THE JOURNAL OF PROSTHETIC DENTISTRY

RESEARCH AND EDUCATION

Investigating the influence of infill pattern and layer height on the mechanical and bonding behavior of additively manufactured PEEK for dental applications

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ABSTRACT

Statement of problem. Current knowledge regarding the influence of infill pattern and layer height on the flexural and shear bond strength of polyetheretherketone (PEEK) manufactured via fused filament fabrication technology remains limited.

Purpose. The purpose of this in vitro study was to investigate the impact of infill pattern and layer height on the shear bond strength (SBS) and the flexural strength (FS) of additively manufactured PEEK bars and disks relevant to dental applications.

Material and methods. The PEEK specimens were prepared in 9 groups (n=10), whereby different layer heights (0.1, 0.2, and 0.3 mm) and different infill patterns (±30, ±45 lines, concentric) were used. The surface roughness (Ra) was recorded with a confocal microscope. For the SBS test, resin composites were applied on the disk surface. All the specimens were subjected to thermal aging. The SBS and FS test was performed through a universal testing device. Two-way ANOVA, 1-way ANOVA, post hoc Tukey, and Tamhane tests were used for statistical analysis. (α=.05)

Results. The highest SBS values were observed at a layer height of 0.1 mm. The infill pattern had a significant effect on FS at all layer heights (0.1 mm *P*=.016, 0.2 mm *P*=.010, 0.3 mm *P*=.010). While the highest FS values at a 0.1-mm layer height were observed in the concentric pattern, no significant difference was identified between the L45 and L30 groups (*P*=.186).

Conclusions. Lower layer heights strongly influenced the Ra, SBS and FS, with the highest SBS achieved with a layer height of 0.1 mm. To improve the mechanical properties of PEEK, the process parameters for additive manufacturing should be optimized. (J Prosthet Dent 2025;134:237.e1-e8)

Polyetheretherketone (PEEK), a polyaryletherketone (PAEK), is a promising dental material.[1,2] In addition to being easily modified by adding different materials, it offers different advantages with its low elastic modulus and low hardness and its wear resistance comparable with that of metal alloys.[2–5] Because of PEEK's dentin-like elastic modulus, it can be used as a framework, abutment, or restoration material.[6–9] In dentistry, PEEK is typically processed by pressing granules into blocks, which are then milled into shapes using computer-aided design and computer-aided manufacturing (CAD-CAM) systems.[10] Alternatively, PEEK can be processed directly from granules or pellets using a vacuum-pressing device.[11,12] Moreover, developments in additive manufacturing (AM) technologies have enabled more precise and complex designs to be produced using PEEK.[8,12]

Additive manufacturing offers an alternative to subtractive manufacturing and has been frequently preferred.[13] AM, which has different advantages such as flexibility in design, less waste material, and the ability to easily produce complex geometries, is basically the assembly of the 3-dimensional (3D) object layer by layer.[13–15] The high degree of design freedom allows for custom products, which makes it particularly interesting for the medical field, where every patient is different. In addition to offering practical

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Clinical Implications

The results of this study highlighted the potential for optimizing the additive manufacturing process parameters of PEEK, particularly in terms of layer height and infill pattern, to improve its mechanical performance in dental applications. By improving SBS and FS, additively manufactured PEEK can be a more durable and reliable option.

solutions in the medical and dental fields, AM has been preferred in the preparation of individual prostheses and the treatment of advanced defects.[16]

Additive manufacturing techniques used in dentistry include stereolithography (SLA), selective laser sintering, (SLS), selective laser melting (SLM), digital light processing (DLP), and fused filament fabrication (FFF).[17–19] However, compared with powder and resin-based processes, FFF, which uses PEEK filaments, poses fewer biocompatibility concerns, making it a highly suitable technology.[20] The use of solid filaments makes it a user-friendly and cost-effective method compared with other methods.[21–23] The solid filament is heated until it reaches a flowable consistency, and, after extrusion, it solidifies. The print head follows a predefined path, forming the object layer by layer according to the design file.[15,24–26]

