
Research article

A parametric study on tribological and mechanical performance of dental acrylic (PMMA)-coated FDM PETG

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Abstract: Fused deposition modeling (FDM) fabricated polyethylene terephthalate glycol (PETG) may have a corrugated surface and voids between the layers, which can restrict performance in sliding contact. In this study, we investigated a low-cost surface engineering process where the tribologically challenging PETG substrate was structurally selected and the protective coating was the self-curing dental polymethyl methacrylate (PMMA). Three levels of each of the four FDM parameters were screened, with three independently printed specimens for each level of the parameter. Three-trial wear indices were analyzed using the original Taguchi smaller-the-better signal-to-noise (S/N) criterion, and factor-level means and sample standard deviations (SDs) were used to summarize the results for tensile strength, Rockwell R hardness (HRR), and inclined-plane static coefficient of friction (COF). The archived measurements were factor-level triplicates as opposed to responses associated with nine simultaneous L9 combinations. Selected PETG specimens were cross-hatched, acetone cleaned, dip-coated, and cured for 48 h. The coating was applied evenly at 0.5 mm on each face, increasing each reduced-section dimension by 1.0 mm in total. The coated condition had a mean maximum load 24.1% greater. Using condition-specific outer-section areas, the calculated tensile strength was 6.9% lower (27.15 ± 0.48 versus 25.29 ± 0.46 MPa), whereas the calculated tensile modulus was 13.8% higher (6.20 ± 0.25 versus 7.05 ± 0.19 MPa). Mean hardness was 44.2% higher (60.0 ± 0.8 versus 86.5 ± 0.7 HRR). The apparent PETG-equivalent wear index, calculated using a common PETG-density normalization due to the inability to separate the lost PMMA and PETG phases, was 50.0% lower ($(27.77 \pm 3.97) \times 10^{-3}$ versus $(13.88 \pm 1.98) \times 10^{-3}$ mm³ N⁻¹ m⁻¹). Static COF was 2.0% lower (0.1643 ± 0.0005 versus 0.1611 ± 0.0005), although the absolute change was small.

The scanning electron microscopy (SEM) images revealed a more continuous coated surface and no large-scale delamination following the short duration abrasive test.

Keywords: FDM; PETG; PMMA coating; tribology; abrasive wear; surface engineering; additive manufacturing

Abbreviations: FDM: Fused deposition modeling; PETG: Polyethylene terephthalate glycol; PMMA: Polymethyl methacrylate; SEM: Scanning electron microscopy; HRR: Rockwell hardness (R scale); ASTM: ASTM International; COF: Coefficient of friction; S/N: Signal-to-noise; SD: Sample standard deviation; CI: Confidence interval

1. Introduction

Fused deposition modeling (FDM) has evolved from rapid prototyping to the direct production of end-use parts like fixtures, jigs, and low-cost functional parts [1,2]. The mechanical and surface properties of FDM parts are highly dependent on the process parameters [3–5], and the mechanical response of printed thermoplastics can depend on loading mode and strain rate [6]. These applications are appealing because polyethylene terephthalate glycol (PETG) offers a useful balance of mechanical performance and processability [7,8]. However, the layer-by-layer surface structure with corrugations, interfilament voids, and anisotropic properties of FDM PETG may restrict its application in sliding contact [8–10]. The crests and voids of the layers can lead to stress concentration, frictional instability, and abrasive material removal under a harder counterface [10,11]. Wear interpretation depends on the contact regime and dominant damage mechanism [12,13].

Some of the post-processing techniques reported are solvent smoothing, mechanical finishing, plasma activation, composite reinforcement, and surface coating [14–17]. Solvent-based treatments can help minimize layer lines but can change the geometry or properties of the substrate and may require controlled chemical handling [14,18]. Selected properties can be enhanced with bulk filament reinforcement but, at the same time, the feedstock and processing complexity are increased [19–21]. Plasma treatment can enhance wettability and surface energy [22], but it is not itself a thick sacrificial coating.

In this study, we thus explore the use of self-curing dental polymethyl methacrylate (PMMA) as a protective coating for FDM PETG. The processability, surface finish, hardness, and wear-related properties of PMMA make it a material of choice in dental applications [23–26]. The continuity, morphology and integrity of the interface have been shown to be important to the functional durability of polymer, thin-film, nanocoating, and bioinspired surface systems [16,17,27–30]. Mechanical roughening and cleaning are employed to enhance mechanical interlocking [18,31,32], and adhesion to a thermoplastic substrate remains a major challenge.

In another study, Salvi et al. investigated the cross-hatch and dip-coating route with a dip-applied resin–graphene coating on FDM-printed acrylonitrile butadiene styrene (ABS), and they found that the substrate pretreatment had a significant effect on the continuity, adhesion, and tribological response of the coating [32]. Studies of PETG with carbon-based phases indicated that coefficient of friction (COF) and specific wear rate may have different responses to material modification [21,33], which further

suggests that they should be interpreted separately. While the material systems are different from PMMA-coated PETG, they put the present strategy into the context of tribological tailoring of FDM polymers.

Here, we aim to investigate if a mechanically keyed, self-curing dental PMMA coating with a 0.5 mm layer on each exposed face can enhance the mechanical and dry abrasive tribological properties of a controlled FDM PETG substrate. First, we investigate the isolated trends of the factor levels extrusion temperature, print speed, layer thickness, and infill density, and then compare the selected uncoated PETG baseline with an otherwise identical PMMA-coated condition using tensile, Rockwell R hardness, inclined-plane friction, modified pin-on-disk wear, and scanning electron microscopy (SEM) measurements.

The research gap is the lack of evidence for the use of dental PMMA as a mechanically interlocked tribological barrier on FDM PETG. The optimization of print parameters, bulk reinforcement, solvent smoothing, and plasma activation have been studied individually in other works [18,21,22,34]. The authors are not aware of any elements being combined as a single sequence that includes FDM parameter screening, cross-hatch surface keying, dental PMMA dip coating, and coated-versus-uncoated mechanical, tribological, and morphological evaluation under the present dry abrasive conditions.

The new contribution is not PMMA or PETG, but rather the combination of both in a carefully planned surface-engineering process. The coating is assessed mainly as a wear protection layer and any change in friction is considered as a secondary response. The claims are limited to the material system, coating thickness, curing route and short duration laboratory conditions used in this test.

To achieve the above objective, we:

1. Use true factor level triplicates to measure isolated factor trends using descriptive Taguchi-style signal-to-noise (S/N) metrics and explicitly exclude run-level L9, percentage-contribution, and interaction claims.
2. Structurally select a PETG baseline and apply a self-curing dental PMMA coating after controlled cross-hatch abrasion and cleaning with a layer of 0.5 mm per face.
3. Measure changes in tensile response, Rockwell R hardness, static COF, mass loss, apparent PETG-equivalent wear index, and surface morphology for coated versus uncoated changes.

This integrated workflow is intended as an accessible preliminary route for extending the service potential of FDM PETG; industrial durability and environmental safety require application-specific validation.

2. Materials and methods

2.1. Materials and experimental equipment

The specimens were made from a single lot of commercially available blue PETG filament that was produced under an ISO 9001 quality-management system. The fabrication was performed using a Creality Ender-3 V3 KE FDM printer with a high-flow copper nozzle (0.4 mm) (Figure 1a). Rockwell R hardness (HRR) was tested using a D-6700 Rockwell hardness tester made by Otto Wolpert Werke GmbH, Germany (Figure 1b), and tensile testing was carried out using a universal testing machine made by Jinan Hensgrand HSTWDW-10E, China (Figure 1c). The dry abrasive wear was tested using a TQ Plint TE91/1 pin-on-disk tribometer (Figure 1d). The surface morphology and wear tracks were

analyzed by SEM using an FEI ESEM Quanta 450 FEG scanning electron microscope (Figure 1e). The inclined plane tester (CF-200i) was used to determine the static coefficient of friction (COF), and is shown schematically in Figure 1f. The representative specimens for hardness/static COF, tensile, and wear testing are presented in Figure 1g–i, respectively, and Figure 1h shows an actual PETG tensile specimen immediately after fracture. The coating used was a self-curing dental PMMA system provided by Hamza Ve M Dental Dış Malzemeleri İç ve Dış Tic. Ltd. The ratio of PMMA powder to liquid was prepared in the manufacturer's recommended ratio prior to dip coating.

