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OPTIMIZING THE TRIBOLOGICAL PROPERTIES OF 3D-PRINTED PETG/PTFE COMPOSITES

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ABSTRACT

This paper examines the optimization of FDM processing parameters for enhancing the tribological performance of polyethylene terephthalate glycol and polytetrafluoroethylene (PETG/PTFE) 3D printing composites. PETG is a popular fused deposition modeling (FDM) material, and PTFE is a self-lubricating fluoropolymer. In this experiment, a composite of 90% PETG and 10% PTFE was used to achieve desirable tribological performance combined with FDM processability. Two understudied FDM parameters of wall count and raster width were assessed as to how they would affect the coefficient of friction (COF) of the printed objects. Tribological testing was conducted using a ball-on-disk tribometer, and tensile testing was carried out for determining mechanical properties. The results indicated that raster width affected the COF negligibly, while wall count made a significant impact. Specifically, fewer walls led to a decreased COF. Tensile testing indicated that the PETG/PTFE composite had lower tensile strength compared to pure PETG yet had a higher elastic modulus. These observations indicate that PETG/PTFE is a promising FDM material for use in tribological applications such as prosthetics. This paper extends previous literature in this subject by further optimizing processing parameters and establishing the potential for tribologically-enhanced materials in FDM application.

Keywords: FDM, PETG/PTFE, tribology, coefficient of friction, 3D printing optimization.

NOMENCLATURE

μ	Coefficient of friction (COF)
F_f	Friction Force
F_N	Normal Force
σ	Stress
F	Force
A	Cross-sectional area
L_0	Original length
ε	Strain
ΔL	Change in length
A_r	Real area of contact
τ	Interfacial shear strength

1. INTRODUCTION

Fused deposition modeling (FDM) is a subset of 3D printing, an additive manufacturing method. Recently, FDM has been a growing topic both in academia and industry; it is becoming a much more viable manufacturing method that is comparable, or even outperforming traditional methods, such as injection molding or machining. The growing popularity of FDM can be attributed to its adaptability due to offering precise control over various processing parameters and materials. This flexibility allows for fine-tuning of the final product to meet specific application requirements. However, this adaptability also presents a challenge: understanding the impact of these parameters on the final part's properties is essential for optimizing FDM for particular use cases. The ability to precisely adjust FDM parameters to enhance the properties of the printed material, along with the growing selection of advanced filaments, allows FDM to compete with and even outperform existing technologies in specific applications. Consequently, in-depth exploration of how process parameters influence the mechanical and tribological performance of materials printed via FDM, and how novel materials behave during and after processing is critical to fully harness its potential. To achieve this, this study aims to focus on optimizing FDM parameters, specifically shell count and raster width, to minimize the COF of PETG/PTFE composites.

1.1 Optimizing Mechanical Properties in FDM

In 2000, 11 years after the invention of FDM, Es-Said, et al. published a paper “Effect of Layer Orientation on Mechanical Properties of Rapid Prototyped Samples”. This paper suggested an optimal layer orientation for the highest tensile strength in Acrylonitrile butadiene styrene (ABS) parts. In doing this, Es-Said, et al., were first to investigate the effect that printing parameters have on the mechanical properties of FDM printed parts [1]. As this field developed through the 2010’s, there was significant work done by multiple groups on optimizing mechanical properties of FDM parts out of materials like Polylactic acid (PLA) and ABS [2-11]. With a correlation between almost every process parameter and the mechanical properties of the FDM part proposed, the field was approaching a solved state with little room to further optimize the mechanical properties of FDM parts. This was until the expiration of the patent on core FDM technology held by Stratasys, Ltd. [12]. This allowed for rapid innovation in FDM technology, importantly new printers that could reach higher temperatures, enabling the use of new materials. At the forefront of this revolution was polyether ether ketone (PEEK), a high-performance polymer invented in 1978 and widely used in the aerospace industry. Now that PEEK could be used for FDM manufacturing, it significantly increased the applications of FDM, especially in high stress applications. In doing this, it also reopened the question of how to optimize these properties via processing parameters, and the field saw the first paper, identifying the optimal printing temperatures for tensile strength in FDM printed PEEK in 2015 [13]. There is still work being done to fully optimize these parameters and understand the mechanisms behind these correlations, as well as work being done to develop new, mechanically advanced materials, and apply them to FDM.

