2023-01-5127 Published 23 Feb 2024

Enhancing Tribological Effectiveness of Polypropylene with Carbon Fiber Composites via Fused deposition modeling Technology by Varying Infill Speeds

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Citation: Surendra, S., Sireesha, S.C., Siva, P., and Suresh, P., "Enhancing Tribological Effectiveness of Polypropylene with Carbon Fiber Composites via Fused deposition modeling Technology by Varying Infill Speeds," SAE Technical Paper 2023-01-5127, 2024, doi:10.4271/2023-01-5127.

Received: 19 Sep 2023 Revised: 20 Oct 2023 Accepted: 21 Nov 2023

Abstract

Additive manufacturing (AM) is a common way to make things faster in manufacturing era today. A mix of polypropylene (PP) and carbon fiber (CF) blended filament is strong and bonded well. Fused deposition modeling (FDM) is a common way to make things. For this research, made the test samples using a mix of PP and CF filament through FDM printer by varying infill speed of 40 meters per sec 50 meters per sec and 60 meters per sec in sequence. The tested these samples on a tribometer testing machine that slides them against a surface with different forces (from 5 to 20 N) and speeds (from 1 to 4 meters per sec). The findings of the study revealed a consistent linear increase in both wear rate and coefficient of friction across every sample analyzed. Nevertheless, noteworthy variations emerged when evaluating the samples subjected to the 40m/s infill speed test. Specifically, these particular samples exhibited notably lower wear rates and coefficients of friction compared to the remaining test samples in various dry sliding test conditions, encompassing applied load and sliding velocity. This outcome strongly indicates that the utilization of a 40m/s infill speed in the fabrication of PP with CF composites yields enhanced tribological performance. This enhancement can be attributed to the proficient bonding of uniformly distributed particles and the efficient adhesion between successive layers throughout the entire sample structure. Visual scrutiny of scanning electron microscope (SEM) images depicting the worn surfaces further elucidated the underlying wear mechanism. Particularly striking was the observation that samples subjected to the 40m/s infill speed exhibited diminished accumulation of debris and reduced plastic flow in comparison to their counterparts. Findings strongly activist the use of this composite in automotive and aerospace components requiring rotational or oscillatory motion.

Keywords

Polypropylene with Carbon Fiber Composites, FDM, Varying infill speed, Wear and friction.

1. Introduction

Fused Deposition Modeling (FDM) represents a form of AM. The rapid advancement of Three-dimensional printing and Fused deposition modeling has underscored the technology's adaptability and environmentally favorable aspects in polymer composite fabrication [1]. This approach involves crafting 3D objects using polymer materials, which are melted to their requisite temperature and subsequently deposited layer by layer via a nozzle. This process adheres to the instructions from CAD data, resulting in the creation of the desired product [2]. In contemporary practice, cost-effective FDM technology employs polymer filament Mediums like PLA, ABS, PP, TPE, TPU, and PETG for the construction of prototype models [3]. Recent developments have introduced enhanced filament options, including reinforcement materials like glass fiber, carbon fiber, and glass beads. These materials can be combined with polymers to produce robust components using the FDM method [4].

Test samples were 3D-printed via FDM using polylactic acid filaments infused with copper, brass, bronze, tungsten, and carbon fiber. Analysis of wear tracks showed prevalent abrasive wear during dry sliding, while adhesive wear was notable in various conditions. Tungsten emerged as the most wear-resistant filler for both dry and wet sliding contexts [5]. ABS and PLA thermoplastics printed parts are assessed for friction and wear using a multi-tribo tester (TR-25) in contrast to EN 8 steel roller. Tests occur under low loads, fixed roller speed, and set rolling time in dry conditions. Plastic flow in the contact zones boosts friction, possibly elevating temperatures beyond material melting points. Porosity in printed parts notably impacts friction and wear, adding to tribological intricacies [6]. FDM-fabricated parts using 20% CFPLA and ABS specimens are examined. Process parameters include layer thickness, infill pattern, and density. Material tribology assessment, involving Pin-on-disc tests varying normal load and sliding speed, evaluates wear rate and coefficient of friction. Layer thickness directly influences wear, with thicker layers lasting longer. Infill pattern inversely impacts wear rate [7]. FDM-printed ABS and PLA samples underwent testing with three raster angles (0°, 45°, and 90°) and three layer thicknesses (0.127 mm, 0.254 mm, 0.33 mm). Pin-on-disk tribometer experiments under dry sliding, with a consistent 10 N load and 300 rpm, revealed that thicker layers correlate with reduced friction force. A 45° angle demonstrated superior wear resistance. ABS exhibited greater wear resistance compared to PLA [8].

