



Research Article

Comparative study of two-body and three-body abrasive wear behaviour of 3D printed carbon fiber reinforced PLA/ABS composites

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ARTICLE INFO

Article history

Received: 30 October 2024

Revised: 08 January 2025

Accepted: 25 February 2025

Keywords:

SCF reinforced PLA/ABS composites, FDM, Abrasive wear, Wear mechanisms

ABSTRACT

The aim of this research is to investigate the tribological behaviour of short carbon fibre (SCF) reinforced polylactic acid (PLA)/acrylonitrile butadiene styrene (ABS) matrix composites using Fused Deposition Modelling (FDM). The major goal is to provide a theoretical foundation and investigate the applicability of SCFs (20 wt.%) for printing a high-quality PLA/ABS composites structure with superior abrasion resistance.

The wear specimen was manufactured using FDM technology. The specimen was produced out of pristine PLA, pristine ABS and SCF reinforced PLA/ABS composites. These composites were tested for multi-pass two-body and three-body abrasive wear behaviour utilising a special purpose abrasion test rig and a rubber-wheel abrasion test rig respectively.

The specific wear rate is primarily controlled by the applied normal load and the abrading distance. Comparing the wear performance of all composites under various loads reveals that two-body abrasive wear (multi-pass condition) is 2 to 2.4 times larger than three-body abrasive wear. Attempts have been made to connect wear performance with certain mechanical parameters. The wear mechanism associated with different experimental conditions was also studied using scanning electron microscope (SEM).

Cite this article as: Anand A, Hemanth R, Raghavendra T, Suresha B, Bharath PB, Govindaraju N. Comparative study of two-body and three-body abrasive wear behaviour of 3D printed carbon fiber reinforced PLA/ABS composites. Sigma J Eng Nat Sci 2026;44(4):2328–2338.

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*This paper was recommended for publication in revised form by
Editor-in-Chief Ahmet Selim Dalkilic*



INTRODUCTION

Digital manufacturing is a process that uses digital models to create products, while additive manufacturing is a type of digital manufacturing that uses 3D printing to create objects. Extruded filaments are utilized in the additive manufacturing technique of fused deposition modelling (FDM) to fabricate polymer matrix composites (PMCs). Fused filament fabrication (FFF) and fibre reinforcements can be combined essentially in two ways. One way to create 3D printed parts in FDM is to impregnate chopped/short fibres with a fibre length range of 0.25 mm to 3 mm into a polymer, then extrude the filament. The printed part is anisotropic, similar to unidirectional fibre reinforced PMCs, because the fibres are arranged randomly. Alternatively, in-situ co-extrusion (fiber is coated with polymer in the nozzle) or dual extrusion (bare fibre are fed through spool into the print head and polymer melt is coated around the fiber in the nozzle). The print head subsequently extrudes polymer melt coated fiber to obtain a composite filament. The potential benefits and drawbacks of each approach have been reported [1, 2].

Investigating the mechanical and tribological behaviour of the 3D printed PMC parts has involved a great deal of research. The process parameters influencing 3D printed polymer composites' mechanical properties have been identified by a number of studies [3–7]. The post-treatment's (i.e. heat treating the 3D printed parts suitably to increase its strength due to the recrystallization process that the materials undergo during heat treatment) has been explored by Sagias et al. and Avila et al. [8, 9]. Several studies [10–12] have used pin-on-disk tester to investigate wear and friction properties of 3D-printed polymers and their composites (PLA, ABS, PA66, and PA6 as matrix and nano-alumina, nano-carbon black and continuous CF as reinforcements). The filler/fibre reinforced composites outperformed pristine polymers. Hemanth et al. [13] examined thermoplastic copolyester elastomer (TCE) hybrid composites with fibre/filler contents of 20, 30, and 40 wt. % in terms of their two-body abrasive wear behaviour under multi-pass conditions. Twin screw extrusion extrudates were injected into moulds to create test samples. It was found that the specific wear rate rises as the fibre/filler content increases and falls as the silicon carbide abrasive grit size and abrading distance increase. Urs et al. examined how short carbon fibres and graphene nanoplatelets (GNPs) affected the abrasive wear behaviour of PA66/TCE composites [14]. They disclosed that 3 wt. % of GNPs enhanced the wear resistance of PA66/TCE in adhesive wear mode, while, under three-body abrasive wear (3-BAW) test conditions, 1 wt. % of GNPs into PA66/TCE hybrid composites showed superior abrasion resistance.