Each of these technologies has been optimized with different parameters.[27] For the FFF-method, factors such as extrusion temperature, raster width, raster orientation, nozzle diameter, print speed, infill pattern, and layer height have been reported to affect the mechanical properties of the printed part, including tensile, compressive, and flexural strength.[28–33] Hence, selecting optimal parameters is of great importance to provide the best clinical performance. In previous studies, relevant parameters, especially nozzle diameter, raster angle, infill density, print orientation, have been examined, and these parameters strongly influence the properties of the printed object.[34–39] Previous studies have indicated that 3D printed PEEK has potential applications in various fields, including inlays, implant abutments, and orthodontic retainers.[17,40–44] However, the studies have primarily focused on the areas of use, and the optimal production parameters remain unclear. Moreover, knowledge of the effect of infill pattern and layer height on the flexural and shear bond strength of PEEK manufactured via FFF material is still limited, especially for small part sizes such as those commonly required for dental restorations. The aim of this study was to evaluate the properties of small FFF PEEK parts (disks and bars) produced with different layer heights and infill patterns. The null hypotheses were that layer height and infill pattern would not have a significant effect on the surface roughness, shear bond strength or flexural strength of small PEEK parts processed by FFF.

MATERIAL AND METHODS

In this study, a Ø1.75-mm PEEK filament (VESTAKEEP i4 3DF-T; Evonik Industries, AG) was used. The test specimens were designed with a computer-aided design software program (Autodesk Fusion 360; Autodesk) and converted into a standard tessellation language (STL) file. The STL file was imported into a slicing software program (UltiMaker Cura 5.2.1; UltiMaker) for parameter assignment and G-code generation. The printing process was carried out on a 3D printer (M150 Medical 3D Printer; Orion Additive Manufacturing GmbH). Bar-shaped specimens (Fig. 1A) were used to evaluate the flexural strength (FS), and Ø10×2-mm disk-shaped specimens (Fig. 1B) were used for the shear bond strength (SBS) tests. The specimens were prepared in 9 groups (n=10), whereby 3 different layer heights (0.1, 0.2, and 0.3 mm) and 3 different infill patterns (±30 and ±45 lines as well as concentric) were used. A total of 180 specimens were prepared, 90 specimens for each test method (SBS, FS). The designation of the specimen groups is given in Table 1.

The printing temperature was 410 °C, the build plate temperature was 250 °C, the build volume temperature was 200 °C, the layer heater was 280 °C, the infill density was 100%, and the print speed was 6 mm/second. Two perimeters were printed, and a raft was used to enhance the adhesion to the build platform. The printer was equipped with a Ø4-mm brass nozzle. Prior to printing, the filament was dried in an oven (Vötschtechnik VCL 4003 Temperature and Climatic Test Chamber; Vötsch Industrietechnik GmbH) at 90 °C for 15 hours and stored in a sealed box with silica gel beads to prevent moisture uptake during the printing process. Each specimen was printed individually. After printing, the raft was manually removed. Subsequently, the disk-shaped specimens were finished with P600 and P800 silicon carbide papers (Struers GmbH) under constant water for 5 minutes and then cleaned in distilled water ultrasonically (M+W Select Dentasonic; M+W Dental Müller Weygandt GmbH).

The surface roughness of the specimens was recorded with a confocal microscope (Alicona Infinite Focus; Alicona Imaging GmbH) using the following settings (vertical resolution= 410 nm, cut-off wavelength value= 800 μm). A total of 5 specimens were selected from each group, and measurements were repeated on each specimen 3 times. For the SBS test, Visio. Link Primer (Visio. Link Primer; bredent GmbH Co KG) was applied to the disks,[45,46] and a light-emitting diode