1.2 Optimizing Tribological Properties in FDM

The aforementioned trend is important to recognize as it manifests itself in other fields as well. In some applications mechanical strength is not the only criteria; One great example of this is in prosthetics. Prosthetics is a field that has been revolutionized with additive manufacturing technology, and an important criterion for performance is the tribological properties of the appliance. This has led to work being done in the field of optimizing the tribological properties of FDM printed parts, however, similar to with mechanical properties, the field is approaching the state of diminishing returns and is ripe for an external innovation to continue to push forward. The timeline of this field is very similar to that of its mechanical properties’ counterpart. The first study to look at tribological properties, in this case *wear*, in relation to FDM process parameters was published in 2012 [14]. This paper investigated orientation, layer thickness, raster angle, part raster width, and raster to raster gap in ABS samples. Similar to the trend seen in optimizing for mechanical properties seen a few years earlier, numerous studies were published following this paper investigating numerous printing parameters with different standard FDM materials, such as PLA, ABS, Polycarbonate (PC), and Nylon [15-25]. The introduction of new tribologically advanced materials - in this study PETG/PTFE composites - offers an opportunity to continue to innovate in this field.

1.3 Tribological Behavior of PETG and PTFE

PETG and PTFE are polymers with distinct properties that influence their tribological performance. PETG is a thermoplastic polyester known for its durability, chemical resistance, and ease of processing, making it a popular choice for FDM. However, its tribological properties, such as wear resistance and COF, are moderate, which limits its suitability for tribological applications. In contrast, PTFE, commonly known as Teflon®, is a fluoropolymer celebrated for its exceptional chemical resistance, thermal stability, and low COF, ranging between 0.02 and 0.20 [26]. These characteristics make PTFE ideal for applications requiring minimal friction, such as bearings and seals. However, PTFE's high melting point and non-melt-processable nature pose challenges for traditional FDM 3D printing techniques. Integrating PTFE's desirable tribological properties with PETG's printability presents an opportunity to develop composites suitable for FDM 3D printing. By incorporating PTFE into PETG, it stands to reason that the resulting filament exhibits enhanced wear resistance and reduced friction (compared to pure PETG). It would also be logical that the resulting composite would demonstrate reduced mechanical properties due to the inferiority of PTFE in that respect. While specific studies on PETG/PTFE composites in FDM 3D printing are not available, research on other PTFE/thermoplastic composites could offer valuable insight. For instance, Polyoxymethylene (POM) reinforced with PTFE fibers has demonstrated excellent wear resistance and low friction, indicating that incorporating PTFE into thermoplastic matrices can significantly enhance tribological performance [27].

1.4 Process Parameters and Tribological Performance

Wall count, referring to the number of perimeter layers in an FDM-printed part, directly impacts the strength of the part and the surface profile. Studies have shown that increasing shell count improves mechanical strength, which can indirectly enhance tribological performance by reducing material deformation under load. For instance, research indicates that samples with a higher number of shells exhibit increased tensile and bending strength and a higher elastic modulus [28]. This suggests that a higher wall count could lead to a lower COF, as contact area is inversely proportional to elastic modulus in a purely elastic, simplified contact [29] and friction force is correlated to contact area (See equations 1, 2).

$$A_r \propto (\frac{F_n}{E})^k \quad (1)$$
$$F_f = \tau A_r \quad (2)$$

However, beyond a certain wall thickness, the impact on local tribological properties may become negligible or even detrimental [30], indicating an optimal shell count for balancing mechanical strength and material usage. It is also logical that more walls will change the top surface profile, which could affect the roughness and contact area, thus affecting the tribological properties.

Raster width, the width of each extruded line of plastic, influences the density and bonding of the printed material. Raster width can be altered independent of layer height, which effectively controls the cross-sectional profile of the extruded lines. It has been established that a greater raster width generally improves interfacial strength and reduces porosity, leading to a stronger structure to some extent [2-4, 8, 31]. As with wall count, these improvements in strength can subsequently improve tribological properties. Tribologically, there has been significantly less work done investigating raster width. Some have suggested it does have an effect on wear [14, 16], however there has yet to be a rigorous explanation for why this is observed.

1.5 Research Gap & Purpose

There have yet to be any studies that examine these process parameters - tribological property correlations in any tribologically advanced materials. This study proposes a PETG/PTFE composite as a material suitable for FDM that also has desirable tribological properties. Not only has this specific material not been studied as a FDM material, but no fluoropolymer has been formally investigated through the lens of FDM. This gives the potential for innovation, as fluoropolymers generally provide very low friction due to their self-lubricating properties. Additionally, raster width and shell count (see Figure 1) are both under-researched parameters in the field for any material, with raster width in particular still not being well understood. Between these, this study has two primary purposes. The first is to build upon other work in the field and continue to optimize all possible process parameters for tribological applications. And the second purpose, which is to make a bigger step towards increasing the tribological applications of FDM by demonstrating tribologically advanced materials in the context of FDM. This research has the potential to open the door for a new round of parameter optimization and continued innovation in creating and adapting materials for FDM in order to broaden its applications.