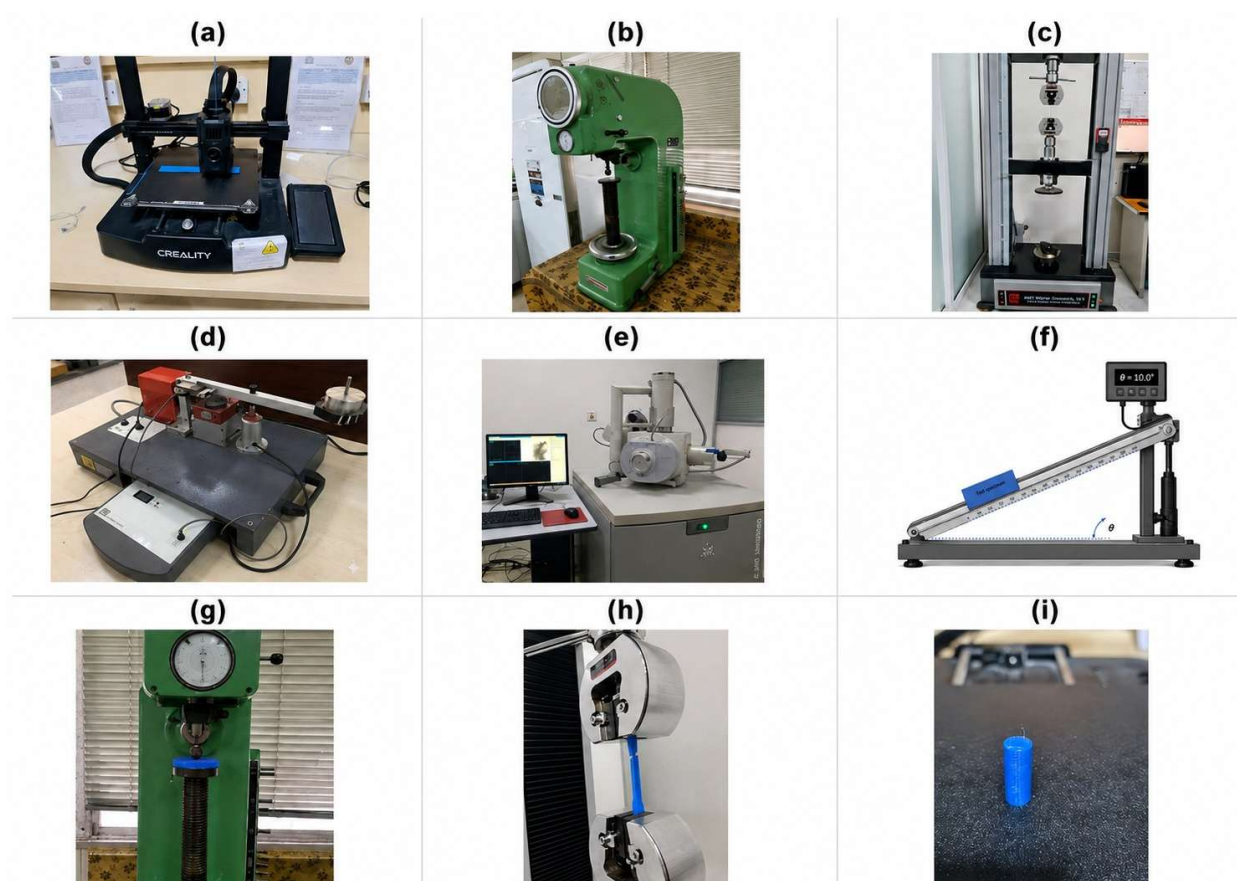


Figure 1. Experimental equipment and representative PETG specimens: (a) FDM printer; (b) Rockwell hardness tester; (c) universal tensile-testing machine; (d) pin-on-disk tribometer; (e) FEI ESEM Quanta 450 FEG scanning electron microscope; (f) schematic of the inclined-plane static-COF tester; (g) square PETG coupon positioned on the Rockwell hardness tester (the same 50 mm $\times$ 50 mm $\times$ 10 mm coupon geometry was used for hardness and static COF); (h) fractured ASTM D638-14 Type I PETG tensile specimen remaining mounted between the grips of the HSTWDW-10E universal testing machine; and (i) cylindrical PETG wear pin (10 mm diameter $\times$ 30 mm height).

2.2. Ethics approval and consent

The study was not conducted in humans or animals and no clinical or patient-specific tissue models were used; therefore, study-specific institutional ethics committee approval and informed consent were not required.

2.3. Factor-level screening and descriptive S/N analysis

The screening and descriptive S/N analysis were performed at the factor level. Four controllable FDM parameters [34–37] were analyzed by a factor-level screening that was resource efficient. Three levels were used for each factor with three independently printed specimens at each level. The intent was to find descriptive single factor trends and choose a controlled substrate for the coating comparison, rather than to fit a multivariable or interaction model. The measurements that were archived were not associated with any four factor simultaneous treatment combinations, and thus were considered one-factor-at-a-time screening data, not experimental L9 run responses.

The four control factors and their levels were chosen from literature on PETG/FDM and the range of the printer-nozzle-material system. The three levels were low, intermediate, and high to enable the descriptive observation of monotonic or curved single-factor trends:

- Extrusion temperature (250, 275, and 300 °C) was the lower, intermediate, and upper thermal setting, respectively, investigated to encompass the trade-off between interlayer fusion and potential thermal degradation.
- Print speed (200, 250, and 300 mm/s) indicated three throughput levels in the high flow printing range employed in this work.
- Layer thickness (0.10, 0.15, and 0.20 mm) was a fine, intermediate, and coarse deposition, respectively, relative to the nozzle diameter of 0.4 mm and changes the number of layer interfaces.
- Infill density (60%, 80%, and 100%) referred to the weight saving, intermediate, and nominally solid internal structure, respectively, and thus varied the subsurface support during mechanical and wear testing.

The resulting factors and levels are summarized in Table 1.

Table 1. Control factors and levels used in the factor-level screening.

Factor	Level 1	Level 2	Level 3
Extrusion temperature (°C)	250	275	300
Print speed (mm/s)	200	250	300
Layer thickness (mm)	0.10	0.15	0.20
Infill density (%)	60	80	100

The specimens were sliced using Creality Print. In each isolated factor series, the named factor was changed to the levels in Table 1. The build-plate temperature was 75 °C. No part-cooling fan was used during printing, and the specimens were cooled naturally at room temperature after printing. The speed factor for the experimental print was achieved by setting the outer-wall speed to 200, 250 or 300 mm/s, whereas the other speed factors for the various roles were kept at their standard-profile values. During the temperature series, the nozzle temperature was set to 250, 275 or 300 °C by Creality Print. No support material was used. The cylindrical wear pins and square coupons for Rockwell R hardness and static COF were printed in a vertical build orientation, while the tensile specimens were printed horizontally (flat on the build plate) to achieve maximum rigidity. The retained constants included a 0.20 mm first-layer height; line widths of 0.45 mm (default), 0.50 mm (first layer),

0.42 mm (outer wall), 0.45 mm (inner wall), 0.42 mm (top surface), 0.45 mm (sparse infill), and 0.42 mm (internal solid infill); two wall loops; four top and four bottom shell layers; rectilinear sparse infill; 45° sparse- and solid-infill directions; monotonic top and bottom surface patterns; the inner/outer wall order; the Arachne wall generator; and no ironing. The first-layer speed was 50 mm/s, the travel speed was 300 mm/s, the normal-printing acceleration was 5000 mm/s², the outer-wall acceleration was 2000 mm/s², and the first-layer acceleration was 500 mm/s². The default jerk was 12 mm/s, with 9 mm/s for the outer wall, inner wall, top surface, and first layer. The printer, nozzle size (0.4 mm), batch of PETG, specimen geometry and test procedures were kept the same. The factor-level worksheets were not completely preserved for the other three experimental factors in every isolated series, nor were any missing settings or combinations of factors reconstructed.

The screening data set included 12 isolated factor-level conditions (4 factors × 3 levels), and $n = 3$ independently printed specimens per condition, resulting in 36 measured observations per response. This structure did not enable orthogonal main-effect estimates that were adjusted for the other factors, but enable factor-level means, standard deviations, and descriptive S/N values. Table 2 therefore presents the standard L9(3⁴) matrix only as a prospective confirmation design.

Table 2. Standard L9 matrix proposed for a future confirmation experiment; no response values in this study were generated from this matrix.

Proposed run	Temperature (°C)	Speed (mm/s)	Layer thickness (mm)	Infill (%)
1	250	200	0.10	60
2	250	250	0.15	80
3	250	300	0.20	100
4	275	200	0.15	100
5	275	250	0.20	60
6	275	300	0.10	80
7	300	200	0.20	80
8	300	250	0.10	100
9	300	300	0.15	60

Arithmetic mean ± sample standard deviation was used to summarize triplicate observations. As in the original manuscript, the wear was evaluated using the Taguchi smaller-the-better relation, Eq 1:

$$S/N = -10 \log_{10}[(1/n)\Sigma(y_i^2)] \quad (1)$$

In this case, y_i is the PETG-density-normalized wear index for one specimen, and $n = 3$. The larger S/N is preferred and the difference between the largest and smallest factor-level S/N values was used to rank each isolated factor series. The mean ± sample SD summaries of tensile strength, Rockwell R hardness, and static COF were retained.

