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THE EFFECT OF THE PROCESS PARAMETERS AND LIGHT CURING PROCESS ON THE DIMENSIONAL ACCURACY OF THE 3D-PRINTED HOLES

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Abstract: *The paper presents an investigation on the influence of the parameter settings and 405 nm wavelength light curing on the dimensional accuracy of 3D-printed holes included in prints manufactured by the material extrusion process (MEX). The hole feature is typically used to enable the assembly of 3D-printed parts by means of fasteners. As the bolt-hole clearance affects the quality and stiffness of the assembly, it becomes relevant to understand how to tune different 3D printing process parameters for achieving an actual clearance as close as possible to the nominal one. It is also relevant to understand how this is affected by different work conditions, such as violet-blue light exposure which is used for its antimicrobial properties. Different values of three parameters (printing speed, layer thickness, number of perimeters) were set for manufacturing test parts that were then subjected to 48 hours light curing. All prints were made of polylactic acid and 3D printed on a Prusa Replica 3D printer. The combined effect of the parameter settings and light treatment was also analyzed. The results showed a decrease in the holes' diameters regardless of the printing settings, the shrinkage being more significant for the holes with the smallest diameter (6 mm). Regarding the dimensional accuracy, layer thickness was the most influential printing parameter. However, a trade-off between printing time and cost, and dimensional accuracy should be considered by the designers.*

Keywords: *3D printing, holes, process parameters, dimensional accuracy, 405 nm light curing.*

1. INTRODUCTION

Additive manufacturing (AM), also known as 3D Printing, is an alternative to the conventional technologies for the prototypes' fabrication and mass customization production [1, 2]. It can efficiently and cost-effectively produce objects directly from 3D digital models by superposing layers of materials [3]. AM based applications cover a plethora of domains such as surgery, robotics, electronics, automotive or aerospace [4]. For all these fields and many others, satisfying the requirements of dimensional accuracy and repeatability is very important for the AM parts. The current research is focused on investigating the dimensional accuracy aspect in different 3D printing and post-processing conditions.

There are seven standardized AM processes [5] among which material extrusion (MEX) is reported as the most commonly used one due to equipment and feedstock availability and affordability [6]. Many parameters characterize the MEX process, their combination influencing the mechanical performances, printing time and cost, accuracy, moisture absorption, etc. in various work environments [7–9]. The study of the dimensional accuracy is relevant as the current trend is to produce functional parts and assemblies, in this regard 3D-printed holes features being typical for applications in which assemblies are built. Since the bolt-hole clearance is influencing the assemblies' quality and stiffness, it is important to know how to set various process variables in order to achieve an actual clearance as close as possible to the nominal one.

The dependence between the dimensional accuracy and the process parameters is well known. There are studies analyzing the 3D-printed through holes and staircase effect [3], the impact of certain specific parameters (extrusion temperature, bed temperature, layer thickness, flow rate) [11–14], and the effect of the slicer used to create the STL file [15]. In comparison to the previous studies, this research analyzes the influence of three 3DP process parameters (printing speed, layer thickness and number of perimeters) and 405 nm light curing process on the dimensional accuracy of 3D-printed holes with diameters of 6 mm, 8 mm and 10 mm. The following research questions were asked: What is the effect of the process parameters on the dimensional accuracy of directly 3D-printed holes? Is the effect of 405 nm light curing dependent on the parameter settings when it comes to the holes' dimensional accuracy?