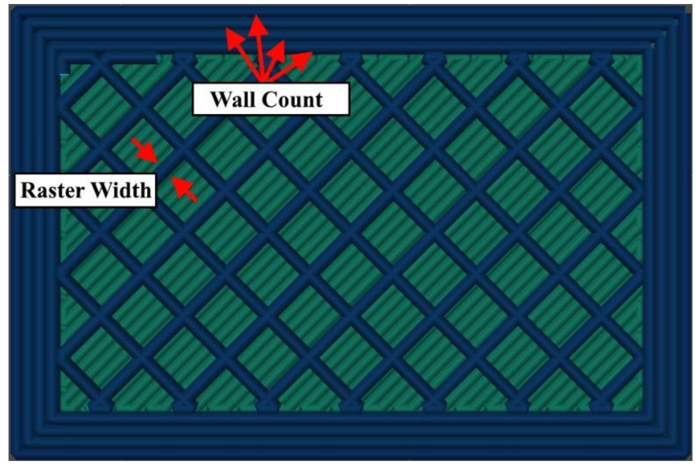

FIGURE 1: VISUAL REPRESENTATION OF PROCESS PARAMETERS.

2. MATERIALS AND METHODS

This study investigated the optimization of FDM parameters to minimize the COF in PETG/PTFE composites. This quantitative, experimental study focused on analyzing the impact of shell count and raster width on the tribological properties of FDM-printed PETG/PTFE parts.

The quantitative approach was justified because it allows for objective, numerical analysis of tribological performance and surface characteristics, providing measurable insights into the effects of FDM parameter variations. Furthermore, the experimental nature of the study was the best for systematically testing the hypotheses regarding the influence of shell count and raster width on COF.

The Bambu Lab X1 Carbon 3D printer with a 0.4 mm diameter nozzle was used to print all PETG/PTFE samples. The PETG/PTFE material was purchased as a spool of filament from commercial filament vendor, Spectrum Group Sp. z o.o. [32]. The software Bambu Studio was used to print the samples. The filament was preset to 0.20 mm Standard @BBL X1C, and all samples were printed on the textured PEI plate. All PETG/PTFE samples were printed with an infill percentage of 70%. To give a smoother surface finish, the flow rate was calibrated using the auto-calibration feature in the Bambu Studio software. This yielded a flow rate calibrated value of 0.957. To ensure all samples were printed at this flow rate, the flow dynamics calibration feature was turned off so that the printer did not auto calibrate the flow rate with each print. All PETG/PTFE samples, ball and disk, were printed at the flow rate value of 95.7%. In FDM 3D printing, flow rate, also known as extrusion multiplier, dictates the amount of filament extruded by the printer's nozzle. The nozzle temperature was kept around 230°C – 255°C, the bed temperature was kept around 60°C-80°C and the print speed was kept around 30-70 mm/s, as recommended by the manufacturer from which the PETG/PTFE filament was bought [32].

It should be noted that Bambu Lab's preset only allows for one wall on top surfaces. Thus, to ensure that wall counts above one can be printed on the top surface, this condition was changed in the Bambu Studio software. To do so in the, in the 'Global' settings, under ‘Quality’ and under ‘Advanced’, the ‘Only one wall on top surfaces’ was changed from ‘Top surfaces’ to ‘Not applied’. It should be noted that for all samples the print sequence was changed to ‘by object’ instead of ‘by layer’. This is due to over extrusion issues being found when the samples were printed ‘by layer’.

To produce the samples, the ball and disk were modeled in SOLIDWORKS, a 3D CAD software according to the dimensions of existing PCS Instruments Mini Traction Machine (MTM)™ ball and disk samples (see Figure 2). These models were then imported into Bambu Studio, a slicer software, where printing parameters were set for each permutation and then sent to the 3D printer.

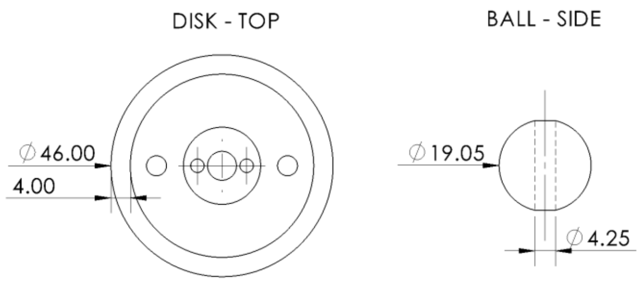

FIGURE 2: MTM SAMPLE DIAGRAM WITH TRACK DIMENSIONS. ALL DIMENSIONS IN mm.