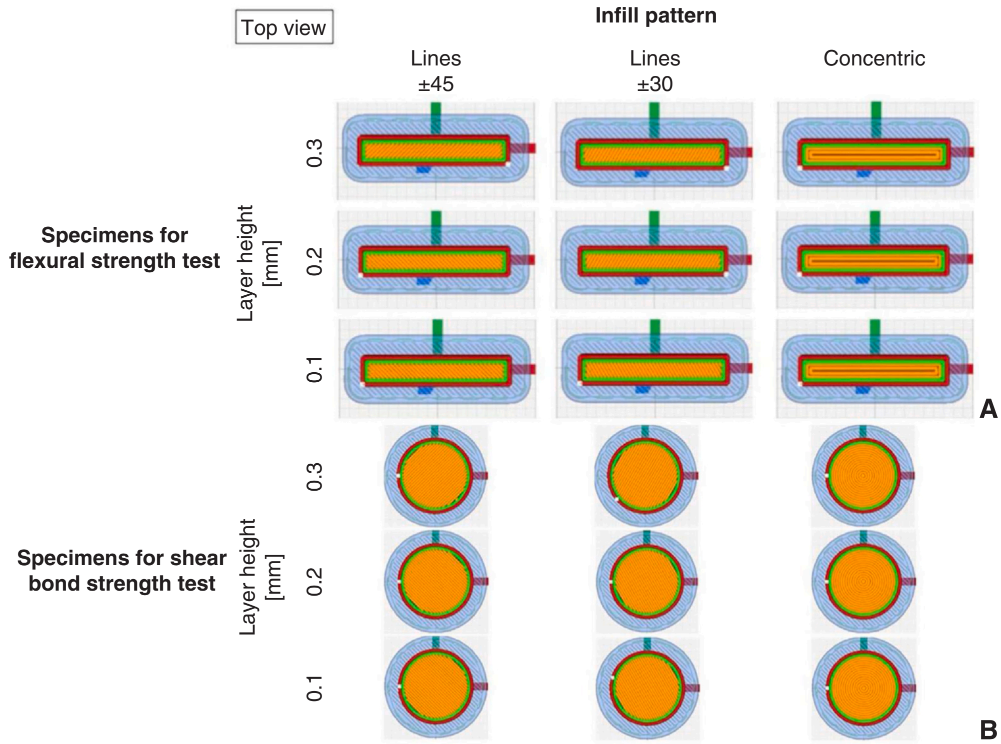

Figure 1. Schematic views. A, Nine groups of bar-shaped specimens to evaluate flexural strength. B, Nine groups of disk specimens to evaluate shear bond strength.

Table 1. Specimen designations for nine different groups and printing parameters

Designation	Infill Pattern	Layer Height (mm)
L45–0.3	±45 lines	0.3
L45–0.2		0.2
L45–0.1		0.1
L30–0.3	±30 lines	0.3
L30–0.2		0.2
L30–0.1		0.1
C–0.3	concentric	0.3
C–0.2		0.2
C–0.1		0.1

polymerization unit (Bluephase; Ivoclar AG) at 1200 mW/cm was used for 90 seconds. A special plate produced for the standard application of resin composites was used on the disk surface. After the resin composites had been applied with this plate, they were polymerized in the same unit for 30 seconds. The plate was then removed, and the polymerization step was repeated for each specimen.

Disk and bar-shaped specimens were thermally aged for 10 000 cycles between 5 and 55 °C with a dwell time of 30 seconds. Then, the acrylic resin was poured into the plastic mold, and the PEEK disks were embedded. The SBS test was performed with a universal testing device (MIC-101; MOD-Dental) at a crosshead speed of 1 mm/minute. The SBS was calculated with formula: $SBS = \frac{F}{A}$, where SBS is the shear bond strength (MPa), F is the fracture load (N), and A is the bond area (mm^2).[8]

Bar-shaped specimens were used to evaluate the FS. The tests were performed on a universal testing device (Lloyd LRX; Lloyd Instruments Ltd) according to the International Organization for Standardization (ISO) 10477 standard.[47] The flexural strength was calculated with the formula: $FS = \frac{3FL}{2bd^2}$, where FS is the flexural strength (MPa), F is the maximum force (N), L is the distance (mm) between supports, b is the specimen's width (mm) and d the specimen's height (mm).[48] Following the SBS test, the failure modes were categorized with a digital microscope (Keyence VHX 500; Keyence Co). The failure modes were classified as adhesive failure, cohesive failure, or mixed failure.[49]

The Shapiro-Wilk was used to assess the normality of data with a statistical software program (IBM SPSS Statistics, v25.0; IBM Corp). The effects of layer height and infill pattern on surface roughness, shear bond strength, and flexural strength were analyzed using 2-way ANOVA. The 1-way ANOVA test was used to assess the interaction between the 2 main factors in the SBS results. Following the results of the Levene test, the post hoc Tukey HSD test was used for homogeneous variances (Ra, FS). For groups with nonhomogeneous variances (SBS), the Tamhane T2 test was applied (α=.05).