Batra and Colleagues [15], investigated the 2-BAW behaviour of hybrid composites reinforced with woven carbon/glass/aramid polyetherimide (PEI). According to their report, the carbon fibre/PEI composite exhibited

reduced wear rate in comparison to the glass fibre/PEI and aramid fibre/PEI composites. Hemanth et al. [16] investigated the abrasive wear behaviour of TCE hybrid composites with fibre/filler loading of 15, 32, and 40 wt. % under 2-BAW in single-pass conditions. They disclosed that the 15 wt. % of PTFE in TCE matrix demonstrated superior abrasion resistance in comparison to the hybrid composites that were being examined. They also stated that the abrasive wear performance was negatively impacted by carbon fibre, glass fibre, and ceramic fillers like silicon carbide and alumina. Surface (circular) texturing can considerably lower the coefficient of friction, especially when sliding in dry conditions, according to studies on the dry sliding wear of PLA. This was due to the less real area of contact and more effective formation of transfer film. The entrapment of wear debris was more effective which helps in the formation of transfer layer that acts as solid lubricant. Surface analysis of the worn samples revealed that the wear was mainly due to adhesive and abrasive action [17]. This is consistent with research by Shipway [18], wherein they found that test parameters can have a big influence on how well polymers perform in abrasive wear tests. The impact of test conditions is further emphasized by Harsha [19], who demonstrates that the specific wear rate (SWR) of two-body abrasive wear (2-BAW) is significantly higher than that of three-body abrasive wear (3-BAW). Jia [20] compares the abrasive wear performance of various polymer coatings; polyurethane coatings showed the superior abrasion resistance. Together, these studies indicate that a number of factors, such as surface texturing, test conditions and the particular properties of the material, affect PLA's abrasive wear.

Based on the results of the aforementioned investigations, it can be concluded that polymer composites made by extrusion and injection molding, with selected functional fillers exhibited superior abrasion resistance in 3-BAW mode. However, the presence of higher loading of fibre/filler into various thermoplastic matrices has a negative impact on resistance to abrasion.

Numerous important conclusions have been drawn from research on the 2-BAW of PLA. Lingesh [21] discovered that grit size and abrading distance affect PLA's SWR, while the presence of additional fibres/fillers affects the resistance to abrasion. By examining the wear loss of PLA composite reinforced with basalt fibre, Kumar [22] discovered that the wt. % of the reinforcement in composite affects both the SWR and coefficient of friction. Zhang [23], examined friction and wear behaviour of 3D printed PLA and found that a crucial printing parameter is the infill-density. Together, these studies demonstrate the intricate interactions between surface texture, printing parameters, and material composition that affect PLA's 2-BAW. Added to this, Suresha et al. [24] examined the PLA and ABS 3D printed composites with short carbon fibre (SCF) reinforcement for their abrasive wear behaviour under 3-BAW test. To print the specimen, PLA and ABS filaments were impregnated with SCF using

an extrusion process. They found that, in comparison to neat PLA, the presence of SCF reduces the wear resistance of PLA and ABS composites by 60% and 78%, respectively. The PLA/ABS composites under study have reduced abrasion resistance as a result of SCF reinforcement.

According to the aforementioned review of literature and the authors' knowledge, there haven't been many studies done on the comparison of abrasive wear behaviour of thermoplastic composites reinforced with short fibre that are fabricated by 3D printing. This has therefore inspired the authors to investigate and comprehend the 2-BAW and 3-BAW behaviour of 3D printed pristine PLA, pristine ABS and SCF reinforced PLA/ABS thermoplastic composites.

MATERIALS AND METHODS

Materials

The PLA, ABS, PLA with 20 wt. % SCFs and ABS with 20 wt. % SCFs filament of ϕ 1.75mm were procured from 3D printing company eSUN 3D, Karnataka, India. Table 1, summarizes the physical and mechanical parameters of the thermoplastic composites developed by the vendors.

Fabrication of Composites by Fused Deposition Modelling

The first stage is creating a CAD model with the required dimensions of 3 mm x 8 mm x 8 mm for 2-BAW, 3 mm x 25 mm x 75 mm for 3-BAW tests and storing it in the Standard Tessellation Language (STL) format. These models are then

transferred to slicing software "UltimakerCura" which slices the STL model and generates G-codes. Figure 1, displays a flow chart of the CAD model and manufacturing processes for PLA/ABS and their composites. Table 2 shows the printing settings that were considered for specimen fabrication. These created G-codes are then sent into the Creality-ender 3 pro FDM printer. The composite filament is provided to the heating unit via rollers. The printer nozzle is heated to the melting temperature of the filament as mentioned in Table 2, and allowing the material to deposit on the built platform with respect to the path developed by the slicing software using G codes. The method is repeated until the desired specimen is obtained.

WEAR TESTING

Two-Body Abrasive Wear Test of SCF Reinforced PLA/ABS Composites

The two-body abrasive wear under multi pass condition test was conducted on pin-on-disk rig in conformance to ASTM G-99-17. The tests were conducted as per the procedure discussed elsewhere [13]. The pictorial representation of the test set up is shown in Figure 2.