There were three post-test length and mass readings for each factor level in the screening-wear dataset. All specimens were printed independently in each trial. The three resulting PETG-density-normalized wear indices at each level were then analyzed using the original smaller-the-better S/N analysis, and the means, sample SDs, and S/N values were calculated. The resulting wear S/N ranges were used only to rank observed factor-level wear responses.

If the reference L9 matrix in Table 2 was conducted with all four three-level factors, its eight column degrees of freedom would be fully assigned to the four main effects; factor-factor interactions would consequently be aliased and could not be estimated independently. The present factor-level dataset provided no interaction estimate. A replicated L27, factorial, or response-surface design with retained run identifiers would be required to quantify interactions and provide an independent residual-error term for ANOVA.

The coating-phase substrate was chosen based on a structural-baseline criterion, not just based on minimum wear. The chosen setting was 100% infill, 300 °C extrusion temperature, 0.15 mm layer height, and 250 mm/s print speed, which resulted in high internal support and a challenging high-temperature surface condition. The 300 °C level had the highest mean PETG-density-normalized wear index, $33.72 \pm 1.98 \times 10^{-3} \text{ mm}^3 \text{ N}^{-1} \text{ m}^{-1}$, and the largest wear S/N range was for extrusion temperature. This condition was thus referred to as the ‘structurally selected baseline’ rather than an optimum wear condition.

2.4. Surface preparation

The selected PETG specimens were manually abraded using 80-grit abrasive paper to remove the crests of the layers, increase the surface area and create micro-cavities for mechanical interlocking [31,32]. All specimens were then cleaned with acetone to remove debris and surface contaminants from abrasion before being coated, as was done for all coated specimens [18].

2.5. PMMA coating formulation and application

A self-curing dental PMMA system was used as the surface-modification material [23]. The polymer powder and liquid monomer were mixed in a 2:1 mass ratio according to the manufacturer’s instructions. The selected PETG specimens were dipped in the mixture with the same controlled dipping process, pulled out to prevent entrapped air as much as possible, and cured at room temperature without disturbance for 48 h. After curing, it was determined that the coating was uniform at 0.5 mm thickness on each face.

2.6. Mechanical and tribological characterization

The chosen uncoated PETG baseline was directly compared to the same baseline except for the PMMA coating. Each condition was tested and printed three times. Tensile specimens were of ASTM D638-14 Type I geometry with a 165 mm overall length, a 19 mm grip width, a 13 mm nominal reduced section width, a 3.2 mm nominal thickness, and a 50 mm nominal gauge length. The uncoated PETG reduced section area was measured to be 44.12 mm^2 . The coating added 1.0 mm to the width and thickness of the reduced section, or 0.5 mm to each side of the section. The nominal coated outer dimensions were therefore $14.0 \text{ mm} \times 4.2 \text{ mm}$, which equated to an estimated coated cross-sectional

area of 58.80 mm². The tensile strength and modulus were normalized to condition-specific areas. The coated area was determined from nominal geometry and not measured separately on each specimen; therefore, the resulting coated values were nominal composite-section properties. The diameter of the cylindrical wear pins was 10 mm and their height was 30 mm. The inclined-plane static-friction test was conducted on square coupons of size 50 mm × 50 mm × 10 mm with the 50 mm × 50 mm face as the contact surface, while the Rockwell R hardness test was performed on the same type of coupon. The statistical treatment and the limitations of remaining data are indicated in Section 2.8.

- Tensile properties: the tensile properties were determined using tensile specimens according to ASTM International (ASTM) D638-14 Type I, including maximum load, instrument-reported apparent tensile strength, instrument-reported apparent tensile modulus and elongation at break [38].

- Surface hardness: 50 mm × 50 mm × 10 mm coupons were tested on the Rockwell R scale according to ASTM D785 [39]. Hardness was not a direct measure of wear resistance, but was reported as an indentation response.

- Abrasive wear: cylindrical pins 10 mm in diameter and 30 mm in height were tested in a modified rotating-track pin-on-disk test using 1000-grit abrasive paper attached to the disk as the counterface, according to ASTM G99-05 [40]. The specimens were run for 15 min at 270 rpm with a normal force of 5.20 N and a track radius of 30 mm.

- Static friction: coupons were 50 mm × 50 mm × 10 mm with the 50 mm × 50 mm face against the inclined plane of the CF-200i according to the principle of ASTM G219-24. The static (breakaway) coefficient was determined by taking the ratio $\mu = \tan(\theta)$ at the onset of macroscopic sliding [41]. Wear measurements were made using the pin-on-disk tribometer, but the dynamic friction signal was not used in the reported comparative results.

2.7. Microstructural evaluation

The 10 mm-diameter cylindrical specimens were cut into approximately 10 mm-high sections for plan-view SEM imaging. The tested 10 mm × 30 mm wear pins were sectioned for post-wear SEM analysis; therefore, the 10 mm dimension refers to the section height cut for mounting in the SEM and not the original height of the printed pin. Before wear, reference surfaces were imaged and then uncoated and coated surfaces were examined after testing. Images were used to qualitatively compare surface corrugation, coating continuity, wear grooves, debris, cracking, and visible delamination. The SEM observations were not used to claim coating penetration depth or interfacial bond strength as cross-sectional imaging and quantitative adhesion testing were not performed.

2.8. Statistical analysis

The factor-level tensile strength and maximum load data were available in triplicate, as were the Rockwell R hardness, static COF and wear responses, and the coated-versus-uncoated comparisons. Each condition was tested and printed three times, and the results are presented as arithmetic mean ± sample SD (n = 3). Entries in the screening tensile dataset for elongation at break remain available only as aggregate values because replicate-level elongation data were not available. Three post-test readings were available for each factor level for screening wear; the three calculated losses were used for the mean, SD, and original smaller-the-better S/N analysis. The recorded friction angles were converted from the original inclined-plane relation in Section 2.6 prior to calculating the mean and SD

of the COF. The coated-versus-uncoated comparisons were analyzed with two-sided Welch independent-samples t tests and 95% confidence intervals (CIs) for mean differences. Normality could not be assessed with only three observations per group, and the p-values were exploratory.

3. Results and discussion

3.1. Influence of FDM parameters on mechanical strength

Prior to the PMMA comparison, the bulk tensile properties of the uncoated PETG specimens were obtained using ASTM D638-14 Type I specimens. Tests were performed at 23 °C; the archived stress calculations used the measured uncoated PETG reduced-section area of 44.12 mm² and a nominal gauge length of 50 mm. Loads recorded in kN were converted to N before division by the measured reduced-section area in mm² to calculate stress in MPa. The tensile responses available in the archived parameter-screening summary are reported in Table 3.

Table 3. Tensile test results from FDM PETG parameter screening.

Variable category	Parameter tested	Maximum load (kN), mean $\pm$ SD	Tensile strength (MPa), mean $\pm$ SD	Elongation at break (%)
Infill density	60%	0.89 $\pm$ 0.04	20.0 $\pm$ 0.8	3.0
	80%	1.02 $\pm$ 0.04	23.0 $\pm$ 0.8	4.0
	100%	1.21 $\pm$ 0.05	27.0 $\pm$ 0.8	3.0
Extrusion temperature	250 °C	0.86 $\pm$ 0.04	19.0 $\pm$ 0.6	10.5
	275 °C	0.90 $\pm$ 0.03	20.0 $\pm$ 0.5	4.0
	300 °C	0.96 $\pm$ 0.04	22.0 $\pm$ 0.6	2.0
Print speed	200 mm/s	0.84 $\pm$ 0.04	19.0 $\pm$ 0.7	2.5
	250 mm/s	0.86 $\pm$ 0.04	19.0 $\pm$ 0.5	10.5
	300 mm/s	0.84 $\pm$ 0.04	19.0 $\pm$ 0.8	5.5
Layer thickness	0.10 mm	0.87 $\pm$ 0.03	20.0 $\pm$ 0.6	0.0
	0.15 mm	0.89 $\pm$ 0.03	20.0 $\pm$ 0.8	2.0
	0.20 mm	0.84 $\pm$ 0.03	19.0 $\pm$ 0.7	2.5

Note: maximum load and tensile strength are given as mean $\pm$ sample SD ($n = 3$) for all three levels of all four factors. Elongation-at-break entries were archived aggregate means because replicate-level elongation values were not available.

The results of the tensile strength showed that it increased with the increase of infill density and the increase of extrusion temperature, and it changed little with print speed and layer thickness in the provided level-wise triplicates. The structurally selected coating-phase baseline was based on the full wear and hardness screening results plus the tensile evidence and was:

- 100% infill density
- 300 °C extrusion temperature
- 0.15 mm layer thickness
- 250 mm/s print speed.