The literature review related to light curing of 3D prints revealed studies on UV curing of dental models 3D printed from a special resin. It was observed that the dimensional accuracy decreased with UV exposure time. However the variation was smaller than for the conventional plaster cast models [16]. In the same field, Shin et al. observed that as the UV post-curing time increased, the dimensional stability increased significantly [17]. The reaction of the most commonly used polymers PLA (pol-

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ylactic acid) and PETG (polyethylene terephthalate, glycol-modified) to sterilizing UV-C radiation was also studied. The results indicated that prolonged exposure to radiation weakens the mechanical properties (particularly for the PETG parts) and accentuates the negative effects of creep [18]. The mechanical strength of the same materials decreased slightly for PLA samples, and significantly for PETG after 24 hours of UV-B irradiation. Contrarily, the UV-B radiation had almost no effect on the specimens' stiffness [19]. The tensile strength of PLA and wood flour blends decreased after subjecting the samples to UV, the chromatic degradation of this composition dramatically changing, and the water absorption rate increased [20].

405 nm light curing is used for its antimicrobial properties [21], in certain application being proved to be a safer alternative to UV-C sterilization for some types of medical devices [22]. The 3D-printed medical devices that include holes might be affected by the light curing process, therefore the rationale of this paper. Moreover, the combined effect of process parameter settings and light curing on the holes dimensional accuracy was studied for gaining useful insides for engineers when prescribing holes' tolerances and establishing the parameter settings.

2. MATERIALS AND METHODS

The following steps describe the methodology applied in this research:

- Design test part with holes of three different diameters;
- 3D print the test parts in a full factorial experiment by considering the three above mentioned parameters with two, respectively three levels each;
- Measure the diameters of the holes;
- Subject the test parts to 405 nm light;
- Measure the cured test parts;
- Compare and discuss the results.

2.1. Design and 3D printing the test parts

A test part with fifteen counterbore holes (Fig. 1) was designed so that to accommodate three different diameters. The part was 70 mm in diameter and included straight (vertical axes) counterbore holes with diameters of 6 mm, 8 mm, and 10 mm (ten of each) in various combinations.

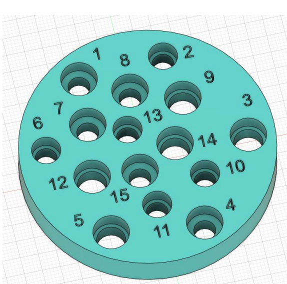


Fig. 1. 3D model of the test part.

Fig. 2. Specimen with counterbore vertical axes holes (specimen 9).

Table 1

Variable process parameters

Item	Variable process parameters		
	No. of perimeters	Layer thickness (mm)	Print speed (mm/s)
1	2	0.2	30
2	2	0.2	50
3	2	0.2	6
4	3	0.2	30
5	3	0.2	50
6	3	0.2	65
7	2	0.32	30
8	2	0.32	50
9	2	0.32	65
10	3	0.32	30
11	3	0.32	50
12	3	0.32	65

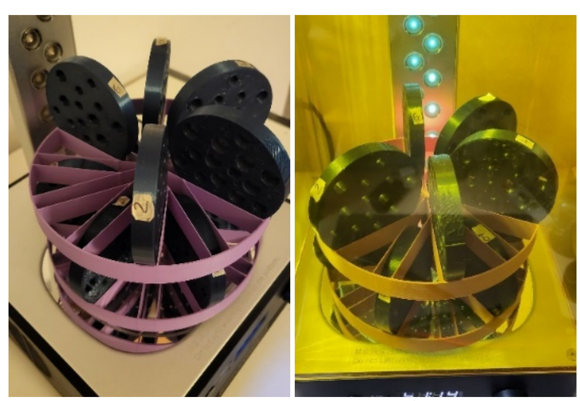
Twelve specimens were manufactured using Prusa 3D printer and Prusa Slicer, from 1.75 mm diameter filament Navy Blue PLA (Devil Design Sp. J., PL) (Fig. 2). After 3D printing the specimens with various combinations of variable parameters (Table 1), the diameter of each hole was measured with an inside micrometer. Mean values were computed.

For all test parts, the following parameters were kept constant: nozzle diameter 0.4 mm, flow rate 100%, fan speed 100%, extrusion temperature 215 °C, bed temperature 60 °C, infill density 15%, infill pattern gyroid, line width 0.45 mm and top/bottom 2 layers.