Three-Body Abrasive Wear Test of SCF Reinforced PLA/ABS Composites

Three body abrasive wear (3-BAW) test was carried out as per ASTM G-65-16(2021) standards. The tests were

Table 1. Physico-Mechanical characteristics of PLA/ABS composites

Properties	PLA	SCF/PLA	ABS	SCF/ABS
Density (gcm ⁻³)	1.3	1.4	1.1	1.2
Tensile strength (MPa)	48	59	43	48
Hardness (Shore D)	75	79	58	61
Melting point (°C)	210	220	245	250
Glass transition temperature (°C)	65	70	105	110

Table 2. Parameters for fabrication of 3D printed specimen

Material	PLA	SCF/PLA	ABS	SCF/ABS
Parameters				
Nozzle temperature (°C)	210	215	240	250
Bed temperature (°C)	65	65	100	110
Infill density (%)	100	100	100	100
Layer thickness (mm)	0.12	0.12	0.2	0.2
Orientation direction	[90, 90]	[90, 90]	[90, 90]	[90, 90]
Printing speed (mm s ⁻¹)	70	70	80	60
Build orientation	Vertical	Vertical	Vertical	Vertical

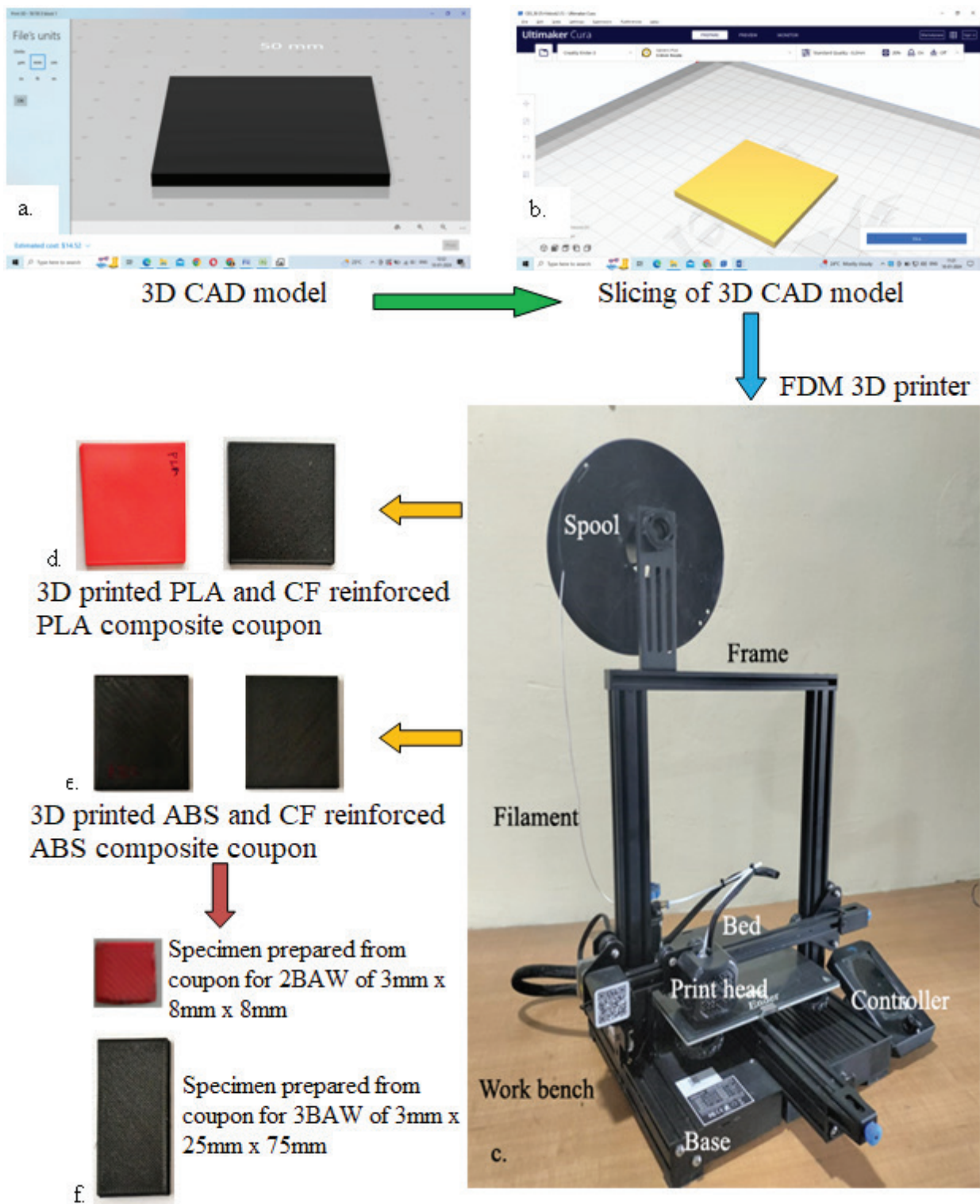


Figure 1. Fabrication process of specimen using FDM method.

conducted as described elsewhere [24]. The pictorial representation of the test set up is shown in Figure 3.

The test conditions for both 2-BMAW and 3-BAW modes are listed in Table 3 and 4 respectively.

Worn Surface Characterization

Scanning Electron Microscopy (SEM) is used to study the surface morphology and topography of a wide range of materials, including polymer and their composite samples.



Figure 2. Two-body multi-pass abrasive wear test setup.