The same 250 mm/s was chosen for the uncoated control and PMMA-coated specimens to ensure that the only difference between the two comparison groups was the coating condition. The tensile properties are given in Table 4.

The comparative tensile properties of the uncoated selected PETG baseline and PMMA-coated PETG are presented in Table 4.

Table 4. Comparative instrument-reported tensile responses of the uncoated selected PETG baseline and PMMA-coated PETG.

Specimen condition			Maximum load (kN), mean $\pm$ SD	Apparent tensile strength (MPa), mean $\pm$ SD	Apparent tensile modulus (MPa), mean $\pm$ SD	Elongation at break (%), mean $\pm$ SD
Uncoated selected PETG baseline			1.198 $\pm$ 0.021	27.2 $\pm$ 0.8	6.20 $\pm$ 0.25	8.2 $\pm$ 0.5
PMMA-coated PETG			1.487 $\pm$ 0.027	33.7 $\pm$ 0.7	9.40 $\pm$ 0.25	5.8 $\pm$ 0.5

Note: values are mean $\pm$ sample SD ($n = 3$, independently printed specimens per condition). Apparent tensile strength and modulus are based on the 44.12 mm² PETG substrate reference area, not the entire coated outer area. The two-sided Welch p values for the values reported in Table 4 are: maximum load, $p = 0.0002$; apparent tensile strength, $p = 0.0004$; apparent tensile modulus, $p < 0.0001$; and elongation at break, $p = 0.0042$.

Mean maximum load increased from 1.198 $\pm$ 0.021 to 1.487 $\pm$ 0.027 kN (24.1%; mean difference 0.289 kN, 95% CI 0.233–0.345 kN; Welch $t(3.79) = 14.56$, $p = 0.0002$). The apparent tensile strength increased from 27.2 $\pm$ 0.8 to 33.7 $\pm$ 0.7 MPa (23.9%; mean difference 6.50 MPa, 95% CI 4.85–8.15 MPa; Welch $t(3.98) = 10.94$, $p = 0.0004$). Apparent tensile modulus increased from 6.20 $\pm$ 0.25 to 9.40 $\pm$ 0.25 MPa (51.6%; mean difference 3.20 MPa, 95% CI 2.63–3.77 MPa; Welch $t(4.00) = 15.68$, $p < 0.0001$). Elongation at break decreased from 8.2 $\pm$ 0.5% to 5.8 $\pm$ 0.5% (29.3%; $p = 0.0042$).

These apparent increases were based on a common substrate-area basis. The mean load-derived tensile strength decreased from 27.15 $\pm$ 0.48 to 25.29 $\pm$ 0.46 MPa (6.9% lower; exploratory Welch $p = 0.0084$) when maximum load was divided by the condition-specific areas of 44.12 mm² for uncoated PETG and the estimated 58.80 mm² coated outer section. Rescaling the coated modulus to the same outer-area basis gave 7.05 $\pm$ 0.19 MPa, 13.8% above the uncoated 6.20 $\pm$ 0.25 MPa value ($p = 0.0109$). Thus, the maximum load increase of 24.1% was independent of area, while changes in strength and modulus were reported by basis. Neither basis was intrinsic properties of PMMA or PETG since the thickness of the coating was not measured on a specimen-by-specimen basis and load sharing between the phases was not resolved.

3.2. Surface hardness response

The surface indentation hardness was determined on the Rockwell R scale, following ASTM D785. The response to infill, temperature, speed and layer thickness was investigated by preliminary measurements across the isolated factor-level conditions, and the factor-level values are presented in Table 5.

Table 5. Rockwell R hardness results for FDM PETG parameter screening.

Variable category	Parameter tested	Rockwell hardness (HRR), mean $\pm$ SD
Infill density	60%	68.5 $\pm$ 0.7
	80%	78.0 $\pm$ 0.8
	100%	86.5 $\pm$ 0.7
Extrusion temperature	250 °C	60.0 $\pm$ 0.8
	275 °C	58.5 $\pm$ 0.7
	300 °C	55.0 $\pm$ 0.8
Print speed	200 mm/s	60.0 $\pm$ 0.7
	250 mm/s	59.5 $\pm$ 0.7
	300 mm/s	58.0 $\pm$ 0.8
Layer thickness	0.10 mm	57.5 $\pm$ 0.7
	0.15 mm	58.8 $\pm$ 0.8
	0.20 mm	60.0 $\pm$ 0.8

The data show that mean hardness increased from 68.5 $\pm$ 0.7 HRR at 60% infill to 86.5 $\pm$ 0.7 HRR at 100% infill. Hardness was 60.0 $\pm$ 0.8 HRR at 250 °C and 55.0 $\pm$ 0.8 HRR at 300 °C across the isolated factor series, and increases slightly with the layer thickness and to change slightly with the print speed.

The coating-phase baseline was chosen for the purpose of having high internal support and interlayer bonding, rather than maximum local hardness and minimum wear. The mean screening wear index for the selected series of 300 °C was the highest, and the mean was the lowest for the isolated speed series of 250 mm/s. The coating effect was isolated in this intentionally challenging substrate condition by making a direct comparison between the uncoated selected baseline and its PMMA-coated counterpart.

The comparative Rockwell R hardness values are presented in Table 6.

Table 6. Comparative Rockwell R hardness of the uncoated selected PETG baseline and PMMA-coated PETG.

Specimen condition	Rockwell hardness (HRR), mean $\pm$ SD
Uncoated selected PETG baseline	60.0 $\pm$ 0.8
PMMA-coated PETG	86.5 $\pm$ 0.7

Note: values are mean $\pm$ sample SD ($n = 3$ specimens/condition). Because no pairing was documented, the exploratory two-sided Welch t-test gave a mean difference of 26.50 HRR (95% CI 24.78–28.22 HRR; Welch $t(3.93) = 43.18$, $p < 0.001$).

The comparative tensile and hardness responses are shown in Figure 2.

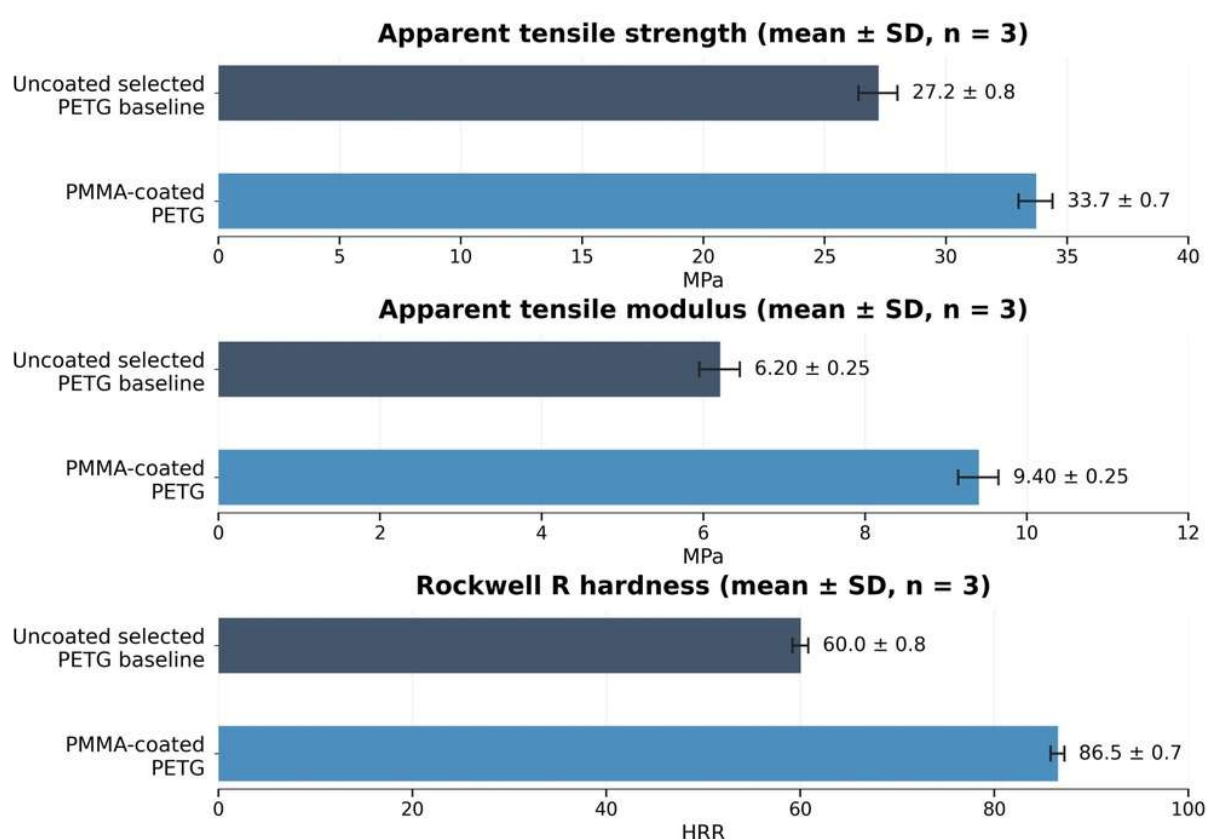


Figure 2. Apparent tensile strength and apparent tensile modulus on the common 44.12 mm² PETG substrate reference-area basis, together with Rockwell R hardness, for the uncoated selected PETG baseline and PMMA-coated PETG. Bars show means and error bars show $\pm$ sample SD ($n = 3$). The condition-specific outer-section interpretation is given in the text following Table 4.