2.2. 405 nm light curing process

The test parts went also through a light curing process using Wash & Cure Machine 2.0, from AnyCubic (China), with 405 nm 40 W UV led light. The exposure duration was 48 hours. For ensuring a uniform access to light curing for all parts and their surfaces, two supports were specially designed to allow changing the orientation of the parts during the process. The supports were manufactured from Violet PLA (Devil Design Sp. J., PL) on Creality Ender 3 3D printer (Fig. 3).

After the 405 nm light treatment, the diameter of each hole was measured again using the inside micrometer, and the results were compared with the first set corresponding to the test parts before curing.



a b

Fig. 3. Violet-blue light curing process in AnyCubic equipment: *a* – before process, *b* – during the process.

3. RESULTS AND DISCUSSIONS

3.1. 3D-printed holes accuracy

Table 2 provides the average values of the measured diameters of the holes after specimens manufacturing ($Ø_p$). $Ø_n$ denotes the nominal diameter.

Table 3 presents the values obtained after computing the dimensional error as the difference between the nominal diameter and the printed diameter. All holes were built undersized regardless the diameter, as it was reported in literature [23].

The holes with 6 mm diameter have the largest dimensional errors, while the 10 mm holes have the smallest dimensional errors.

As expected, the printing time varied with the process parameters values (Table 4). The reason for analyzing this aspect is that a trade-off between the accuracy and cost/time is often required. For instance, test parts no.1 and 2 have similar dimensional accuracies for the 10 mm and 8 mm diameters, but the first part takes 18 min (11%) longer to be 3D printed.

For a better visualization of the results, Figs. 4 and 5 illustrate the correspondence between the measured values and the process parameters. Thus, for all the holes diameters (10, 8, 6) mm, the layer thickness is the most influential process parameter, followed by the number of perimeters and the printing speed.

For the holes of 10 mm and 8 mm, the difference between the 30 mm/s printing speed and 50 mm/s printing speed is not significant in terms of the dimensional accuracy, but it is influencing the printing time as it can be seen in the Table 4.

The diagrams for layer thickness show that the 0.2 mm value allows obtaining several holes with diameters closer to the nominal, which can also be seen from the data in Table 5. As for the number of perimeters, the use of 2 shells generated more holes with diameters closer to the nominal. This process parameter has a smaller influence on the dimensional accuracy than the layer thickness, as evidenced by the difference between the nominal diameters and the arithmetic average, where the diameter values for the layer thickness are closer to the nominal diameter (Table 5).

Table 2

Results: Mean values of diameters

Specimen	10 mm ($Ø_n$)	8 mm ($Ø_n$)	6 mm ($Ø_n$)
	$Ø_p$ (mm)		
1	9.866	7.873	5.876
2	9.864	7.868	5.844
3	9.837	7.84	5.824
4	9.8	7.803	5.816
5	9.812	7.809	5.785
6	9.826	7.778	5.762
7	9.784	7.75	5.753
8	9.774	7.727	5.734
9	9.758	7.728	5.688
10	9.734	7.698	5.681
11	9.718	7.683	5.639
12	9.708	7.667	5.63

Table 3

Results: Dimensional error

Specimen	10 mm ($Ø_n$)	8 mm ($Ø_n$)	6 mm ($Ø_n$)
	$Ø_n - Ø_p$ (mm)		
1	0.134	0.127	0.124
2	0.136	0.132	0.156
3	0.163	0.16	0.176
4	0.2	0.197	0.184
5	0.188	0.191	0.215
6	0.174	0.222	0.238
7	0.216	0.25	0.247
8	0.226	0.273	0.266
9	0.242	0.272	0.312
10	0.266	0.302	0.319
11	0.282	0.317	0.361
12	0.292	0.333	0.37