Fused Deposition Modeling was employed to craft short CF-reinforced nylon composites. Diverse surface textures, including convex squares and triangles, were introduced through printing. Fiber reinforcements notably bolstered load-bearing capabilities in the polymeric materials. Additionally, surface textures augmented tribological efficiency of the print sample. Microscopic analysis indicated that these textures effectively curtailed wear by accumulating resilient debris, such as fractured fibers [9]. Regarding tribological properties, the investigation revealed noteworthy findings. Annealing PEEK at 200°C exhibited a minimal wear rate of 1.37 × 10−6 millimeters cubed per Newton meter during parallel testing. Notably, the interplay of annealing and filament orientation was evident, indicating that optimal annealing temperature fosters consistent and cohesive transfer films on the counter steel surfaces, which contributes to enhanced tribological performance [10]. Tribometer testing of polypropylene with carbon fiber composite filament samples revealed a linear rise in wear rate and COF across different infill densities (60%, 80%, 100%). Notably, 100% infill density samples exhibited superior tribological performance in dry sliding conditions, attributed to particle bonding and layer cohesion. Worn surface SEM analysis indicated reduced debris and plastic flow for 100% infill density [11].

Existing literature underscores the significant impact of diverse Fused deposition modeling process parameters on the mechanical and tribological traits of three-dimensional fabricated models. While much attention has been directed toward developing FDM models using various commercial polymer materials, limited research exists on composite filament usage in FDM printing, and filament pre-preparation remains largely unexplored. Moreover, suppliers have provided comprehensive data on the filament's mechanical properties. Therefore, our focus lies in exploring the uncharted territory of tribological properties, which remains relatively unexplored in the scientific domain. This study probes the tribological attributes of Polypropylene-Carbon Fiber Composites through FDM Technology, focusing on the influence of varying infill speeds. Tribological assessments encompass wear measurements and coefficient of friction analysis, conducted under load variations of 5N to 20N and sliding velocities ranging from 1m/s to 4m/s.

2. Materials Used for Printing

In this study, an investigation utilized a filament crafted from a combination of PP and chopped CF, boasting 1.75 mm diameter and a total mass of 750 gram. The selection of polypropylene was underpinned by its dual attributes of robustness and cost-efficiency. These inherent characteristics render it exceptionally suitable for applications necessitating wear-resistant components for spinning. To amplify its efficacy, a 20% concentration of carbon fiber was incorporated into the composition. This infusion of chopped carbon fiber into the polypropylene matrix augments melt viscosity, alters thermal expansion coefficients, and elevates heat tolerance.

The investigation procured a composite filament incorporating PP and CF directly from a reputable supplier recommended by the machinery manufacturer. The composite filament entailed an approximate blending of 20% carbon fiber into the polypropylene matrix. Mechanical testing of the obtained polypropylene-carbon fiber filament revealed a tensile strength of 78 Megapascal, a flexural strength of 68 MPa, and a flexural modulus of 6100 Megapascal. These values then matched against the specifications outlined in the data sheet from the supplier.