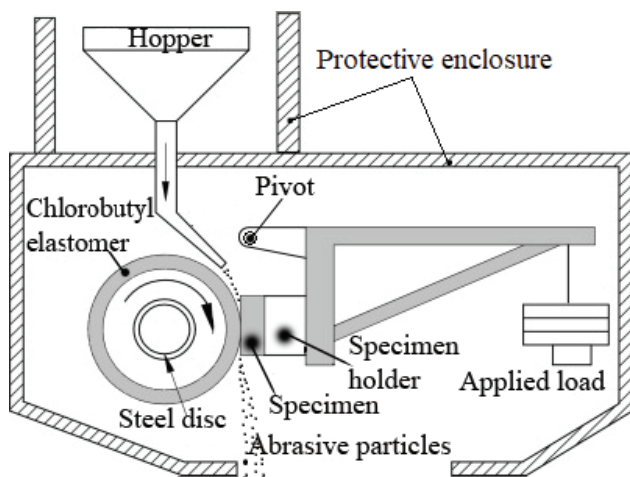


Figure 3. Three-body abrasive wear test rig.

Table 3. Two-body multi-pass abrasive wear test conditions used in the present work

Test conditions	Units	Values
Abrading distance	m	75, 100, 125, and 150
Load	N	10 and 20
Velocity	m/s	0.25
Abrasive grit size	μm	90

Polymer and polymer matrix composite samples need to be properly prepared for SEM to provide accurate information. For proper conduction, all the samples are coated with a thin layer of a gold to prevent charging effects and

Table 4. Three-body abrasive wear test conditions used in the present work

Test conditions	Units	Values
Abrading distance	m	750, 1000, 1250 and 1500
Load	N	10, 20 and 30
Speed	RPM	200
Silica sand abrasives	μm	80-95

enhance signal quality. In the present investigation, the surface morphology of worn surfaces of the composites was investigated using E-SEM, Quanta 200 model, FEI-Netherland make, with a voltage of 20 kV.

RESULTS AND DISCUSSION

Effect of Short Carbon Fibers on Two-Body Abrasive Wear of PLA/ABS Composites

For PLA, ABS, SCF/PLA and SCF/ABS composites, two-body multi-pass abrasive wear (2-BMAW) tests were conducted. Table 3, lists the operational test conditions that were used during the experiment. For the grit 225 grade (90 μm) SiC emery paper used, the experiments were carried out to determine the range of abrading distance and load to be applied at lower velocity under 2-BMAW conditions. This can be explained by the fact that after a certain number of revolutions, the abrasive paper will no longer effectively abrade the material. The frictional force decreased at this point and stayed nearly constant thereafter. The material that has been abraded will act as a cushion and a barrier to lessen abrasion. The first stage of the 2-BMAW (75 to 100 m) is depicted in Figure 4 (a, b), where specimens are exposed to abrasive paper that penetrates the polymer/composite material and significantly removes material as debris due to the application of a normal load. For the range of abrading distance 100 m to 150 m shown in Figure 4 (a, b) where abrasive paper loses its ability to remove material. Similar observations were also made by Hemanth et. al. [13]. The authors have discussed about the formation of debris and space occupied by them between the abrasives and their adherence to the abrasive particles with the help of SEM. This action reduces the efficiency of abrasive particle cutting edge, resulting in steady state wear. The steady state wear is responsible for the decrease in frictional force that was noted in the tribometer's instrument cluster dashboard. Additionally, when comparing run-in wear to steady-state wear conditions, the wear crater also gets reduced.

The experimental findings for a specific wear rate (SWR) are shown in Figure 4a and 4b. Figure 4 illustrates the load-dependent variations in SWR for PLA, ABS, SCF/PLA and SCF/ABS composites. At low load (10 N), SWR was seen to be lower. This results from fewer abrasive

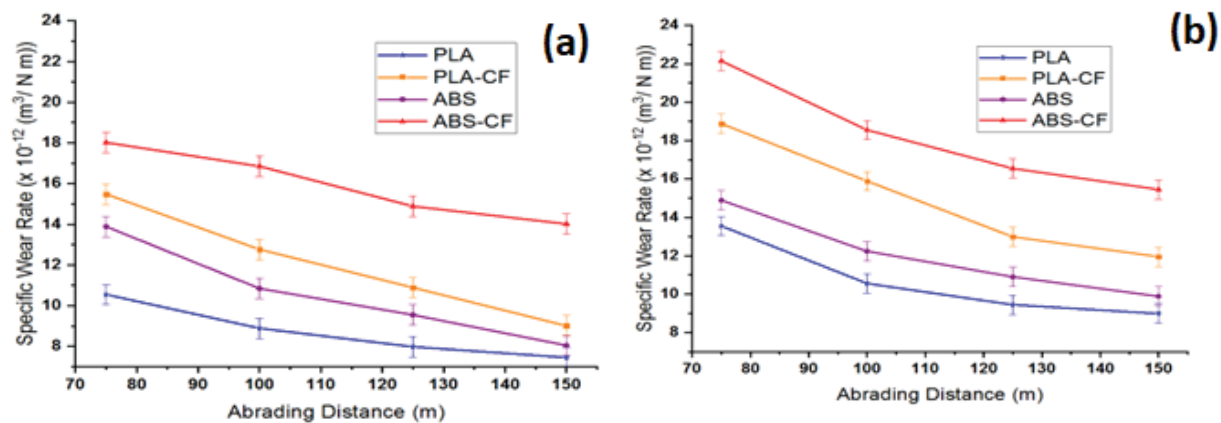


Figure 4. Specific wear rate of SCF reinforced PLA/ABS composites: (a) 10 N and (b) 20 N.

particles coming into contact with the rubbing surface and from reduced penetration. The surface's initial roughness and irregularities tend to disappear as the abrading distance increases. Debris fills the spaces left by the abrasive, further decreasing the depth of penetration. This can result in a smoother surface, reducing the abrasive interaction and, consequently, reducing the SWR. With an increase in applied load (20 N), the SWR of PLA, ABS, SCF/PLA and SCF/ABS composites rise. This is because the SiC particles penetrated the material surface more deeply, resulting in the creation of deeper grooves, resulting in increased SWR.