The mean Rockwell R hardness for the selected baseline was 60.0 $\pm$ 0.8 HRR and 86.5 $\pm$ 0.7 HRR for the PMMA-coated condition. The mean difference was 26.50 HRR (95% CI 24.78–28.22 HRR; Welch $t(3.93) = 43.18$, $p < 0.001$), equivalent to a 44.2% increase. The higher indentation response was in line with the existence of a cured PMMA surface layer [23,26]. Since $n = 3$ per group, and normality could not be determined, the inference was exploratory; hardness should not be interpreted

as a measure of wear resistance, which was more directly relevant to the independent material-loss measurements in Section 3.3.

3.3. Tribological performance (friction and wear)

Dry-abrasive wear was tested using a modified rotating-track pin-on-disk configuration with the abrasive paper attached to the disk as the counterface. The tests were conducted for 15 min at 270 rpm and a track radius of 30 mm, which resulted in a sliding speed of 0.848 m/s and a total sliding distance of 763.4 m. The applied mass was 530 g and the normal force was 5.20 N. This abrasive-paper contact was more severe than a conventional smooth-disk test, so the results were not a direct prediction of a specific industrial component, but rather an accelerated comparative laboratory test [10,21,40].

Three independently printed specimens were used for each setting in the factor-level screening. Loss estimates were determined by subtracting a post-test reading from the single initial reading recorded for each level. These estimates were not paired before and after readings, but were repeatability estimates based on a common reference. The mass loss was converted to PETG-equivalent volume by dividing it by the PETG density of 1.27 g/cm³. The resulting volume was then divided by the 5.20 N force and 763.4 m sliding distance to obtain the PETG-density-normalized wear index. The means, sample SDs, and original smaller-the-better S/N values were calculated without replacement or transformation since all calculated screening losses were positive.

The COF values reported in the factor-level and comparative tribological results are not continuously recorded or dynamic pin-on-disk values, but were static breakaway values obtained from the CF-200i inclined plane test in Section 2.6.

The factor-level wear and static-COF results are presented in Table 7.

Table 7. Three-trial length loss, mass loss, PETG-density-normalized wear index, and inclined-plane static COF for FDM PETG factor-level screening.

Variable	Level	Length loss (mm), mean $\pm$ SD	Mass loss (g), mean $\pm$ SD	PETG-density-normalized wear index ($\times 10^{-3}$ mm ³ N ⁻¹ m ⁻¹), mean $\pm$ SD	Static COF, μ , mean $\pm$ SD
Print speed	200 mm/s	0.40 $\pm$ 0.10	0.047 $\pm$ 0.015	9.26 $\pm$ 3.03	0.1638 $\pm$ 0.0007
	250 mm/s	0.35 $\pm$ 0.05	0.020 $\pm$ 0.010	3.97 $\pm$ 1.98	0.1647 $\pm$ 0.0005
	300 mm/s	0.70 $\pm$ 0.10	0.050 $\pm$ 0.020	9.92 $\pm$ 3.97	0.1664 $\pm$ 0.0009
Extrusion temperature	250 °C	0.35 $\pm$ 0.05	0.030 $\pm$ 0.010	5.95 $\pm$ 1.98	0.1629 $\pm$ 0.0009
	275 °C	0.45 $\pm$ 0.10	0.060 $\pm$ 0.010	11.90 $\pm$ 1.98	0.1652 $\pm$ 0.0007
	300 °C	2.00 $\pm$ 0.10	0.170 $\pm$ 0.010	33.72 $\pm$ 1.98	0.1691 $\pm$ 0.0009
Layer thickness	0.10 mm	1.10 $\pm$ 0.10	0.110 $\pm$ 0.010	21.82 $\pm$ 1.98	0.1673 $\pm$ 0.0007
	0.15 mm	0.95 $\pm$ 0.05	0.050 $\pm$ 0.010	9.92 $\pm$ 1.98	0.1652 $\pm$ 0.0005
	0.20 mm	0.40 $\pm$ 0.05	0.060 $\pm$ 0.010	11.90 $\pm$ 1.98	0.1634 $\pm$ 0.0007

Continued on next page

Variable	Level	Length loss (mm), mean $\pm$ SD	Mass loss (g), mean $\pm$ SD	PETG-density-normalized wear index ($\times 10^{-3}$ mm ³ N ⁻¹ m ⁻¹), mean $\pm$ SD	Static COF, μ , mean $\pm$ SD
Infill density	60%	0.40 $\pm$ 0.10	0.050 $\pm$ 0.010	9.92 $\pm$ 1.98	0.1682 $\pm$ 0.0009
	80%	0.90 $\pm$ 0.10	0.050 $\pm$ 0.010	9.92 $\pm$ 1.98	0.1652 $\pm$ 0.0005
	100%	0.90 $\pm$ 0.10	0.090 $\pm$ 0.020	17.85 $\pm$ 3.97	0.1629 $\pm$ 0.0005

Note: mean $\pm$ sample SD ($n = 3$, independently printed specimens per factor level). Each loss estimate was calculated by subtracting one of the three post-test readings from the single initial reference recorded for that factor level. Mass loss was converted to PETG-equivalent volume with the density of 1.27 g/cm³ and normalized by 5.20 N and 763.4 m.

The descriptive smaller-the-better wear S/N response summary is presented in Table 8.

Table 8. Descriptive smaller-the-better wear S/N response summary calculated from the supplied three-trial measurements (dB).

Response/objective	Factor	S/N L1	S/N L2	S/N L3	S/N range	Rank
Wear index/lower	Extrusion temperature	44.198	38.408	29.432	14.766	1
	Print speed	40.371	47.361	39.632	7.730	2
	Layer thickness	33.199	39.957	38.408	6.758	3
	Infill density	39.957	39.957	34.826	5.132	4

The identities of the levels are given in Table 1. The highest S/N range (14.766 dB) was obtained for the extrusion temperature, followed by the print speed (7.730 dB), the layer thickness (6.758 dB), and the infill density (5.132 dB) for the PETG-density-normalized wear index. For each isolated factor series, a higher S/N value indicated a better lower-loss level according to the smaller-the-better criterion. The absolute dB values were dependent on the unit scale, but not the within-response ranking. These were factor-level descriptive summaries and did not include percentage contributions, orthogonally adjusted major effects, or interaction estimates. The wear S/N summary was retained to implement the analytical relation stated in Section 2.3. The factor-level wear responses are shown in Figure 3.