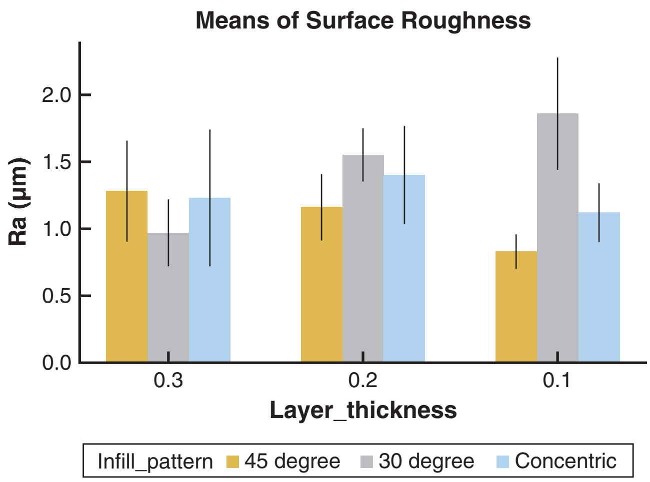

Figure 2. Bar graph of Ra values.

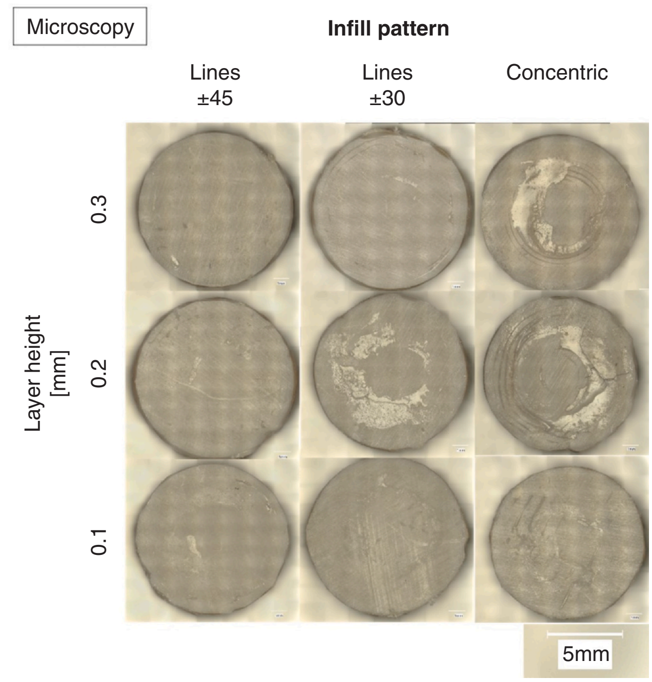

Figure 3. Microscope images (original magnification ×100) of representative disk specimens after shear bond testing.

RESULTS

Figure 2 presents the mean Ra values for the different layer heights and infill patterns. According to the 2-way ANOVA, different infill patterns did not significantly affect the Ra values of the FFF PEEK specimens (df=2, F=1.441, *P*=.250). However, layer height (df=2, F=4.513, *P*=.018) and their interactions (df=4, F=5.453, *P*=.002) were found to have significant effects on Ra. The lowest Ra was observed at the 0.3-mm layer height, while the highest Ra value was at the 0.2-mm layer height.