For the tests conducted under 2-BMAW, the pristine ABS and SCF/ABS composites showed maximum SWR of $14.89 \times 10^{-12} \text{ m}^3/\text{N m}$ and $22.15 \times 10^{-12} \text{ m}^3/\text{N m}$, respectively. The abrasion resistance of ABS has been found to be negatively impacted by SCF reinforcement. Under the same test conditions, PLA and SCF/PLA composites showed maximum SWR of $13.55 \times 10^{-12} \text{ m}^3/\text{N m}$ and $18.89 \times 10^{-12} \text{ m}^3/\text{N m}$, respectively.

It is note worthy that the SWR may vary depending on the constituents of the composite materials used, the type of abrasives used, and the surrounding environment. Furthermore, depending on the predominant wear mechanisms in a given system, the relationship between abrading distance and SWR may not be applicable to all systems. Abrasive wear of thermoplastic polymers involves the removal of material from the surface due to the mechanical action of abrasive particles. When compared to pristine ABS and SCF/PLA as well as SCF/ABS composites, pristine PLA demonstrated better abrasion resistance in the current study. The thermoplastic polymer known as PLA is biodegradable and sourced from sustainable sources like sugarcane or corn starch. Abrasion resistance is one of the mechanical properties of PLA that can be influenced by its molecular structure and crystallinity. PLA's degree of crystallinity and molecular weight may improve its toughness and hardness, which

lead to better abrasion resistance. In comparison to PLA, ABS appears to be a softer material based on the observed increase in SWR under 2-BMAW. Hence, ABS is therefore more prone to abrasive wear, and the SiC abrasive particles are able to remove material more readily from the surface, increasing the SWR.

When adding SCFs to thermoplastics, their abrasion resistance can be affected in a variety of ways, so it's important to take a number of factors into account when attempting to explain an increase in SWR. Here are several reasons why the incorporation of SCFs might lead to an increased SWR in PLA or ABS materials are poor adhesion, fibres are randomly distributed, and short fibres could not provide as much reinforcement as longer fibres and may not effectively distribute loads or resist wear. Furthermore, SCFs may increase SWR by functioning more like particulate fillers than reinforcing elements.

Wear Mechanisms of SCF-Reinforced PLAS/ABS Composites Under 2-BMAW

SEM images were used to study the worn surface morphologies of PLA, ABS, SCF/PLA and SCF/ABS composites. Soft fragments of debris are left on hard surfaces as a result of material being removed from one surface by another harder material, causing abrasive wear. The samples tested under 2-BMAW; SEM images of selected worn surfaces are shown in Figure 5 (a to d).

Figure 5a and 5b display the worn surfaces of both the pristine PLA and pristine ABS samples. There are grooves in the abrading direction (indicated with arrows), plastic deformation (indicated with P), wear debris (W), micro-cracking (K), and micro-cutting (C) can be seen from the SEM images. This has occurred at a high load of 20 N. The SEM images shown in Figs 5c and 5b indicate a decrease in plastic deformation and more wear debris when SCFs are integrated into PLA of ABS matrices. According to Figs. 5c and 5d, the worn surface of 20 wt. % SCFs into PLA or ABS composites at 20 N load revealed more deep grooves