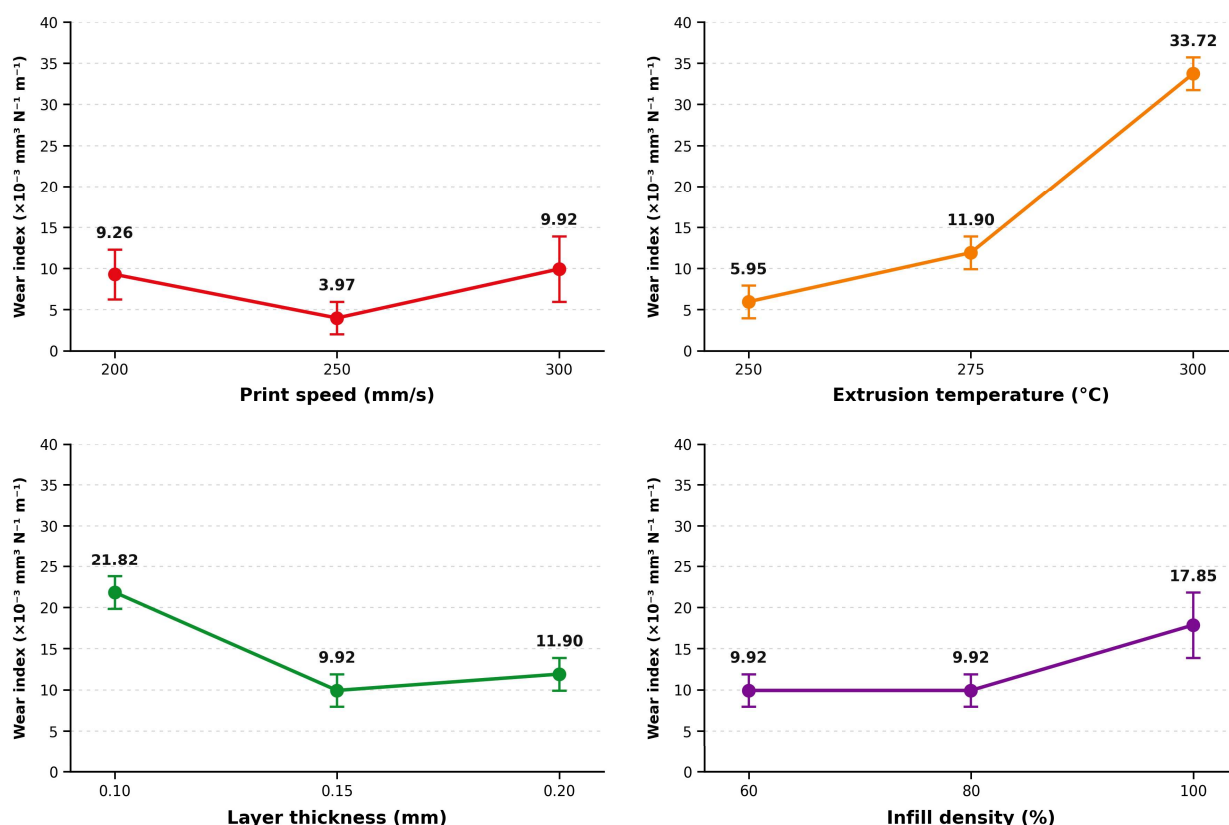


Figure 3. Mean PETG-density-normalized wear index across isolated factor levels, calculated from the supplied three-trial measurements. Error bars show $\pm$ sample SD ($n = 3$ independently printed specimens per level). All calculated trial losses were positive; the figure is descriptive and not interaction-adjusted.

Among the screening results in Table 7, the 300 $^{\circ}\text{C}$ series had the highest mean PETG-density-normalized wear index, $33.72 \pm 1.98 \times 10^{-3} \text{ mm}^3 \text{ N}^{-1} \text{ m}^{-1}$, with a mean length loss of $2.00 \pm 0.10 \text{ mm}$ and mass loss of $0.170 \pm 0.010 \text{ g}$. The highest wear S/N range (14.766 dB) was obtained for extrusion temperature. The higher 300 $^{\circ}\text{C}$ response may be due to thermal-history effects at the upper processing level, but the chemical degradation was not measured, and the concurrent-factor effects were not tested [7,34–36]. The 300 $^{\circ}\text{C}$ condition was deliberately included in the baseline of the coating-phase to evaluate the PMMA layer on a structurally dense and challenging substrate and was not presented as a wear optimum.

The 50.0% reduction in mass loss for the coating trial may seem high compared to a representative industrial or lower-wear PETG substrate, due to the fact that the baseline used for the coating trial was the structurally dense 300 $^{\circ}\text{C}$ level, which had the highest mean wear index among the temperatures. A factorial coating/no-coating study will need to be conducted on representative and lower-wear substrates to isolate the effect of coating from baseline susceptibility.

The inclined plane data indicated a small range of static-COF. Mean COF increased from 0.1629 ± 0.0009 at 250 $^{\circ}\text{C}$ to 0.1691 ± 0.0009 at 300 $^{\circ}\text{C}$, while the infill series decreased from 0.1682 ± 0.0009 at 60% to 0.1629 ± 0.0005 at 100%. These were based on the given angle triplicates and the inclined plane relation.

The comparative coated-versus-uncoated tribological results are presented in Table 9.

Table 9. Comparative material loss, apparent PETG-equivalent wear index, and inclined-plane static COF of the uncoated selected PETG baseline and PMMA-coated PETG.

Specimen condition	Length loss (mm), mean $\pm$ SD	Mass loss (g), mean $\pm$ SD	Apparent wear index, W_e ($\times 10^{-3} \text{ mm}^3 \text{ N}^{-1} \text{ m}^{-1}$), mean $\pm$ SD	PETG-equivalent Static COF, μ , mean $\pm$ SD
Uncoated selected PETG baseline	2.40 ± 0.10	0.140 ± 0.020	27.77 ± 3.97	0.1643 ± 0.0005
PMMA-coated PETG	1.50 ± 0.10	0.070 ± 0.010	13.88 ± 1.98	0.1611 ± 0.0005

Note: values are mean $\pm$ sample SD ($n = 3$, independently printed and tested specimens per condition). The two-sided Welch p values for length loss, mass loss, and static COF are 0.0004, 0.013, and 0.0018, respectively. The PETG-density-normalized W_e value is an apparent common-basis index for the coated condition, as the lost PMMA and PETG phases could not be separated, and is not a phase-resolved specific wear rate. The corresponding comparative wear and static-COF values are shown in Figure 4.

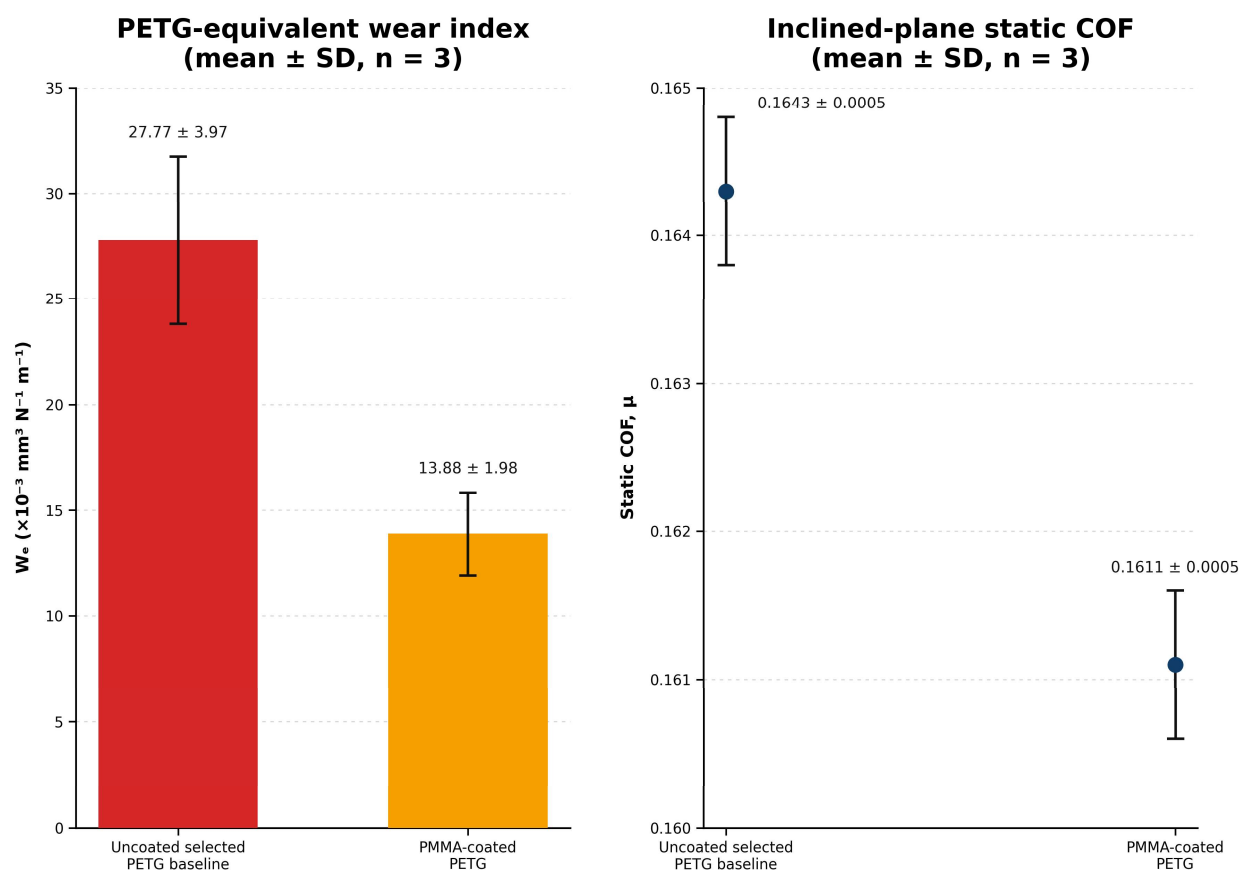


Figure 4. Apparent PETG-equivalent wear index and inclined-plane static COF of the uncoated selected PETG baseline and PMMA-coated PETG. Symbols show means and error bars show $\pm$ sample SD ($n = 3$); the COF panel uses an expanded vertical scale. The coated wear value was an apparent common-density index rather than a phase-resolved rate.