The primary research method involved experimental testing using a ball-on-disk tribometer, PCS MTM as shown in Figure 3, to measure tribological performance, specifically COF, of the FDM-printed samples. Both the ball and the disk specimens were printed out of the PETG/PTFE material with varying shell counts and raster widths to assess how these parameters influenced their tribological properties. The ball-on-disk tribometer was chosen because it provides precise control over testing variables and accurately simulates real-world frictional conditions [20]. Quantitative tribological data was collected to provide insight into the effects of process parameter variations.

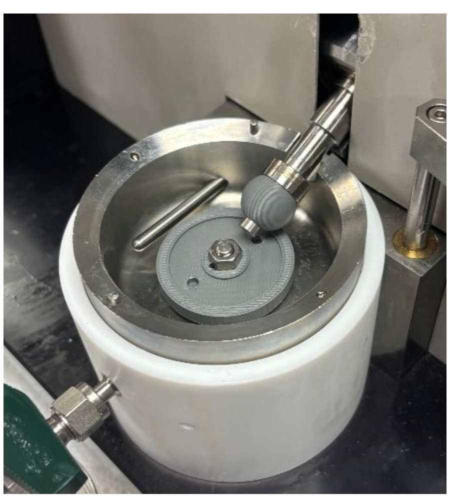

FIGURE 3: PCS MTM BALL ON DISK TRIBOMETER WITH PETG/PTFE SPECIMENS AFFIXED

The MTM measures the friction force (F_f) between the two specimens while controlling other factors. COF is then determined by using equation (3) where μ is COF and F_N is normal force.

$$\mu = \frac{F_f}{F_N} \tag{3}$$

The MTM testing parameters were set at mild values (see Table 1) so as not to cause excessive wear as PTFE/PETG is relatively soft. A pure sliding condition - meaning that the ball was held stationary while the disk was spinning - was chosen to increase comparability with the pure sliding contact of pin on disk tribometers more commonly seen in the literature.

Parameter	**Value**
Duration (s)	600, 3600
Speed (m/s)	.1
Normal load (N)	7
Testing mode	Pure sliding (no rolling)

TABLE 1: MTM TESTING PARAMETERS

Each set (ball, disk) of samples was then affixed in the MTM. For the first set of trials, the tests were run for 5 minutes. For the second set of tribometer trials, one sample from each wall count was run with the same conditions for 1 hour. The test results were then saved and analyzed.

Additionally, tensile tests were performed with both the PETG/PTFE material and plain PETG in order to characterize the mechanical properties of each material. Samples for tensile tests were prepared based on the ASTM D638 standards. It should be noted that ASTM D638 is a standard for sheet, plate or molded specimens; there is no standard for the tensile testing of FDM specimens at the time of publication, so ASTM D638 was used as the closest reference. Figure 4 shows the dimensions of the tensile samples used. The dogbone tensile samples were printed with 2 walls, 0.42 mm raster width, and 100% infill. These parameters were chosen to best characterize the tensile properties of the material, independent of the variables altered in the tribological side of this study.

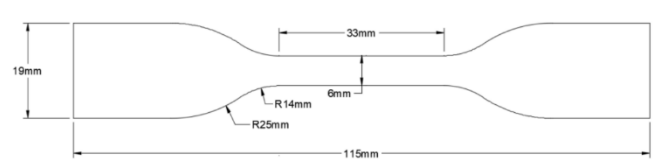

FIGURE 4: ASTM D638 TENSILE SAMPLE DIMENSIONS

Tests were performed according to ASTM D638 and tested on a Tinius Olsen ST150 Universal Testing Machine (see Figure 5).

FIGURE 5: TINIUS OLSEN TESTING APPARATUS USED FOR ASTM D638 TESTING.

The Tinius Olsen collected the force applied (F) and the change in position of the head, which can be used to find the change in the length of the sample (ΔL). By knowing the initial cross-sectional area (A) and length (L_o), the stress (σ) and strain (ε) at each data point can be determined using Equations (4) and (5), respectively.

$$\sigma = \frac{F}{A} \tag{4}$$

$$\varepsilon = \frac{\Delta L}{L_o} \tag{5}$$

By graphing the stress versus strain, the slope of the linear elastic region is Young's modulus or modulus of electricity, and the maximum stress is the Ultimate Tensile Strength. Four dogbone tensile samples each of the PETG/PTFE and PETG material were printed and tensile tested, with the average stress and average strain data across the four samples plotted in figure 6.

The experimental design was structured to ensure consistency and reliability, with controlled sample production and calibrated FDM printing conditions. Samples underwent identical environmental conditions during testing to eliminate external variability. Data from the ball-on-disk tribometer was analyzed to draw conclusions about the impact of FDM parameters. This systematic approach provided insights into optimizing FDM processes for advanced tribological applications.