For the purpose of Fused Deposition Modeling (FDM) printing, optimal extruder temperatures were advised to fall within the range of 220 to 250 °C. Concurrently, bed temperatures were recommended to be set between 23 and 60 °C.

3. Printing of Test Samples

Within the realm of Fused Deposition Modeling (FDM), the primary phase encompassed the process of modeling. The prototype for testing purposes was fashioned using

FIGURE 1 (a) FDM printer (b) Printed test samples

SolidWorks 2019, adhering to the specifications outlined by ASTM standards. Preparation of the tribological test material adhered adhered to the guidelines outlined in ASTM G99. The resultant design was subsequently converted into .STL format to facilitate segmentation. Snapmaker Luban 4.4.0 software was employed for this segmentation process, as illustrated in Figures 1 (a). Prior to printing, the .STL file and pertinent printing parameters were inputted. The extrusion of the polypropylene carbon fiber filament maintained a constant heat setting of 250 degrees Celsius, while the bed temperature was held at 70 °C. Simultaneously, preheating parameters (extruder heat) and bed temperature stood at 265 degrees Celsius and 85 degrees Celsius, respectively, and remained upheld prior to the commencement of printing.

The filament used possessed a diameter of 1.75 mm, and the extrusion was carried out through a 2-mm brass nozzle. Essential printing variables including layer thickness, infill density, infill pattern, wall thickness, and alignment remained uniform across all test sample prints. Additionally, our proposed methodology centered on the manipulation of infill speed, varying the values to 40 m/s, 50 m/s, and 60 m/s, correspondingly. The parameters of 40, 50, and 60m/s for infill speed were chosen to comprehensively evaluate the FDM printer's performance across varying speeds. This range allows for understanding the printer's capabilities and limitations, aiding in determining the optimal infill speed for efficient yet high-quality printing results. The determination of crucial parameters for this experiment was based on a comprehensive literature review, expert consultations, and preliminary tests to ascertain the most influential variables within the scope of the study. For each specific infill speed, multiple samples were strategically positioned on the FDM printing platform. The conclusive step involved generating G-code, which was then transmitted to the FDM printer, leading to the successful creation of the assortment of composite samples, as depicted in Figure 1(b).

4. Tribological Examination

Tribological assessments were carried out utilizing a pin-on-disc tribometer (M108 model) employing the dry reciprocating method. All trials were conducted under ambient temperature conditions. The specimen was securely held in the fixture to ensure consistent contact with the counter face - a rotating steel disc (EN-32)/ (polypropylene with carbon fiber disc) - possessing a plate hardness of 65 Hardness Rockwell C. The model, along with the steel disc, exhibited average surface roughness (Ra) values of 0.8 micrometers and 1.6 micrometers, respectively.

Variations in the tribology testing were introduced by manipulating the controlled parameters. These adjustments encompassed altering the applied force (5 N, 10 N, 15 N, and 20 N) and maintaining a consistent swinging distance, while the disc's rotational speeds were set at either 1 m/s, 2m/s, 3 m/s and 4m/s. The choice to limit the applied load to 20N and the sliding velocity to 4m/s during tribometer testing was made to ensure a controlled and standardized testing environment that aligns with the typical operating conditions encountered in practical industrial applications. This approach facilitated a comprehensive evaluation of the material's performance under realistic stress conditions while preventing excessive wear or damage to the test specimens.

In pursuit of comprehensive results, each sample underwent a four set of measurements to calculate wear and friction values, and the resulting ranges were documented for subsequent computations. To assess wear rate and COF, an electronic balance of Type ATY224 with an accuracy of 0.0001 g was employed. This facilitated the measurement of starting and concluding weights for each test specimen. These values were then utilized to compute the wear rate by dividing the mass reduction of the specimens by the distance traversed during sliding. Furthermore, the coefficient of friction was deduced by dividing the frictional force, as indicated by the tribometer equipment's display, by the applied load.