Directly measured mean mass loss decreased from 0.140 ± 0.020 to 0.070 ± 0.010 g, a 50.0% reduction (Welch $t(2.94) = 5.42$, $p = 0.013$). This density-independent result was the main wear outcome. Both conditions were normalized using the PETG density to provide a common basis; the apparent PETG-equivalent wear index decreased from $(27.77 \pm 3.97) \times 10^{-3}$ to $(13.88 \pm 1.98) \times 10^{-3} \text{ mm}^3 \text{ N}^{-1} \text{ m}^{-1}$. The mean index difference was $13.88 \times 10^{-3} \text{ mm}^3 \text{ N}^{-1} \text{ m}^{-1}$ (95% CI $5.64\text{--}22.13 \times 10^{-3}$; Welch $t(2.94) = 5.42$, $p = 0.013$). Mean length loss decreased from 2.40 ± 0.10 to 1.50 ± 0.10 mm (37.5%; exploratory Welch $p = 0.0004$). Mean static COF decreased by 0.0032 (95% CI $0.0020\text{--}0.0044$; Welch $t(4.00) = 7.35$, $p = 0.0018$), equivalent to 2.0%. The COF difference was distinguishable within these triplicates, but the magnitude of the COF difference was small; the main tribological benefit measured was the reduction in material loss under the tested abrasive condition. The volume loss or wear contribution of either the PMMA or PETG phases could not be separated because the lost phases were not separated.

3.4. Microstructural analysis (SEM)

Plan-view SEM was used to compare the surface morphology of uncoated and PMMA-coated PETG before and after the abrasive test. The interpretation was qualitative and considered only features that could be seen on the surfaces being imaged.

3.4.1. Baseline morphology (uncoated, pre-wear)

The uncoated baseline selected PETG exhibited the typical FDM topography when viewed layer-by-layer prior to wear testing [8,11]. At lower magnification (Figure 5a), parallel crests and valleys corresponding to the adjacent extruded filaments were seen. At higher magnification (Figure 5b), interfilament voids and incomplete fusion zones were seen. These features can focus the contact stress and offer initiation points for material removal in sliding [10–12].

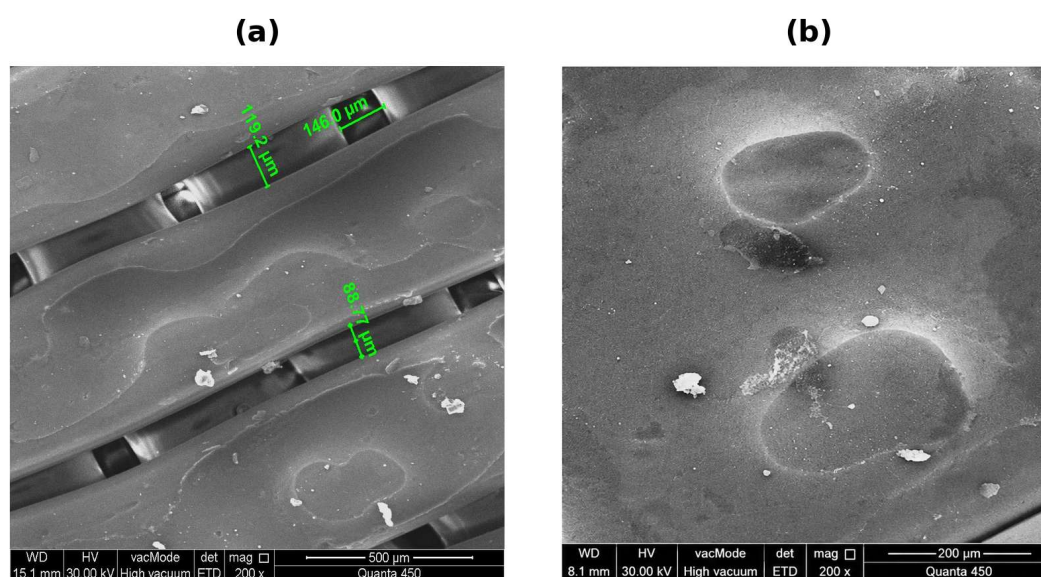


Figure 5. SEM micrographs of the uncoated selected FDM PETG baseline before wear testing: (a) lower-magnification view showing parallel layer crests and valleys; and (b) higher-magnification view showing interfilament voids and incomplete fusion zones.

3.4.2. Coating integration and homogeneity (coated, pre-wear)

The PMMA-coated surface was more continuous and less corrugated than the uncoated FDM surface before the wear test (Figure 6). The circular surface features were consistent with shallow pores formed by trapped air and/or monomer volatilization during ambient curing, but were not measured separately [23]. The plan-view image could be used to determine surface coverage but did not provide any information on coating penetration depth or quantitative interfacial adhesion.

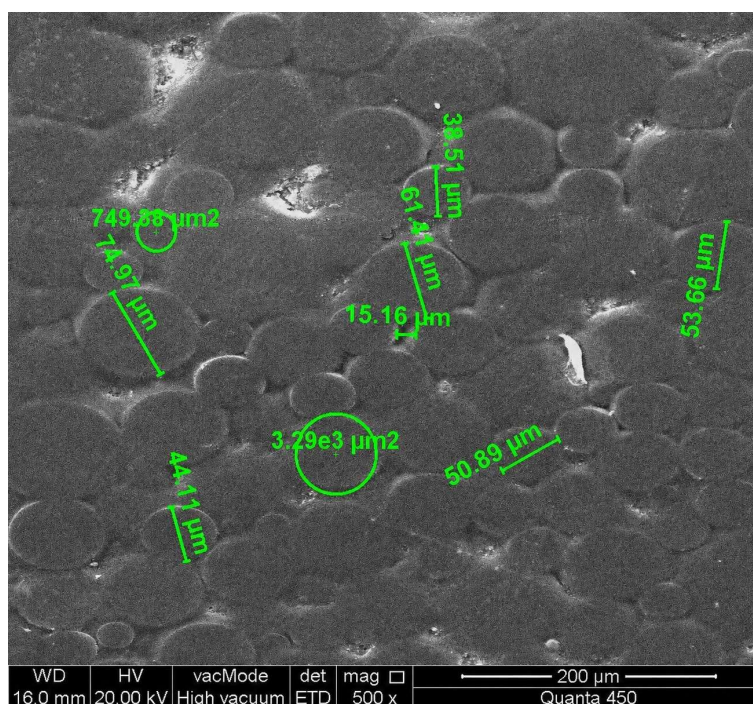


Figure 6. SEM micrograph of PMMA-coated FDM PETG before wear testing, showing a comparatively continuous acrylic surface with distributed shallow circular pores.

3.4.3. Severe degradation and failure morphology (uncoated, post-wear)

The uncoated PETG surface exhibited significant micro-ploughing, flattened layer ridges, and polymer debris (Figure 7) after the 15 min abrasive test. These features were similar to direct contact between the abrasive counterface and the crests of the FDM surface [9,10,42] and to the mean specific wear rate of $27.77 \pm 3.97 \times 10^{-3} \text{ mm}^3 \text{ N}^{-1} \text{ m}^{-1}$.

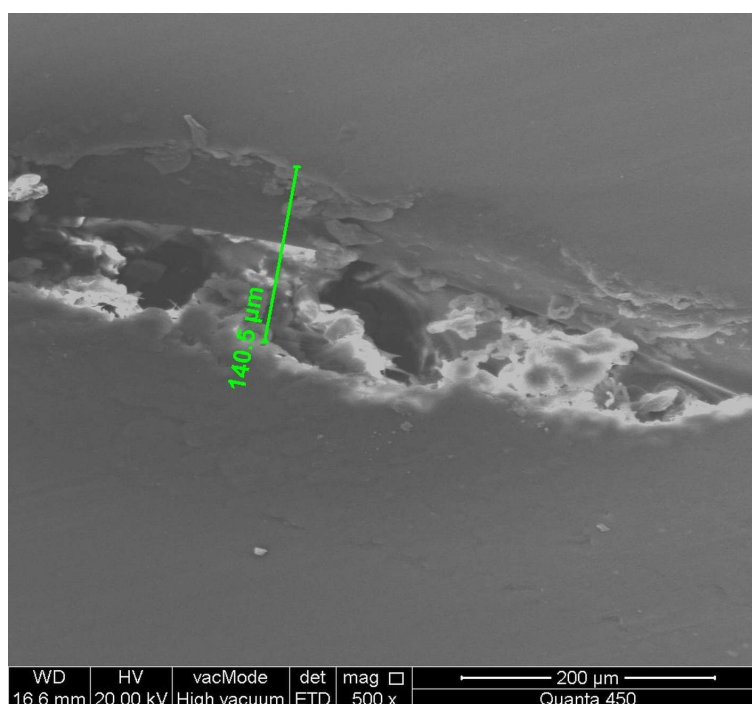


Figure 7. SEM micrograph of the uncoated selected PETG baseline after the 15 min abrasive test, showing micro-ploughing, flattened ridges, and accumulated wear debris.