2.1 Design of experiment

In order to optimize the parameters investigated in this study, a traditional design of experiment matrix was used (see Table 2).

Trial	Wall Count	Raster Width (mm)
1	1	.4
2	1	.5
3	1	.6
4	4	.4
5	4	.5
6	4	.6

TABLE 2: DESIGN OF EXPERIMENT MATRIX

Raster widths of .4 mm, .5 mm, and .6 mm were chosen based on a 2012 paper by Masood, et al [2]. Wall counts of 1 and 4 were chosen as the minimum and maximum values that would fit on the track of the designed disk. 3 replicates were manufactured for each permutation.

2.2 Sample Selection

PETG, a thermoplastic polyester, is a commonly used material for FDM because of its excellent balance between strength, flexibility, and durability [33]. PTFE is a fluoropolymer, a subset of plastics that are characterized by their chain of C-F bonds. This unique atomic structure allows fluoropolymers, such as PTFE, to have multiple desirable properties, such as chemical resistance, electrical insulation, and self-lubrication. PTFE is an excellent material for low friction applications, however, it is unable to be manufactured using FDM because of its thermal properties, which cause it to degrade before it reaches its melting point. The composite used in this study is made up of 90% PETG and 10% PTFE. This allows the material to be easily manufactured with FDM, while providing desirable tribological properties from the PTFE as well as strength from the PETG.

2.3 Validity

In terms of validity, this experimental setup ensured both internal and external validity. Internal validity was ensured by both manufacturing and testing the samples in a controlled laboratory environment. External validity was considered by choosing to have both the ball and disk samples manufactured out of the material being investigated. This is important as the vast majority of FDM applications involve polymer-on-polymer contact, whereas some studies investigated polymer-on-steel contact.

The MTM provided content validity in regard to tribological data. Ball on disk tribometers are prevalent in the field of tribology and have been used to test FDM specimens [20]. Additionally, for this study, the ball was set to be stationary to increase compatibility to the more common pin-on-disk tribometers. Each set of parameters had 3 sets of corresponding samples to ensure validity and repeatability.

3. RESULTS

Recall that the purpose of this study was to determine the optimal parameters for FDM 3d printing in the context of tribological applications. To do this, the question posed was: To what extent does raster width and wall count have on the COF of PETG/PTFE parts manufactured by FDM?

3.1 Tensile characterization

For the PETG/PTFE tensile samples, the average ultimate tensile strength of all four samples was 46.5 MPa. The average young's modulus of the PETG/PTFE samples was 474 MPa. For the plain PETG tensile samples, the average ultimate tensile strength of the four samples was 57.7 MPa. The average young's modulus of all four samples of the PETG/PTFE filament of the material is 361 MPa. These values were captured from the stress/strain graph resulting from the tests by calculating the slope of the first linear portion of the graph, typically appearing below 0.2% strain (see Figure 6). It can be seen that the addition of PTFE to the filament resulted in less tensile strength, but higher stiffness.

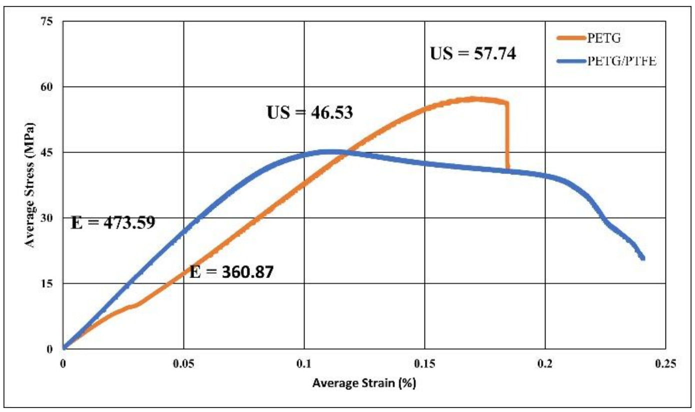

FIGURE 6: AVERAGE STRESS OVER STRAIN CURVE FROM 4 TENSILE TESTS FOR EACH MATERIAL. Y AXIS REPRESENTS THE AVERAGE STRESS IN MPA, AND THE X AXIS REPRESENTS AVERAGE STRAIN IN % CHANGE. LABELED IS ULTIMATE TENSILE STRENGTH (US, MPa) AND ELASTIC MODULUS (E, MPa).

3.2 Tribological testing

For the short term tribometer tests, friction stayed relatively constant over the 5 minute test (see Figure 7). To calculate the average COF of each test, this study used a trimmed mean of the middle two quartiles to remove any noise from the beginning of the test or any other artifacts. There was an issue with the first test of the 1 wall, 0.4mm raster width samples, so the data was omitted as an outlier in all average calculations.

