA	polyamide
PPS	polyphenylene sulfide
PEEK	polyether ether ketone
PPSR	reference PPS material
PTFE	polytetrafluroethylene
R'	mean radius of the wear marks in mm
s	amplitude in mm
SEM	scanning electron microscope
SCF	short carbon fiber
SRV	SRV" stands for "Schwingung Reibung Verschleiß" (oscillation, friction, wear) and is a registered trademark of Optimol Instruments Prüftechnik GmbH
W_q	wear track across the sliding direction in mm^2
W_d	wear depth in mm

ACKNOWLEDGMENTS

The authors would like to thank Klueber Lubrication India for their assistance with the SRV tests, Solvay for providing Ryton® polyphenylene sulfide (PPS), and SGL Carbon for providing C M80-3.0 SIGRAFIL® for this study.

REFERENCES

Akıncıoglu, G., Öktem, H., Uygur, I., Akıncıoglu, S. (2018). Determination of Friction-Wear Performance and Properties of Eco-Friendly Brake Pads Reinforced with Hazelnut Shell and Boron Dusts, Arabian Journal for Science and Engineering, 43, 4727–4737.

Birleanu, C., Pustan, M., Pop, G., Cioaza, M., Popa, F., Lazarescu, L., Contiu, G. (2022). Experimental investigation of the tribological behaviors of carbon fiber reinforced polymer composites under boundary lubrication. Polymers, 14, 1- 22.

Chukov, D.I., Stepashkin, A.A., Maksimkin, A.V., Tcherdyntsev, V.V., Kaloshkin, S.D., Kuskov, K.V., Bugakov, V.I. (2015). Investigation of structure, mechanical and tribological properties of short carbon fiber reinforced UHMWPE-matrix composites. Composite: Part B: Engineering. 76, 79 - 88.

Crăciun, A. L., Pinca-Bretotean, C., Birtok-Băneasă, C. and Josan, A., (2017). Composites materials for friction and braking application. IOP Conf. Series: Materials Science and Engineering, 200, 012009, 1-11.

Fei, J., Wang, H.K., Huang, J.F., Zeng, X.R. and Luo, W., (2014). Effects of carbon fiber length on the tribological properties of paper-based friction materials. Tribology international, 72, 179-186.

Friedrich, K. (2018). Polymer composites for tribological applications. Advanced Industrial and Engineering Polymer Research, 1, Issue 1, 3-39.

Friedrich, K., Zhang, Z., Schlarb, A. K., (2005). Effects of various fillers on the sliding wear of polymer composites. Composites Science and Technology, 65, 2329 – 2343.

Gadow, R. and Jiménez, M. (2019). Carbon fiber reinforced carbon composites for aircraft brakes. American Ceramic Society Bulletin, 98, No. 6, 28-34.

Gbadeyan O. J. and Kanny, K., (2017). Tribological Behaviors of Polymer-Based Hybrid Nanocomposite Brake Pad, Journal of Tribology, 140 (3), 7 pages.

Golchin, A., Friedrich, K., Noll, A., Prakash, B. (2015). Tribological behavior of carbon-filled PPS composites in water lubricated contacts. Wear, 328–329, 456–463.

Gu, X. Q. A., Tang, W., Tang, S., and Yu, Z. (2022). Effect of perfluoropolymers on the anti-wear properties of carbon fiber/polyphenylene sulfide composites: A comparative study, ACS Omega, 7, 44, 1-18.

Jain, A., Somberg, J., Emami N. (2019). Development and characterization of multi-scale carbon reinforced PPS composites for tribological applications, Lubricants, 7(34), 1-18.

Jian, L. and Tao, S. (2014). The mechanical and tribological properties of CF/PPS composite filled with PA6', Journal of Thermoplastic Composite Materials. 27 (5), 594-602.

Jin, F. L., Lee, S. Y., Park, S. J. (2013). Polymer matrices for carbon fiber-reinforced polymer composites. Carbon Letters, 14, 76 – 88.

Khan, S. M., Gull, N., Munawar, M. A., Zia, S., Anjum, F., Iqbal, M. S., Shafiq, M., Islam, A., Awais, S. M., Butt, M. A., Butt, M. T. Z., Jamil, T. (2016). Polyphenylene sulphide/carbon fiber composites: study on their thermal, mechanical and microscopic properties, Iranian Polymer Journal, 25, 475 – 485.