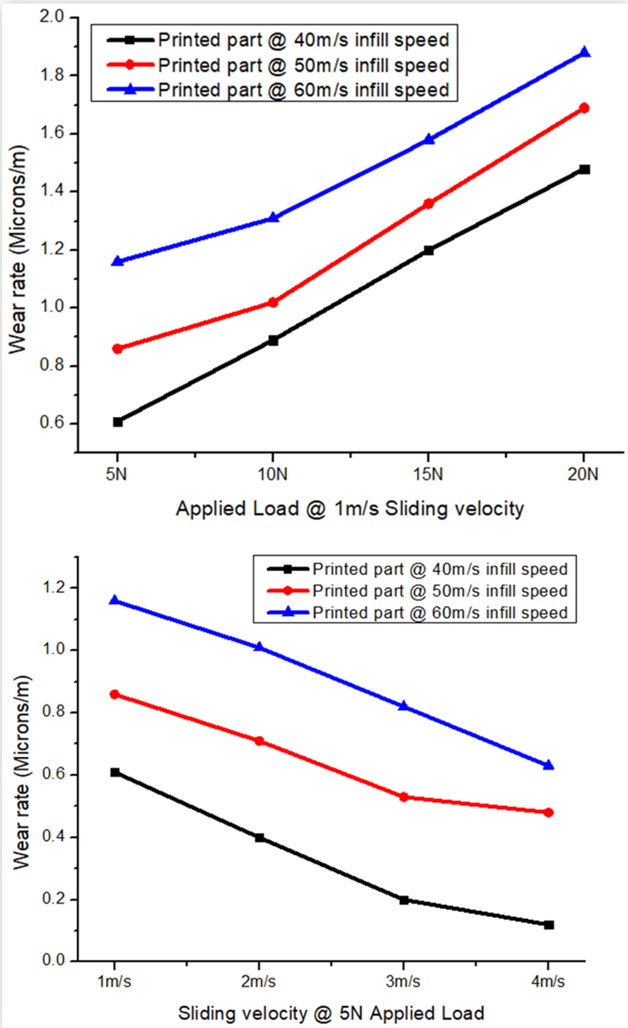
In this research well calibrated FDM machine, tribometer, and weight machine was used and maintaining accuracy in the experimental data. The FDM machine calibration error was within ±0.02mm, the tribometer's error was ±1.5%, and the weight machine error was ±0.1 grams. Obtained values are taken for further wear and friction analysis.

5. Result and Discussion

5.1. Analysis of Wear Rate

This study explores the wear behavior of Polypropylene with Carbon Fiber Composites parts created using fused deposition modeling (FDM), focusing on applied load and sliding velocity variation. The figures 2(a) illustrate wear rate variation under different loads (5N-20N) with a sliding velocity of 1m/s. The figures 2(b) illustrate wear rate variation under sliding velocity variations (1m/s-4m/s) with an applied load of 5N. While Polypropylene with Carbon Fiber Composites parts are printed with a 60m/s and 50m/s infill speed showed increased wear rate with lower load to higher load variants at the 1m/s sliding velocities condition, those with 40m/s infill speeds exhibited decreased wear rate compared to the 60m/s and 50m/s samples.

FIGURE 2 (a) Wear rate with respect to load (b) Wear rate with respect to sliding velocity



As sliding velocity increased, wear rates decreased significantly for parts printed with 60m/s, 50m/s, and 40m/s infill speeds condition respectively. Notably, parts printed at 40m/s infill speed consistently had lower wear rates than those printed at 50m/s and 60m/s infill speed samples. An increase in the proportion of 40m/s infill speed parts corresponded to reduced wear rate under varying load conditions. This suggests that higher 40m/s infill speed led to decreased wear rate compared to 50m/s and 60m/s infill speed samples under similar conditions.