3.4.4. Coating survival and wear morphology (coated, post-wear)

The same 15 min test on the coated surface revealed a wear track with parallel abrasive striations, plastic deformation in the local regions, and small cracked areas (Figure 8). Within the area of imaging, no large-scale flaking or any exposure of the underlying FDM layer pattern was observed. The measured mean reduction in pin height (1.50 ± 0.10 mm) was greater than the coating thickness (0.5 mm) on the loaded face, however, and the plan-view micrograph could not confirm the survival of the coating over the wear track. It also did not substitute the pull-off, peel, or scratch adhesion measurement [31,32].

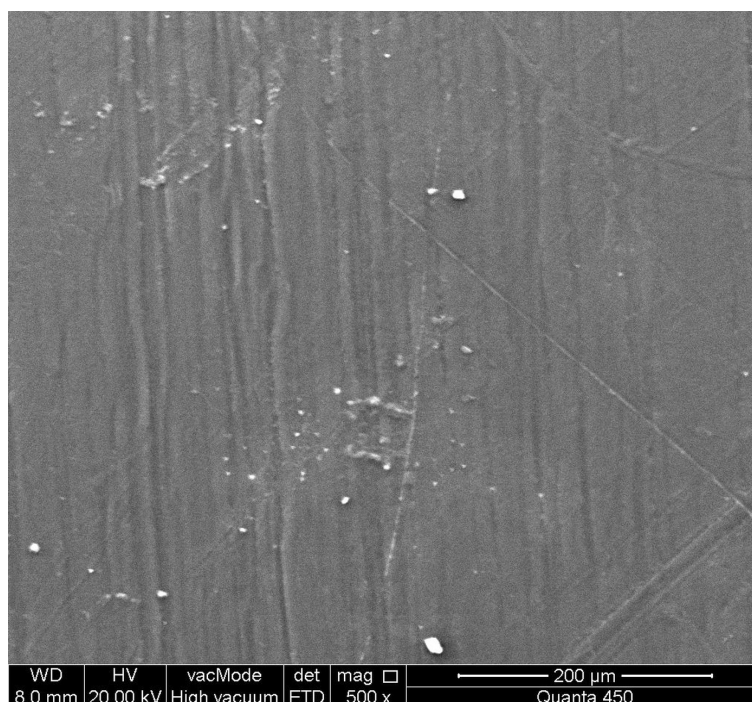


Figure 8. SEM micrograph of PMMA-coated PETG after the 15 min abrasive test, showing parallel wear striations and local surface damage without large-scale delamination in the imaged area.

4. Limitations of the study

The main drawback is that the recovered data consist of factor-level triplicates and not responses associated with a replicated L9 array. Therefore, reported wear S/N values are descriptive isolated-factor summaries only, and no run-level Taguchi response table, ANOVA, percentage contribution or interaction estimate is available. The small replicate count ($n = 3$) also limits precision. The screening elongation-at-break values remain aggregate without the variability of replicates. The normality assumption cannot be tested for three observations per group, and the exploratory Welch tests for the coated-versus-uncoated comparisons are based on this assumption. The only deliberately challenging substrate used for the coating comparison was 100% infill, 300 °C extrusion temperature, 0.15 mm layer thickness, and 250 mm/s print speed. The 300 °C series had the highest mean screening wear index, which could exaggerate the relative coating benefit compared to typical industrial applications. Table 4 and Figure 2 show the instrument-reported strength and modulus values on the common 44.12 mm² substrate reference area. The nominal coated outer area of 58.80 mm² is calculated from the reported total dimensional increase of 1.0 mm (0.5 mm per face) and the outer area is not archived as a specimen-specific coated width or thickness. The apparent-strength and apparent-modulus increases of 23.9% and 51.6% are therefore substrate-referenced system indices, whereas the full-section calculation results in a 6.9% lower calculated tensile strength and 13.8% higher calculated tensile modulus. Furthermore, the length loss of the coated pin (1.50 ± 0.10 mm) is greater than the coating on the loaded face (0.5 mm) and only selected plan-view regions are sampled by SEM. The coating comparison also employed a single PMMA thickness, a single curing schedule, a single load, a single speed, a single test duration, and a single dry 1000-grit counterface, and thus

does not provide a basis for comparison of performance under lubricated contact, long-duration sliding, impact, thermal cycling, ultraviolet exposure, humidity, or chemical aging. Plan-view SEM gives only qualitative surface evidence, and the roughness, porosity, penetration depth, and interfacial adhesion are not quantified. The results should thus be considered as a proof-of-concept comparison and not as a service-life qualification for the tested baseline.

5. Conclusions

The results of this study indicate that the short duration dry abrasive material loss of a structurally selected FDM PETG substrate was reduced under the conditions tested by the mechanically keyed, self-curing dental PMMA layer, with mixed mechanical effects measured.

- The mean maximum load for the coated condition was 1.487 ± 0.027 kN, which was 24.1% higher than the uncoated selected baseline (1.198 ± 0.021 kN; exploratory Welch $p = 0.0002$). On the common 44.12 mm^2 instrument-report basis, apparent tensile strength increased from 27.2 ± 0.8 to 33.7 ± 0.7 MPa (23.9%; exploratory Welch $p = 0.0004$), and apparent tensile modulus increased from 6.20 ± 0.25 to 9.40 ± 0.25 MPa (51.6%; $p < 0.0001$). On the condition-specific outer-section basis, load-derived strength changed from 27.15 ± 0.48 to 25.29 ± 0.46 MPa (6.9% lower), while modulus changed from 6.20 ± 0.25 to 7.05 ± 0.19 MPa (13.8% higher). Rockwell R hardness increased from 60.0 ± 0.8 to 86.5 ± 0.7 HRR (44.2%; mean difference 26.50 HRR, 95% CI 24.78–28.22 HRR; exploratory Welch $p < 0.001$). Mean mass loss decreased from 0.140 ± 0.020 to 0.070 ± 0.010 g (50.0%; exploratory Welch $p = 0.013$). On the common PETG-density basis, the apparent wear index decreased from $(27.77 \pm 3.97) \times 10^{-3}$ to $(13.88 \pm 1.98) \times 10^{-3} \text{ mm}^3 \text{ N}^{-1} \text{ m}^{-1}$. Static COF decreased from 0.1643 ± 0.0005 to 0.1611 ± 0.0005 (2.0%; exploratory Welch $p = 0.0018$). The small absolute COF difference suggests that the main tribological improvement measured was reduced material loss.

- The 50.0% mass-loss reduction was observed in the structurally dense 300 °C substrate, which had the highest mean wear index in the temperature screening, so the results should not be extrapolated to typical or lower-wear PETG settings.

- The SEM images were consistent with the PMMA layer covering the corrugated FDM surface; no large-scale delamination was observed in the areas of the post-wear images.

- In future work, researchers should include and store a replicated L9 or larger confirmation experiment with run identifiers and simultaneous factor combinations with specimen-specific initial and final wear measurements for each test. To convert coated mass loss to true volume loss, it is also necessary to measure the wear using a phase-resolved method or to determine the composition-specific density. The next step should be to use an L27, factorial, or response-surface design to estimate parameter interactions and to obtain an independent residual-error term. Coated and uncoated specimens should be compared under representative, structurally selected, and wear-optimal print settings. The coating thickness, surface roughness, porosity, and adhesion should also be measured and then long-term wear tests conducted under various loads, speeds, counterfaces, temperatures, humidity, and lubricated conditions.

- With this validation, the coating may be used in low-to-moderate-load guides, jigs, fixtures, sacrificial wear pads, and other replaceable sliding surfaces where low-cost manufacture by FDM and enhanced abrasion resistance is desired. The present data are insufficient to recommend gears, bearings, safety-critical parts, or continuous high-load service.

The results of this study show that surface hardness increased and abrasive material loss decreased for FDM-fabricated PETG parts with PMMA dental acrylic coatings, although the measured mechanical effects were mixed. The coating system showed no large-scale delamination in the imaged regions and reduced the susceptibility of the printed-layer morphology to abrasive degradation under severe dry-sliding conditions. As such, the proposed coating strategy is a practical and low-cost post-processing technique for enhancing the industrial applicability of FDM PETG components for low-to-moderate-load and non-safety-critical sliding-contact applications, although further long-term validation is needed.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Author contributions

All authors were involved in the study conception and design. The material preparation, data collection and data analysis were carried out by Mahmood M. Mustafa, Haitham M. Wadullah and Omar D. Mohammed. The first draft of the manuscript was written by Mahmood M. Mustafa and all the authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Conflict of interest

The authors declare no conflict of interest.

Data transparency

The authors confirm that all data, materials and measurement parameters support the published claims and meet the requirements of the discipline. The data sets obtained and analyzed in the present study will be made available by the corresponding author upon reasonable request.

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