Table 2 shows the descriptive statistics of the SBS of each group. The 2-way ANOVA revealed that the infill pattern had no significant effect on SBS (df=2, F=0.656, *P*=.522, ηp^2=0.016). However, layer height significantly affected SBS (df=2, F=5.076, *P*=.008, ηp^2=0.111), and a significant interaction effect between infill pattern and layer height was observed (df=4, F=5.434, *P*<.001, ηp^2=0.212). For interaction post hoc comparisons, the Tukey HSD test indicated that the SBS of the 0.1-mm layer height was significantly higher than the 0.2-mm layer height (*P*=.003) and 0.3 mm (*P*=.024) The SBS values for a layer height of 0.3 mm were similar to those observed for layer heights of 0.2 mm (*P*=.449) The failure type in all groups was adhesive after the SBS test (Fig. 3).

Table 3 lists the descriptive statistics of the FS of each group. According to the 2-way ANOVA, while infill pattern (df=2, F=34.249, *P*<.001, ηp^2=0.489) and layer height (df=2, F=38.704, *P*<.001, ηp^2=0.458) had a significant effect on FS, their interaction had no significant effect (df=4, F=2.182, *P*=.078, ηp^2=0.097). A layer height of 0.1 mm yielded significantly higher flexural strength compared with both 0.3-mm and 0.2-mm layer heights (*P*<.001). According to the infill patterns, the highest FS was in the concentric group (*P*<.001), followed by L30. The lowest FS was in the L45 group (*P*=.002).

Table 2. Mean ±standard deviation for shear bond strength of PEEK disks manufactured via FFF

SBS		Infill Pattern			
		±45 Lines (n=10)	±30 Lines (n=10)	Concentric (n=10)	Total (N=30)
Layer height [mm]	0.3 (n=10)	21.77 ±6.64^{A} (17.01–26.52)	31.55 ±6.80^{ABC} (26.67–36.42)	37.85 ±25.17^{ABC} (19.84–55.85)	27.29 ±8.51$^{\wedge}$ (23.27–31.30)
	0.2 (n=10)	25.16 ±4.61^{ABC} (20.75–29.56)	22.06 ±8.30^{ABC} (16.12–27.99)	39.00 ±11.81^{BC} (30.54–47.45)	25.11 ±8.71$^{\#}$ (21.10–29.13)
	0.1 (n=10)	34.93 ±6.87^{C} (30.01–39.84)	21.73 ±7.74^{AB} (16.19–27.26)	24.70 ±4.77^{AB} (21.28–28.11)	33.85 ±17.05$^{\#}$ (29.83–37.87)
	Total (N=30)	30.39 ±16.43 (26.37–34.41)	28.74 ±11.51 (24.72–32.76)	27.12 ±8.57 (23.10–31.14)	

FFF, fused filament fabrication; PEEK, polyetheretherketone.

Different superscript uppercase letters indicate significant differences. Different superscript symbols indicate significant differences within pooled data of layer height or infill pattern. (*P*<.05)

Table 3. Mean ±standard deviation, 95% confidence interval lower and upper bound values for flexural strength of PEEK bars manufactured via FFF

FS		Infill Pattern			
		±45 Lines (n=10)	±30 Lines (n=10)	Concentric (n=10)	Total (N=30)
Layer height [mm]	0.3 (n=10)	142.97 ±15.58 (131.82–154.11)	183.34 ±4.616 (180.04–186.64)	204.97 ±27.84 (185.05–224.9)	177.09 ±31.71^ (169.30–184.89)
	0.2 (n=10)	160.87 ±9.37 (154.16–167.57)	162.01 ±10.9 (154.21–169.80)	200.1 ±18.63 (186.77–213.43)	174.32 ±22.71^ (166.53–182.12)
	0.1 (n=10)	194.78 ±16.93 (182.67–206.89)	212.33 ±22.58 (196.18–228.49)	238.94 ±41.89 (208.97–268.91)	215.35 ±33.66# (207.56–223.15)
	Total (N=30)	166.20 ±25.87^ (158.41–174.00)	185.90 ±25.33# (178.10–193.69)	214.67 ±34.67* (206.88–222.47)	

FFF, fused filament fabrication; PEEK, polyetheretherketone.
Different superscript symbols indicate significant differences within pooled data of layer height or infill pattern. (P<.05)

DISCUSSION

The present study examined the influence of infill pattern and layer height on the Ra, SBS, and FS of additively manufactured PEEK bars and disks, with dimensions suitable for dental applications. The study results indicated that infill patterns did not significantly affect Ra or SBS values (P>.05) but did have a significant impact on FS values (P<.05). Consequently, the null hypothesis that layer height and infill pattern would not have a significant effect on the surface roughness, shear bond, or flexural strength of small PEEK parts processed by FFF was partially rejected, as variations in layer height significantly affected Ra, SBS, and FS (P<.05).