The uniform distribution of shear stress, facilitated by the higher strength part having Polypropylene with Carbon Fiber Composites due to the lower 40m/s print speed sample, contributed to wear reduction, along with the enhanced Polypropylene matrix and carbon fiber bonding. Additionally, specimen printed with 40m/s infill speed high-strength parts increased Polypropylene with Carbon Fiber Composites FDM printed part shear strength, generating tiny particles during wear. These particles bonded with Polypropylene and carbon fiber, forming a protective transfer film that reduced wear rate.

The improved strength of 40m/s infill speed parts enhanced load-bearing capability, minimizing surface cracks and wear rate. These parts also exhibited more homogenous and stable transfer films between the part and counter surface, further reducing wear. Notably, FDM parts at 40m/s infill speed displayed the lowest wear rate compared to 50m/s and 60m/s infill speed parts.

Elevated sliding velocities increased surface temperature, leading to part softening and surface deterioration. Wear rate varied with load, increasing for all materials studied. Nonetheless, 40m/s infill speed parts consistently demonstrated significantly lower wear loss compared to 50m/s and 60m/s infill speed parts. For instance, at 60m/s infill speed, wear loss ranged from 110 to 510 micrometers per meter for loads of 5N to 20N, while 50m/s infill speed parts showed wear loss of 82 to 380 micrometers per meter for the same loads. Also, while 40m/s infill speed parts showed wear loss of 58 to 210 micrometers per meter for the same loads.

Analyzing wear rates against sliding velocities revealed that parts with 60m/s infill speed experienced decreasing wear rates as sliding velocity increased. At the outset, for 1 meter per second of sliding velocity the wear rate value of parts with 60m/s infill speed sample is found to be 1.16 micrometers per meter, whereas for sliding velocity of 4 m/s the wear rate of 0.63 micrometers per meter was recorded. For 50m/s infill speed parts, wear rates were 0.86 micrometers per meter and 0.48 micrometers per meter at sliding velocities of 4 m/s and 1 m/s, respectively. Also, for 40m/s infill speed parts, wear rates were 0.61 micrometers per meter and 0.12 micrometers per meter at sliding velocities of 4 m/s and 1 m/s, respectively. These findings demonstrated significantly lower wear rates for 40m/s infill speed FDM parts compared to 50m/s and 60m/s infill speed parts, both at lower and higher loads. Furthermore, the enhanced strength of 40m/s infill speed parts led to a reduction in wear rate.

All the printed samples primarily due to better load-bearing properties due to Polypropylene with Carbon Fiber Composites parts created using fused deposition modeling and a reduction in the formation of surface cracks, thereby contributing to reduced wear rate, particularly at higher loads 20N and sliding velocities 4m/s. The wear process involved abrasion and adhesion mechanisms, both of which were affected by friction and wear. Increased load 20N (@4m/s) led to mild plastic flow for parts printed with 40m/s infill speed, more plastic flow for parts printed with 50m/s infill speed and more plastic flow and surface crack initiation for parts printed with 60m/s infill speed specimens, resulting in higher material removal, it was evident from figure 3 (b-d). Lower load and sliding velocity condition wear rate contributes mild plastic flow initiation it was evident from figure 3 (a). However, the presence of high-strength Polypropylene with Carbon Fiber Composites, as seen in the parts printed at 40m/s infill speed, contributed to enhanced load-bearing capacity and a reduction in wear loss, aligning with previous research findings [12, 13, 14, 15, 16].

FIGURE 3 (a) Printed part at 40m/s infill speed (low load of 5N and low sliding velocity of 1m/s) (b) Printed part at 40m/s infill speed (c) Printed part at 50m/s infill speed (c) Printed part at 60m/s infill speed (High load of 20N and higher sliding velocity of 4m/s)