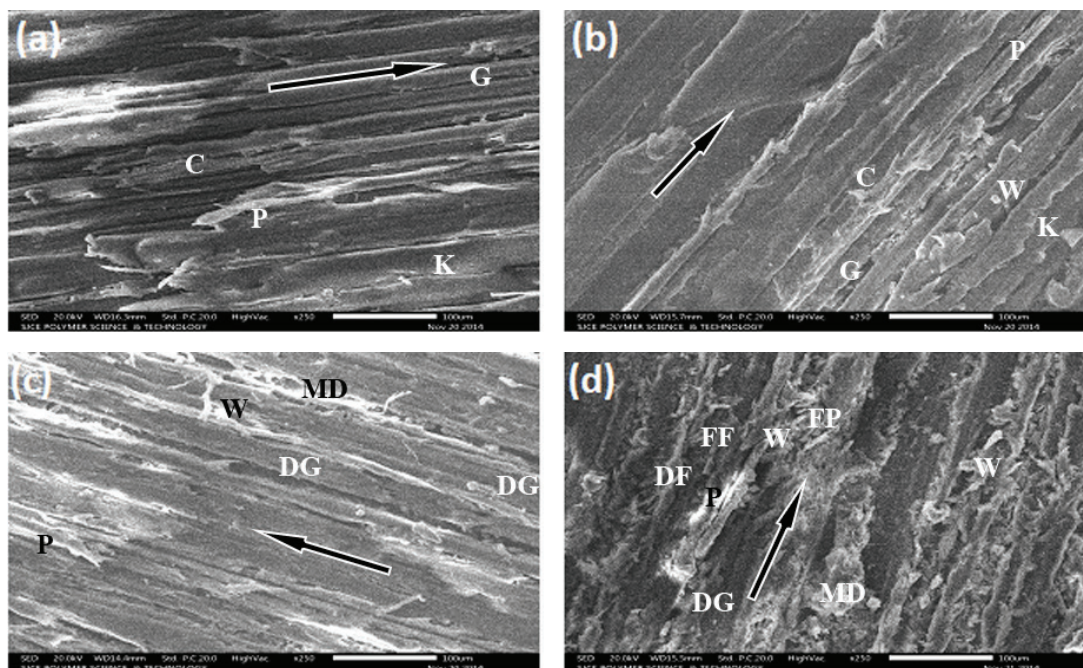


Figure 5. SEM images of wear surfaces of the composites at 20 N: (a) PLA, (b) ABS, (c) SCF/PLA, (d) SCF/ABS under 2-BMAW (with 250 x magnification).

(DG), fibrepull-out (FP), plastic deformation (P), and wear debris (W). Additionally, the surface morphology demonstrates that the fibre fracture (FF) and severe matrix damage (MD), leads to the debonding of the fibres (DF).

Effect of SCF on Three-Body Abrasive Wear of PLA/ABS Composites

In three-body abrasive wear (3-BAW), the test specimen is fixed in the specimen holder which is as shown in Figure 3. The chlorobutyl elastomer surrounding the steel disc is rotated against the specimen and abrasive particles are made to pass through between the specimen surface and the rotating disc. The abrasive particles at the interface acts as free third body and engage in abrasion wear of specimen by sliding and rolling. The normal load at the fulcrum engages the specimen with the rotating disc and abrasives. Thermoplastic polymer matrix composites are frequently reinforced with short fibres, like glass, carbon, or basalt, to improve their mechanical properties [25, 26]. These fibres have the ability to increase wear resistance, decrease friction coefficient, increase hardness, and reinforce the polymer matrix material [27-30]. Nonetheless, in 3-BAW scenario, the short fibres interaction with the thermoplastic matrix is critical. Durability of the composite is preserved by a robust interface, which stops the fibres from pulling out during abrasion.

Since thermoplastics do not require a curing stage and have less hazardous chemical compositions, they are more convenient to recycle and can be produced in large quantities

than conventional thermoset. For these reasons, thermoplastics have drawn a lot of attention as polymer matrices. In addition to recent 3D printing techniques, traditional molding techniques are frequently used to create fibre-reinforced thermoplastic composites [31, 32]. PMCs have extremely intricate wear mechanisms that are influenced by various factors such as contact conditions, mechanical properties of the constituent materials, and the way in which these characteristics affect the formation of transfer films and debris. However, the types of reinforcement and the conditions of contact also matter, and there may be additional wear mechanisms, such as abrasive ones [32].

The SWR for PLA/ABS and their composites at varying loads (10 to 30 N) is displayed in Figures 6a, 6b and 6c as a function of abrading distance. Typical wear scars of PLA, ABS, SCF/PLA and SCF/ABS are displayed in Figure 7. By comparing the width of the wear scars, it is observed that the PLA and SCF/ABS exhibits better and least resistance to abrasion in the study group. Figure 8, shows worn surfaces captured by scanning electron micrographs of polymers and their composites under normal applied load of 20 N.

Important findings from the investigations included the following:

- i) At different loads, the resistance to abrasion among neat PLA and ABS was found to occur in the order $PLA > ABS$. On the other hand, SCF/PLA composites showed better abrasion resistance in PLA/ABS composites reinforced with SCF.