An analysis of the Ra values indicated that the layer height exerted a pronounced influence on surface roughness, consistent with previous studies.[7,50] A recent study evaluated FFF PEEK specimens and reported that a layer height of 0.3 mm resulted in greater surface roughness than a height of 0.1 mm[7]. In another study,[23] the surface roughness observed in filament-based production was attributed to gaps between layers. Consequently, they proposed that, as the layering height decreases, the surface roughness will also decrease. However, these results may vary depending on the specific printing parameters, filament content, and test conditions used. In previous studies evaluating PEEK material, different Ra values were presented when using abrasive papers with different grit sizes.[4,7,45] Furthermore, the results of this study indicate that Ra values were found to be higher than 0.2 µm in all groups, which is the clinically acceptable threshold for decreasing bacterial accumulation,[51] regardless of the layering height and infill pattern. Therefore, additional polishing should be recommended for 3D printed PEEK surfaces in direct intraoral contact.

In the present study, layer height was found to affect SBS. A similar study[23] reported that stratification occurred between the layers in specimens with a layer height of 0.4 mm. In specimens with layer height greater than 0.35 mm, interlayers significantly negatively influenced the compression and adhesion strength. It has been suggested that when the layer height exceeds half the nozzle diameter, the surface quality in the vertical direction deteriorates significantly.[23,39] Moreover, optimum surface quality has been reported when the layer height is equal to half the nozzle diameter.[23,27] In the present study, the highest SBS values were observed in specimens with a 0.2-mm layer height and a concentric infill pattern, although 0.1-mm specimens exhibited statistically similar results. Considering that the nozzle diameter used in this study was 0.4 mm, the higher SBS values observed at 0.2 mm and below supported this finding.

The SBS values in the present study were higher than the 5-MPa minimum specified in the ISO 10477:2020 standard in all test groups.[3] The clinically acceptable SBS value was reported as 10 MPa,[1,10] and all groups exhibited higher SBS values, regardless of layer height and infill pattern. Therefore, PEEK processed by FFF appears to be an appropriate material for prosthetic use, given its satisfactory bond strength. A recent study indicated that milled PEEK specimens tested with a bonding protocol comparable with that used in the present study, exhibited an SBS value exceeding both ISO standards and clinical reliability values. However, the mode of separation seen in all specimens tested was determined to be adhesive failure, as reported in previous studies (Fig. 4).[1,45]

The FS of the groups with a layer height of 0.1 mm was higher than of the groups with a layer height of 0.2 mm and 0.3 mm. Enhanced strength in thinner layers can be attributed to the increased compression and cross-flow of deposited filaments associated with reduced layer height.[30–32] Moreover, the geometry of the printed part plays a crucial role, as the heated nozzle interacts with more underlying strands at lower layer heights, sustaining elevated temperatures for an extended duration and inducing an annealing effect.[30] A recent study evaluated the impact of different layer heights (0.1, 0.2, 0.3 mm) on FS,[18] reporting that, although the average FS values were lower (102.63 MPa) than in the present study, the highest FS values were observed at a layer height of 0.1 mm, consistent with the findings of the present study. The discrepancy in the FS values between the 2 studies can be attributed to the