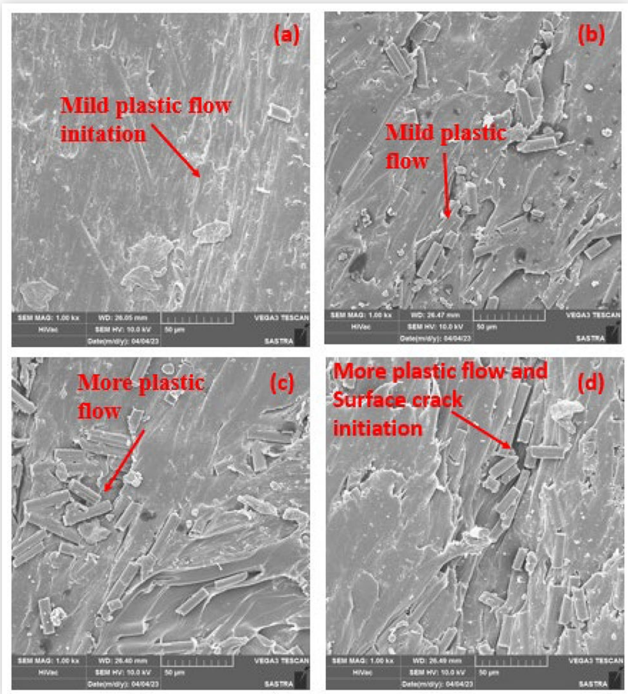
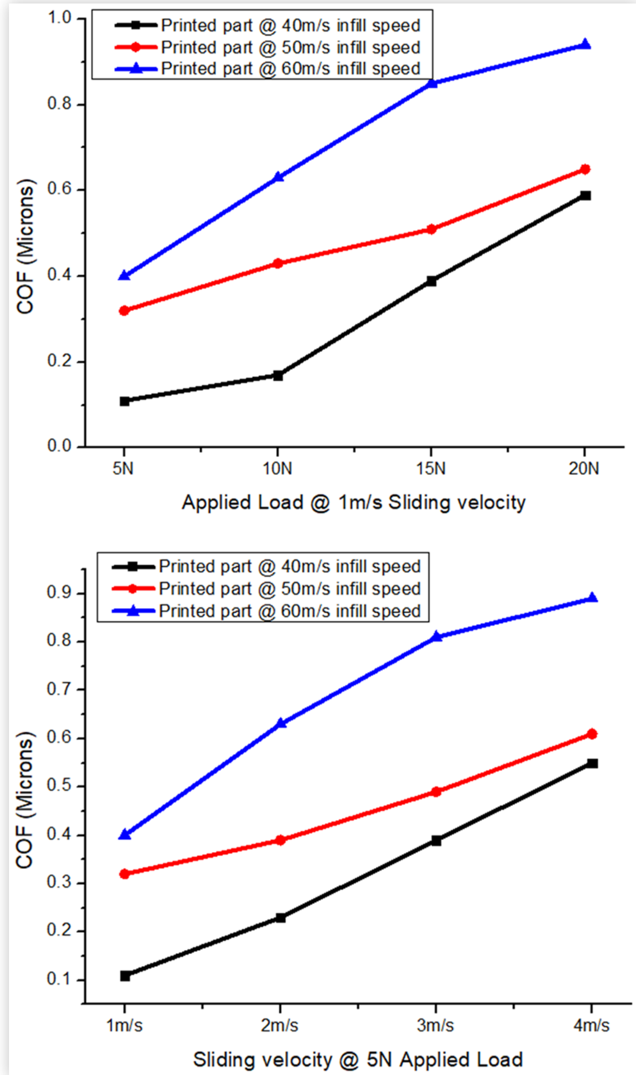


FIGURE 4 (a) Wear rate with respect to load (b) Wear rate with respect to sliding velocity



5.2. Friction Coefficient Analysis

Figures 4(a) and (b) illustrate the variations in the COF concerning load and sliding velocities. Notably, it is evident that the COF escalates alongside increasing loads and sliding velocities for Fused Deposition Modeling (FDM) printed Polypropylene with Carbon Fiber Composites, employing infill speeds of 60m/s, 50m/s, and 40m/s. Nevertheless, amidst all the examined load and sliding velocity conditions, the samples produced using a 40m/s infill speed exhibit significantly reduced coefficients of friction compared to their counterparts produced at 60m/s and 50m/s infill speeds.