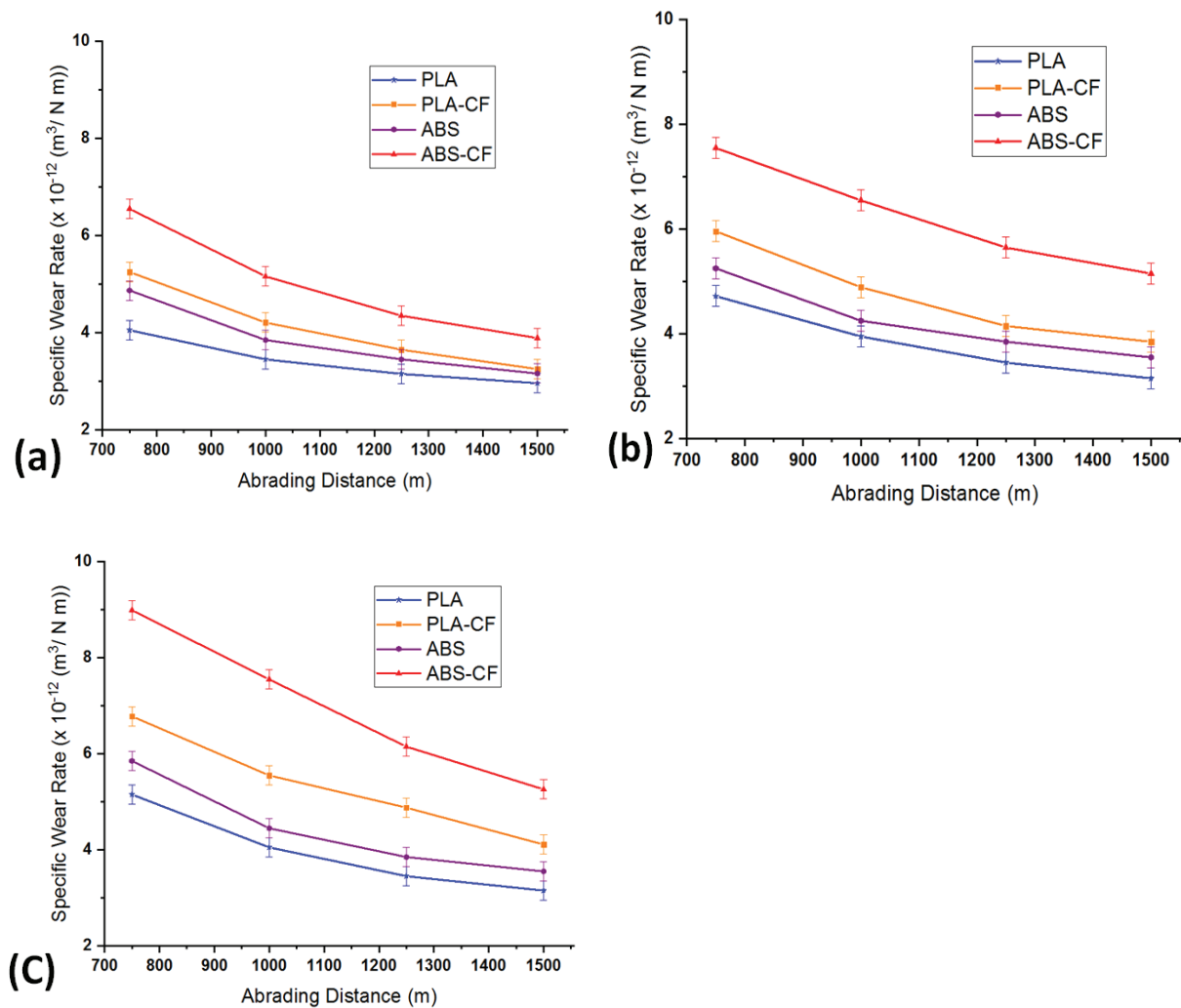


Figure 6. SWR of SCF-reinforced PLA/ABS composites: (a) 10 N, (b) 20 N and (c) 30 N.

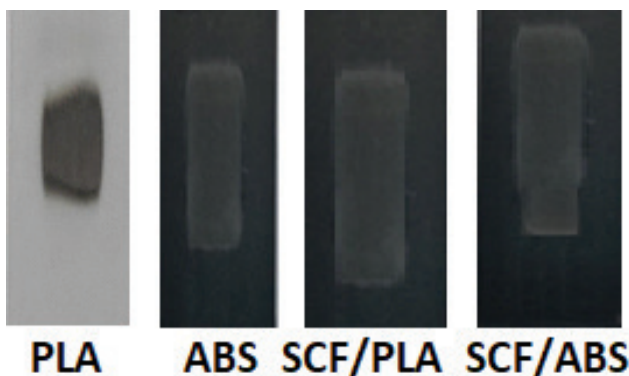


Figure 7. Typical wear scars of SCF-reinforced PLA/ABS composites.

- ii) The materials were found to have specific wear rates (SWR) ranging from $2.96 \times 10^{-12} \text{ m}^3/\text{N m}$ (pristine PLA) to $6.55 \times 10^{-12} \text{ m}^3/\text{N m}$ (SCF/ABS) at low load of 10 N,

$3.15 \times 10^{-12} \text{ m}^3/\text{N m}$ (pristine PLA) to $7.55 \times 10^{-12} \text{ m}^3/\text{N m}$ (SCF/ABS) at 20 N load, and $3.15 \times 10^{-12} \text{ m}^3/\text{N m}$ (pristine PLA) to $8.99 \times 10^{-12} \text{ m}^3/\text{N m}$ (SCF/ABS) at 30 N load (Fig. 6).