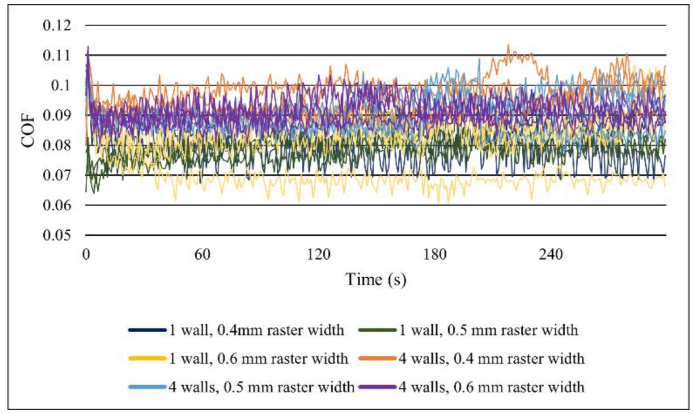

FIGURE 7: COF OVER TIME OF SHORT TERM PETG/PTFE TRIBOMETER TESTS

Compared to plain PETG, PETG/PTFE exhibited lower friction over both 1 and 4 walls (see Figure 8). Over all samples, plain PETG had an average COF of 0.102 and PETG/PTFE had an average COF of 0.085 (17.7% difference). Unexpectedly however, both materials exhibited closer to similar COF with 4 walls contrary to the hypothesized difference being independent of process parameters. Raster Width was not altered for these tests as it was already shown to be inconsequential (see Figure 9).

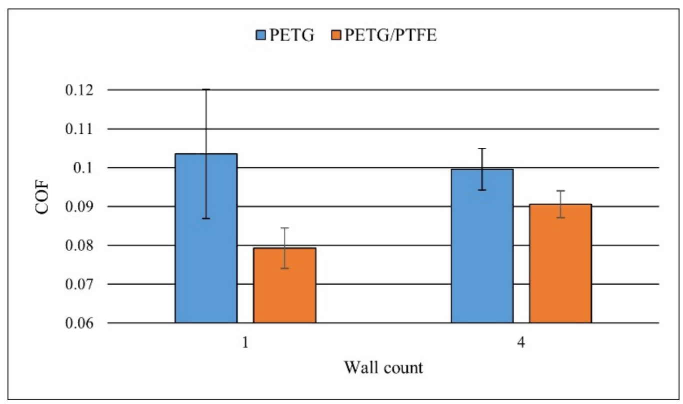

FIGURE 8: AVERAGE COF OF SAMPLES OF EACH MATERIAL BY WALL COUNT (AVERAGE OVER 3 SAMPLES FOR EACH PETG WALL COUNT, AVERAGE OVER 9 SAMPLES FOR EACH PETG/PTFE WALL COUNT)

When altering the parameters for the short-term tribometer tests, Raster width appeared to have minimal effect on COF values, which suggests that the raster width does not have any substantial impact on the tribological performance of FDM parts. The samples demonstrated a minimum average COF of 0.0844 (0.5 mm raster width) and a maximum average COF of 0.088 (0.4 mm raster width) over the different raster widths (4.5% difference) (see Figure 9).

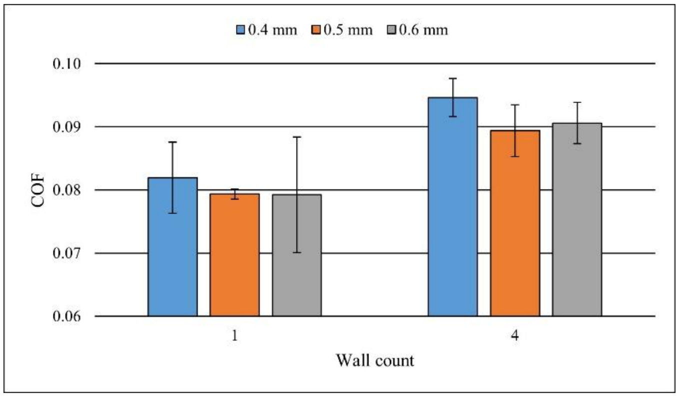

FIGURE 9: AVERAGE COF OF SAMPLES WITH EACH WALL COUNT (AVERAGE OVER 3 SAMPLES FOR EACH RASTER WIDTH).

The wall count, however, had a noticeable effect on the COF of the tribopairs, with a minimum average COF of 0.080 (1 wall) and a maximum average COF of 0.092 (4 walls) over the different wall counts (13.2% difference) (Figure 9). This trend was contrary to what was hypothesized, indicating that higher wall counts actually have a negative effect on the tribological performance of FDM parts.

Additionally, there was no apparent relationship between the combination of the two parameters, which suggests that the parameters affect the properties of the part independently (See Figure 9).