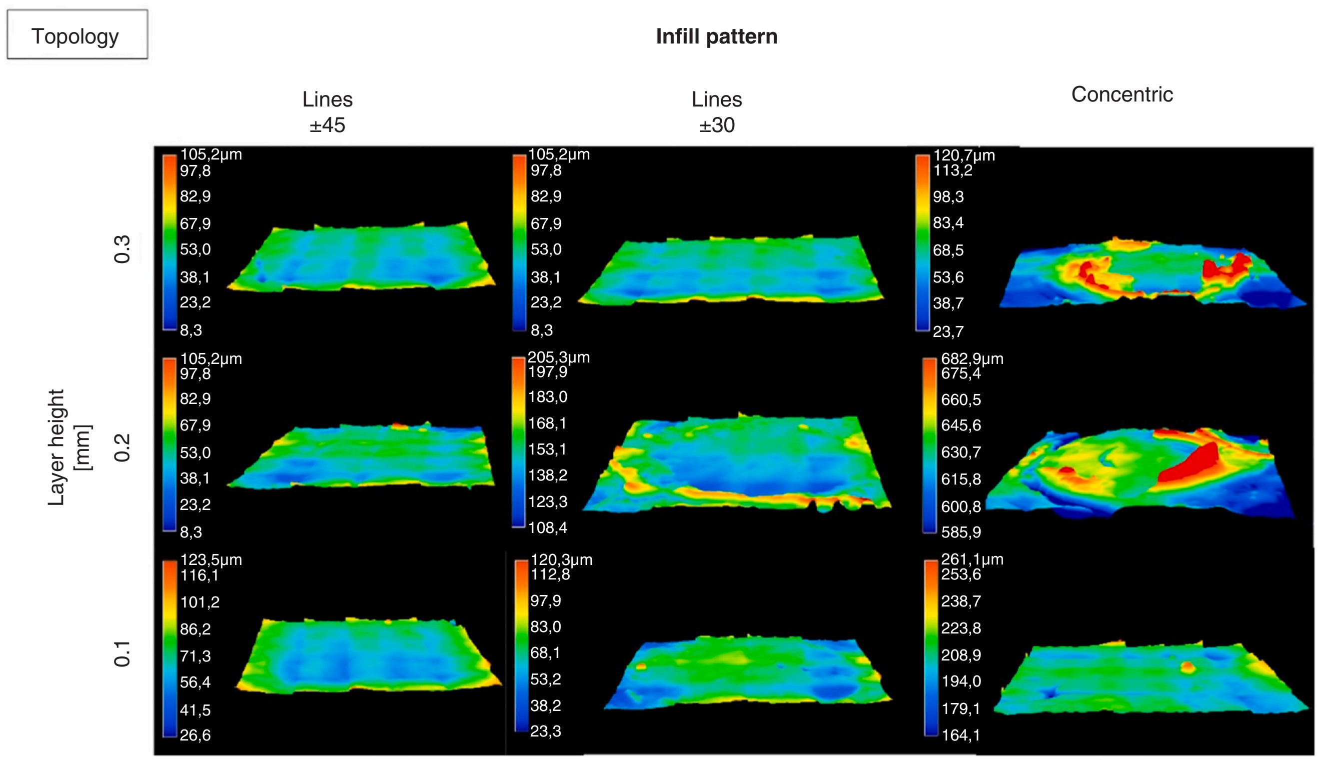

Figure 4. Topology of representative disk specimens after shear bond testing.

differences in the filament type, 3D printer, and test conditions. Rinaldi et al[25] investigated the impact of infill pattern on mechanical properties, reporting that the concentric infill pattern exhibited better bend strength than other patterns. Their finding was consistent with the results of the present study, which found that specimens with the concentric infill pattern exhibited the highest FS values.

The inherent characteristics of FFF technology make the manufactured AM parts anisotropic, meaning that parts are constructed directionally. Consequently, this results in orientation-dependent mechanical performance within the component. Typically, the strength of a part is at its peak when the load is applied in the direction of the filament, resembling a bulk volume structure. However, as the raster angle increases, the performance of the component relies more heavily on the interlayer weld strength between adjacent layers.[19,33,52]