- iii) When the surfaces are brand-new, pristine PLA, pristine ABS, and their SCF reinforced composite surfaces show comparatively high initial SWR values, which progressively drop to nearly constant values with the increase in abrading distance (Fig.6).
- iv) SCF/PLA composites exhibited superior abrasion resistance over SCF/ABS composites.
- v) The investigations revealed that the hardness and tensile strength of the polymer and their composites (Table 1) have impacted the SWR. The pristine PLA exhibits better mechanical properties compared to pristine ABS and demonstrated very good abrasion wear resistance. The inclusion of SCF into PLA and ABS have improved the mechanical properties of the composites, however their presence deteriorates the wear performances of

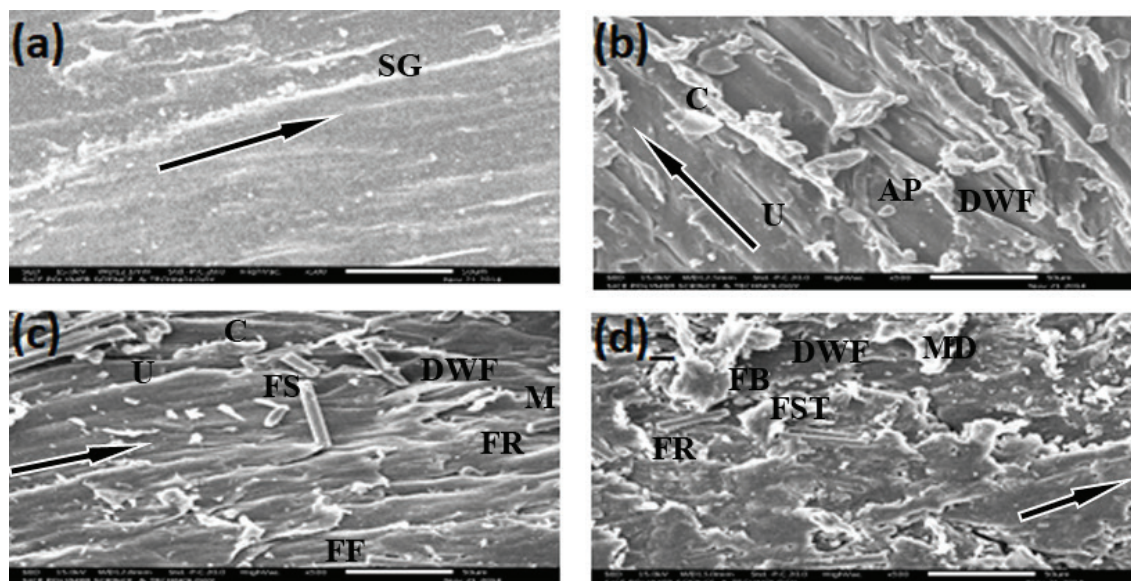


Figure 8. SEM images of wear surfaces of the composites at 20 N: (a) PLA, (b) ABS, (c) SCF/PLA, (d) SCF/ABS under 3-BAW.

the PLA and ABS composites, which is in line with the investigations reported by researchers [19, 24 and 33].

Wear Mechanisms of SCF-Reinforced PLA/ABS Composites Under 3-BAW

To determine the abrasive wear behaviour mechanisms, authors examined the worn surfaces of the pristine PLA, pristine ABS, and SCF reinforced PLA/ABS composites following 3-BAW testing (20 N, 1000 m).

According to Figure 8, the wear mode for PLA is moderate abrasive wear (Fig. 8a), which generates shallow grooves (SG) in the direction of abrasion (arrow) on the surface, whereas pristine ABS has severe abrasive wear (Fig. 8b). Thus, extreme abrasive wear on ABS produced fracture start, which resulted to catastrophic rupture. Deep wear furrows (DWF) created by ploughing (U) and cutting (C) operations operating on the polymer surface may be seen on virgin ABS sample. In addition, a few silica particles (AP) in the worn surface are noticeable.

Figure 8c, depicts the worn surfaces of a SCF/PLA composite sample abraded at 20 N for 1000 m. Few fibres are dragged out in the direction of abrasion (arrow) and split into smaller pieces (FS), as visible on the worn surface. SEM images show fibre debonding (M) from the matrix, while ploughing (U) and cutting (C) with silica abrasive particles causes less damage to the PLA matrix. Under comparable test settings, Figure 8d, depicts the worn surfaces of a SCF/ABS composite sample. Both fibres and the ABS matrix are substantially degraded, with more fibres split (FST) into tiny pieces than in Fig. 8c. More fractures in the ABS worn surface and deep wear furrows (DWF) owing to cutting action appear to be produced by silica abrasives.

CONCLUSION

The specific wear rate results obtained with pristine PLA, ABS and SCF reinforced PLA/ABS composites under 2-BMAW and 3-BAW conditions can be summarized as follows.

- The SWR of PLA/ABS and their composites increased with an increase in load in both wear-modes, but it decreased as the abrading distance increased.
- The pristine PLA matrix demonstrated best abrasion resistance in 2-BMAW and 3-BAW modes.
- Wear under 2-BMAW conditions is 2 to 2.4 of magnitude higher than the 3-BAW of PLA/ABS and SCF reinforced PLA/ABS composites. It upsurges as the load increases and gets reduced with increase in abrading distance. Furthermore, the addition of carbon fibre reinforcement did not increase PLA/ABS's abrasion resistance.
- By using SEM various wear mechanisms involved in the abrasive wear of composites under 2-BMAW and 3-BAW was discussed.

ACKNOWLEDGEMENT

This work was supported by The National Institute of Engineering (NIE), Centre for Research and Development (CRD). The authors thanks the Board of Management, Principal, Dean (R & D), NIE. Further, authors thanks Mr. Byresh, technical person in Centre for Composite Materials research, NIE, for his assistance in performing experiments.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

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