For the longer duration tribometer tests, the disparity between COF values for different wall counts was maintained. However, each wall count showed different behavior over the duration of the test. While not outwardly significant, the sample with 1 wall showed a greater increase in COF over time when compared with the sample with 4 walls, the slope of the friction over time graph with 1 wall was approximately twice that of the sample with 4 walls (2E-06 vs 4E-06) (see Figure 10).

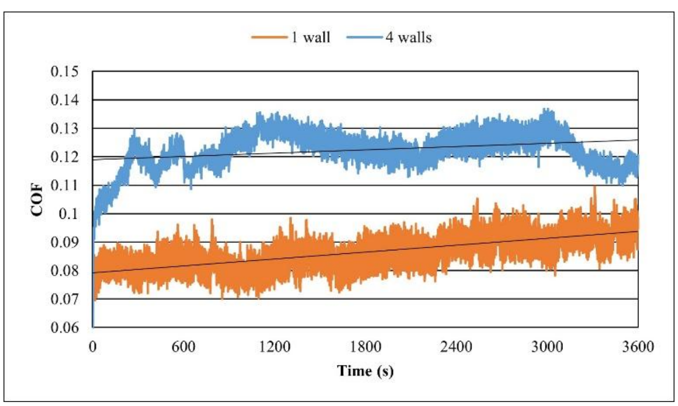

FIGURE 10: COF OVER TIME FOR TWO SAMPLES (1 WALL, 0.6 mm RASTER WITH AND 4 WALLS, 0.6 mm RASTER WIDTH)

4. DISCUSSION

The problem addressed in this study is the extent to which the tribological properties of PETG/PTFE parts manufactured by FDM can be optimized by altering raster width and wall count. It was found that raster width has a negligible effect on the COF of the parts, whereas a lower wall count results in lower COF.

4.1 Tensile characterization

This study demonstrated that the addition of PTFE to PETG filaments for FDM manufacturing has a significant impact on the properties of the material. PETG/PTFE samples exhibited lower tensile strength during tensile testing, however it was also stiffer with a noticeably greater elastic modulus (see Figure 6). This was an unexpected result, as, in bulk, PTFE has a much lower elastic modulus than PTFE [26, 32]. A possible explanation for this is that the addition of PTFE increased the crystallinity of the PETG, which changes the structure and has been shown to increase stiffness; this was seen when adding PTFE to POM [27]. Crystallinity also influences tensile strength, so it is curious that there was only an increase in stiffness, and not strength. Additional differential scanning calorimetry or x-ray diffraction testing is needed to test this hypothesis.

4.2 Tribological testing

For the short term tribological tests, this study suggested that raster width has a negligible effect on the COF of the FDM samples (see Figure 9). This could be due to the fact that the changes in structure as a result of modifying raster width occurred at too small a scale to have a significant effect on macro-scale friction, contrary to what was hypothesized. Mohammed et al. [16] reached a similar conclusion, finding that raster width has a minimal effect on wear as an individual factor. Another study [14] claimed that a higher raster width would lead to less wear. This study [14] suggests that a higher raster width would lead to less distortion effect due to a fewer number of rasters. While this is a reasonable assumption, the scale at which wear was influenced in the study is comparably small with this study and the other study [16], this suggests that raster width does have a negligible to small effect on tribological properties.

In terms of wall count, this study found that a lower number of walls leads to a lower COF (see Figure 9). Because of the difference in surface profile of the track with the different wall counts there becomes two completely different sliding conditions, so it is rational that they would exhibit different COF. However, it is not readily apparent why one wall leads to lower friction. With the one wall disk specimens, the ball is contacting only the top surface rasters, however with four walls, the ball is contacting both the top surface pattern as well as the wall loops (see Figure 11).

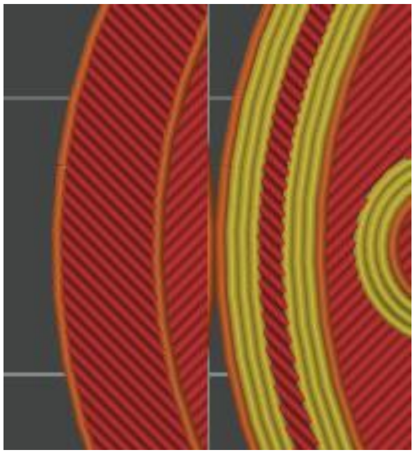

FIGURE 11: TRACK PROFILES FOR 1 WALL (LEFT) AND 4 WALL (RIGHT) SAMPLES. TOP SURFACE FILL LABELED RED, WALL LOOPS IN ORANGE (EXTERIOR) AND YELLOW (INTERIOR).