When considering a constant sliding velocity of 1m/s, the samples printed at 60m/s infill speed display average COF values of 0.64, 0.73, 0.85, and 0.94 for load values of 5N, 10N, 15N, and 20N, respectively. In comparison, samples printed at 50m/s infill speed present average COF values of 0.32, 0.45, 0.51, and 0.65 for the corresponding load values. Remarkably, specimens printed at 40m/s infill speed showcase notably lower COF values of 0.11, 0.17, 0.39, and 0.59 for load values of 5N, 10N, 15N, and 20N, respectively.

Similarly, for a consistent load of 5N, samples produced at 60m/s infill speed exhibit average COF values of 0.4, 0.78, 0.81, and 0.89 when subjected to sliding velocities of 1m/s, 2m/s, 3m/s, and 4m/s, respectively. In comparison, samples fabricated at 50m/s infill speed demonstrate frictional coefficients of 0.32, 0.39, 0.49, and 0.61 under the corresponding sliding velocities. Notably, specimens created at 40m/s infill speed display frictional coefficients of 0.11, 0.23, 0.39, and 0.55 for sliding velocities of 1m/s, 2m/s, 3m/s, and 4m/s, respectively.

The escalation in the coefficient of friction resulting from an increase in sliding velocity can be attributed to heightened engagement among the particles in the transferred layer and those within the test specimen. This intensified rubbing action between the particles contributes to the observed increase in the COF as sliding velocity rises. Conversely, the correlation between a higher coefficient of friction and an increased load might stem from alterations in the wear mechanism. With an augmented load, the transfer film at the interface demonstrates stick-slip behavior, resulting in elevated frictional values.

Remarkably, throughout all the examined test conditions, components produced using the 40m/s infill speed sample consistently exhibit the lowest coefficients of friction. This can be attributed to the improved thermal conductivity and stiffness inherent in FDM parts printed at this speed. The heightened thermal conductivity of components manufactured using the 40m/s infill speed enhances the rate of heat dissipation at the interface, thereby contributing to a decrease in the COF [12, 13, 14, 15, 16].

6. Conclusion

In this study, the focus was on examining the printed aspect of Polypropylene combined with Carbon Fiber Composites, utilizing Fused Deposition Modeling (FDM) Technology. This examination involved varying the infill speeds at rates of 40m/s, 50m/s, and 60m/s. To assess the performance, tribometer tests were conducted, aimed at determining the wear rate and COF under diverse conditions, encompassing various loads (ranging from 5 N to 20 N) and disc velocities (ranging from 1 meter per second to 4 meter per second). Furthermore, the samples subjected to extreme parametric conditions were analyzed through scanning electron microscopy (SEM) of worn surfaces, allowing for an in-depth exploration of the damage mechanisms. The study delved into the wear rate and COF behaviors of printed samples with infill speeds of 60m/s, 50m/s, and 40m/s. Notably, the results highlighted that the FDM printed parts with a composite utilizing 40m/s infill speed exhibited reduced wear loss and a COF when compared to those printed with a 60m/s infill speed. Interestingly, it was observed that the COF and wear loss decreased as the CF content within the polymer increased, along with a lower level of infill speed. The wear rate exhibited an upward trend with increasing load, whereas it decreased as the sliding velocity increased. Additionally, the COF decreased with higher loads and sliding velocities. Throughout all the loads and sliding velocities examined, the printed parts with a 40m/s infill speed demonstrated superior wear and friction performance. This performance was accompanied by minimal plastic deformation and an absence of crack initiation, as confirmed by SEM analysis.

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This paper is based upon a presentation at the *International Conference on Trends in Automotive Parts Systems and Applications*.

ISSN 0148-7191