Rahman et al[48] investigated various raster angles (0-, 90-, and alternating 0- and 90-degrees) and their subsequent effects on tensile, compressive, and bend strengths. They reported that tensile specimens printed at 0 degrees exhibited higher stiffness and strength compared with 90-degree and alternating 0- and 90-degree prints. In bending, alternating 0 and 90 degrees exhibited the highest stiffness. Nevertheless, 0-degree prints exhibited higher strength levels compared with 90-degree and alternating 0- and 90-degree specimens. Wu et al[34] examined the effect of layer height (0.2, 0.3, and 0.4 mm) and raster angle (alternating 0 and 90 degrees, alternating 30 and 60 degrees, alternating 45 and 45 degrees) on the mechanical properties of PEEK, reporting that specimens produced with a 0.3-mm layer height and alternating 0- and 90-degree raster angles had the highest strength in all mechanical tests. However, the effect of layer height on bending and compressive strengths was minimal.

Although infill patterns have been reported to significantly influence the mechanical properties of materials,[53] the present study found no effect on SBS (P>.05). However, infill patterns did have a significant impact on FS (P<.05). Previous studies have also reported that the infill pattern affected FS.[19,22,52,53] In a similar study,[26] specimens with concentric and 45-degree linear infill patterns were compared, and the flexural strength of concentric specimens was reported to be higher, similar to the present study. In the present study, the mechanical properties of the material were influenced by changing the printing pattern. Specimens with concentric infill pattern and a 0.1-mm layer height had higher flexural strength than the other groups.

Bonding PEEK to composite resin is problematic because of the low surface energy of PEEK[12] and its resistance to surface modification by chemical treatments.[8] Therefore, previous studies[1,4] have evaluated the effects of different bonding agents, as well as airborne particle abrasion with alumina. The Visio.link material containing pentaerythritol triacrylate (PETIA) and methyl methacrylate (MMA) has been reported to increase bond strength.[49]

The PEEK surface, once dissolved with PETIA, has been reported to swell with MMA monomers, thereby increasing the bond strength by forming active reaction surfaces.[46] A recent study[1] reported that airborne particle abrasion with 110-µm alumina and MMA-containing adhesive to the milled PEEK surface resulted in an increase in SBS. As evidence for increasing the bond strength of additively manufacturing PEEK material is lacking, Visio.link was used in this study, as used previously.[8]

Limitations of the study included the evaluation of solely unreinforced PEEK, limited exploration of surface treatments, and constraints on nozzle diameter variation. PEEK material used in subtractive manufacturing has been reinforced with ceramics to improve esthetic and mechanical properties.[9] However, filaments used in additive manufacturing are often unfilled. In the future, the production of ceramic-filled 3D printed materials may improve the mechanical properties of additively manufactured PEEK. In this study, no surface treatment other than abrasive paper was applied. In addition, the surface of the specimens was treated with the Visio.link primer,[54] which has been reported to significantly affect the bond strength.[41] However, as various postprocessing techniques (thermal annealing or chemical treatments such as solvent vapor annealing) could further enhance the properties of additively manufacturing PEEK,[52] different surface treatments should be evaluated in future studies. Another constraint of this study was the single nozzle size. Given that the Ø0.4-mm nozzle may be relatively large for the specimen size, using smaller diameter nozzles could enhance the mechanical properties of the printed material.

CONCLUSIONS

Based on the findings of this in vitro study, the following conclusions were drawn:

1. Different infill patterns did not significantly affect the Ra or the SBS values of FFF PEEK but did affect the FS.
2. Regardless of infill pattern and layer height, all groups exhibited higher SBS values than the clinically acceptable threshold (10 MPa).
3. Regardless of infill pattern and layer height, adhesive failure was observed in all specimens.
4. Lower layer heights significantly improved Ra, SBS and FS, with the best SBS achieved with a layer height of 0.2 mm and a concentric filling pattern.

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Acknowledgments
The authors thank Evonik Industries for providing materials used in the study. The authors also thank Orion Additive Manufacturing GmbH for providing a printer. Mustafa Yeşil is acknowledged for his contribution to the testing process of the specimens. This study was funded by the Biruni University Scientific Research Projects Unit (Grant No: 2022-01-05/ 02-2023-01-14).

https://doi.org/10.1016/j.prosdent.2025.03.010