Kukureka, S.N., Hooke, C.J. Rao, M., Liao, P., Chen, Y.K. (1999). The effect of fiber reinforcement on the friction and wear of polyamide 66 under dry rolling–sliding contact. Tribology International, 32, 107–16.

Lin, Leyu and Schlarb, Alois K. (2018). The roles of rigid particles on the friction and wear behavior of short carbon fiber reinforced PBT hybrid materials in the absence of solid lubricants, panel. Tribology International, 119, 404 – 410.

Luo, W., Liu, Q., Li, Y., Zhou, S., Zou, H., Liang, M. (2016). Enhanced mechanical and tribological properties in polyphenylene sulfide/polytetrafluoroethylene composites reinforced by short carbon fiber. Composites Part B: Engineering, 91, 579-588.

Maiti S., Islam M. R., Afroj, M. A. U. S., Eichhorn, S. J., Karim, N., (2022). Sustainable Fiber-Reinforced Composites: A Review, Advanced Sustainable Systems, 6, 2200258.

Milosevic, M., Valášek P., and Ruggiero, A., (2020). Tribology of natural fibers composite materials: An Overview. Lubricants, 8(4), 42, 19.

Mohamad N., Latiff, A. A., Razak, J. A., A. Maulod, H. E., Jun, L. P., Kasim, Md. S. Ahsan, Q., (2021). Morphological Characteristics and Wear Mechanism of Recycled Carbon Fibre Prepreg reinforced Polypropylene Composites. Malaysian Journal on Composites Science and Manufacturing, 5, Issue 1, 1-10.

Newman, B., Creighton, C., Henderson, Luke C., Stojcevski, F. (2022). A review of milled carbon fibres in composite materials. Composites Part A: Applied Science and Manufacturing, 163, 107249.

Palabiyik, M. and Bahadur, S. (2002). Tribological studies of polyamide 6 and high-density polyethylene blends filled with PTFE and copper oxide and reinforced with short glass fibers. Wear, 253(3–4), 369–376.

Quintelier J., Samyn P., De Baets P., Ost, W. Van Paepegem, W., (2005). Wear of steel against carbon fibre reinforced PPS, Tribology in Industry, 27(3), 29-35.

Rezaei, F., Yunus, R., Ibrahim, N.A. (2009). Effect of fiber length on thermo-mechanical properties of short carbon fiber reinforced polypropylene composites, Materials and Design, 30, 260–263.

Stoeffler, K., Andjelic, S., Legros, N., Roberge, J., Steen, B., Schougaard, S. B. (2013). Polyphenylene sulfide (PPS) composites reinforced with recycled carbon fiber. Composites Science and Technology, 84, 65-71.

Sudhagar, S. and Kumar S. S., (2020), Determination of Wear, Friction Behavior and Characterization of Carbon Fiber Reinforced Epoxy Composites for Transport Applications. Materials Research, 23(6): E20200268, 1-8.

Suresha, B., Kumar, K. S., Seetharamu, S., Kumaran, P. (2010). Friction and dry sliding behavior of carbon and glass fabric reinforced vinyl ester composites. Tribology international, 43(3), 602-609.

Szymański, P., Czarnecka-Komorowska, D., Gawdzińska, K., Trubas, Kostecka, A. E., (2020). A review of composite materials used in brake disc pad manufacturing process. Composites Theory and Practice, 20(2), 60-66.

Wang, H., Liu, D., Yan L, Li, M., Wang, C., Zhu, Y., (2014). A computed model for tribological properties of porous self-lubricating PPS composites: numerical analysis and experimental verification. Wear, 320, 94–102.

Wang, Y. and Yan, F. (2006). Tribological properties of transfer films of PTFE-based composites. Wear, 261, 1359–1366.

Yu, L., Yang, S., Lium W., (2000). An investigation of the friction and wear behaviors of polyphenylene sulfide filled with solid lubricants. Polymer Engineering Science, 40(8), 1825–32.

Zhang, J., Chevali, V. S., Wang, H., Wan, Chun-H. (2020). Current status of carbon fibre and carbon fibre composites recycling. Composites Part B: Engineering, 193, 108053.

Zhao, Q. and Bahadur, S., (2002). Investigation of the transition state in the wear of polyphenylene sulfide sliding against steel. Tribology Letters, 12, 23–33.

Zuo, P., Tcharkhtchi, A., Shirinbayan, M., Fitoussi, J., Farid Bakir, F., (2019). Overall investigation of poly (phenylene sulfide) from synthesis and process to applications - A review. Macromolecular Materials and Engineering, 304(5), 1-27.