One explanation for the 1 wall samples exhibiting lower friction than the samples with 4 walls could be that when the ball is contacting the wall loops with the 4 wall samples, the rasters are parallel to those of the ball and could even be aligned, which would lead to less roughness in the direction of sliding and a higher contact area, which would lead to the higher friction observed (see Equation 2).

With this explanation, the 1 wall samples would have contact on the top surface fill rasters, which are diagonal with respect to the layer lines on the ball specimen, possibly leading to higher roughness, lower contact area, and lower friction.

It is also possible that with the profile of the 1 wall samples there is higher roughness but also less structural stiffness in the contact area. This would cause more deformation from the contact, which would lead to a larger contact area, contradicting the explanation above. There are many factors that could affect the COF of friction in this system, and more testing is necessary to determine the driving factor.

This behavior of lower friction with less wall count contradicts the findings of other papers [16], whose results generally followed this study's original hypothesis: more walls will increase the stiffness/hardness of the part and thus lower the COF. This discrepancy is logical; however, other studies [16] used disk specimens with flat top surfaces rather than a raised track, so the effect on contact area seen in this study would not be as prominent. This is because there will only be wall loops on the circumference of the disk, whereas the samples used in this study have wall loops on both the major and minor circumferences of the track. The raised track introduced many new factors that could affect friction, making data analysis significantly more challenging. For future research, a flat disk could be better to isolate the effects of wall count.

Additionally, there was no apparent interplay between the two parameters. This was as hypothesized as the two parameters modify the structure of the part independently. Mohammed et al's study [16] suggested the same independent behavior.

For the longer (60 minute) tribological tests, this study suggested that samples with one wall had lower thermal stability than the four wall samples, due to the fact that there was a greater increase in COF over time with the one wall samples (see Figure 10). This did follow the hypothesis that was proposed, as a higher wall count leads to more density, especially near the contact area, which leads to higher thermal stability. No other studies noted the change in COF over time when optimizing parameters.

4.3 Implications

In a broader context, this study suggests that PTFE/PETG is a viable composite for FDM in tribological applications. Compared to plain PETG It demonstrated lower COF (see Figure 8) while maintaining a majority of the mechanical properties, even showing an increase in stiffness (see Figure 6). This suggests that PTFE/PETG could have potential in applications such as bearings, prosthetics, or any other tribological application that could benefit from the versatility of FDM.

In terms of the experimental part of this study, the findings suggest that wall count should be considered when manufacturing parts for tribological applications, however raster width does not need to be considered. This means that raster width can be optimized for mechanical properties, printing speed, or surface quality without having to consider any sacrifices in COF. As for wall count, this study along with others suggest that it does have an effect on COF, however it strongly depends on the profile of the part. There is also a potential tradeoff between mechanical and tribological properties when altering wall count, which also must be considered based on the desired application.

4.4 Limitations

The tribological tests performed in this study were run at relatively low speeds and loads, which could have led to the lack of significance seen in the results, especially in terms of raster width. Additionally, this study used a DOE with a moderate range of parameters, a greater difference could have brought out more exaggerated results. Additionally, the DOE used in this study was limited to two values by three values for the altered parameters as a result of the time constraints on this study; more levels could have revealed a more complex behavior as the parameters change. Also as a result of time constraints, only one sample of each wall count was tested for the one-hour tribological tests, so the data might not be representative of all the samples. Tests longer than an hour might also show a different behavior with the wall counts. Another limitation that prevented investigating the alternative explanation proposed for wall count is the fact that there is currently no standard testing procedure for the shear strength of FDM parts, unlike tensile strength. Finally, this study utilized a ball on disk tribometer, which is a very valid instrument for testing COF, however it is not directly comparable to results obtained with a pin on disk tribometer, which is more prevalent in the field of FDM optimization, limiting the comparability of the results.

4.5 Future Research

After this study, there is the opportunity to build upon it by investigating other tribologically advanced materials in the context of FDM. Materials that are particularly promising for this application are FEP, PC/PTFE, and fully formulated IGUS filaments. It would also be interesting to investigate other previously investigated FDM parameters with these new advanced materials, to see if previously found trends still hold.

5. CONCLUSION

This study has demonstrated that the addition of PTFE to PETG filaments significantly influences the mechanical and tribological properties of FDM manufactured parts. PETG/PTFE samples exhibited a decrease in tensile strength and displayed increased stiffness, possibly due to an increase in crystallinity. Tribological testing suggested that raster width has a negligible effect on COF whereas wall count significantly influences COF. Lower wall counts exhibited reduced COF but decreased thermal stability. These findings suggest that PTFE/PETG is a promising composite material for tribological applications in FDM, such as bearings and prosthetics, as it offers a lower COF while preserving mechanical properties.

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