Table 4

Results: Printing time

Specimen	Printing time	Specimen	Printing time
1	2h 44 min	7	2h
2	2h 26 min	8	1h 51 min
3	2h 25 min	9	1h 48 min
4	3h 7 min	10	2h 12 min
5	2h 42 min	11	1h 58 min
6	2h 36 min	12	1h 54 min

Table 5

Results: process parameters effect on dimensional accuracy

Specimen	Layer thickness (mm)	10 mm ($Ø_n$)	8 mm ($Ø_n$)	6 mm ($Ø_n$)
		$Ø_p$ (mm)		
Avg. diameter ($Ø_a$)	0.2	9.834	7.829	5.818
	0.32	9.746	7.709	5.688
Error ΔØ ($Ø_n - Ø_a$)	0.2	0.166	0.172	0.182
	0.32	0.254	0.291	0.313
Specimen	**No. of perim.**	**10 mm ($Ø_n$)**	**8 mm ($Ø_n$)**	**6 mm ($Ø_n$)**
		$Ø_p$ (mm)		
Avg. diameter ($Ø_a$)	2	9.814	7.798	5.787
	3	9.766	7.740	5.719
Error ΔØ ($Ø_n - Ø_a$)	2	0.186	0.202	0.214
	3	0.234	0.260	0.281
Specimen	**Print speed (mm/s)**	**10 mm ($Ø_n$)**	**8 mm ($Ø_n$)**	**6 mm ($Ø_n$)**
		$Ø_p$ (mm)		
Avg. diameter ($Ø_a$)	30	9.796	7.781	5.782
	50	9.792	7.772	5.751
	65	9.782	7.753	5.726
Error ΔØ ($Ø_n - Ø_a$)	30	0.204	0.219	0.219
	50	0.208	0.228	0.250
	65	0.218	0.247	0.274

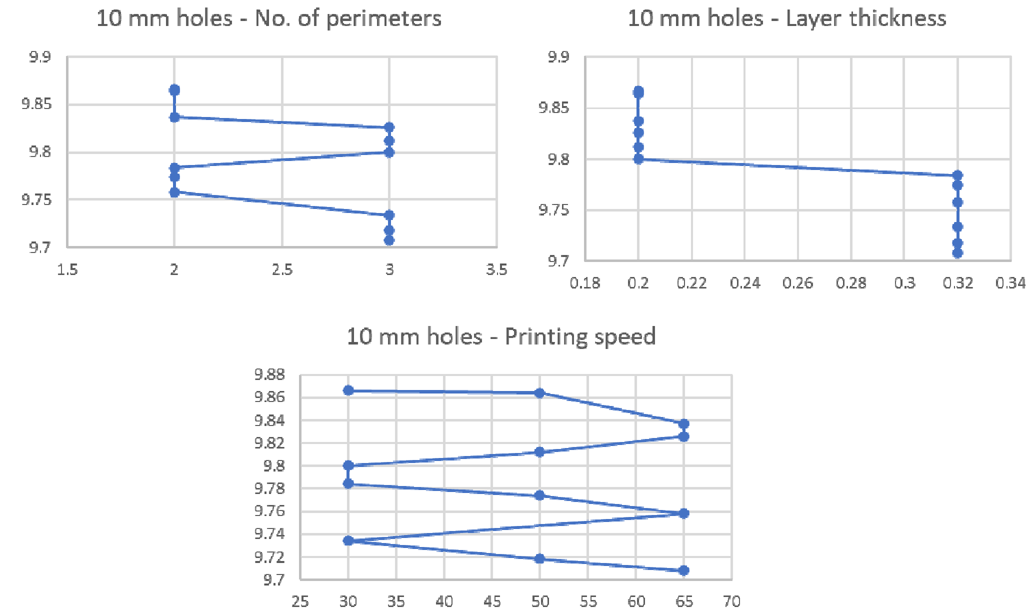


Fig. 4. Diagrams for 10 mm diameter holes.

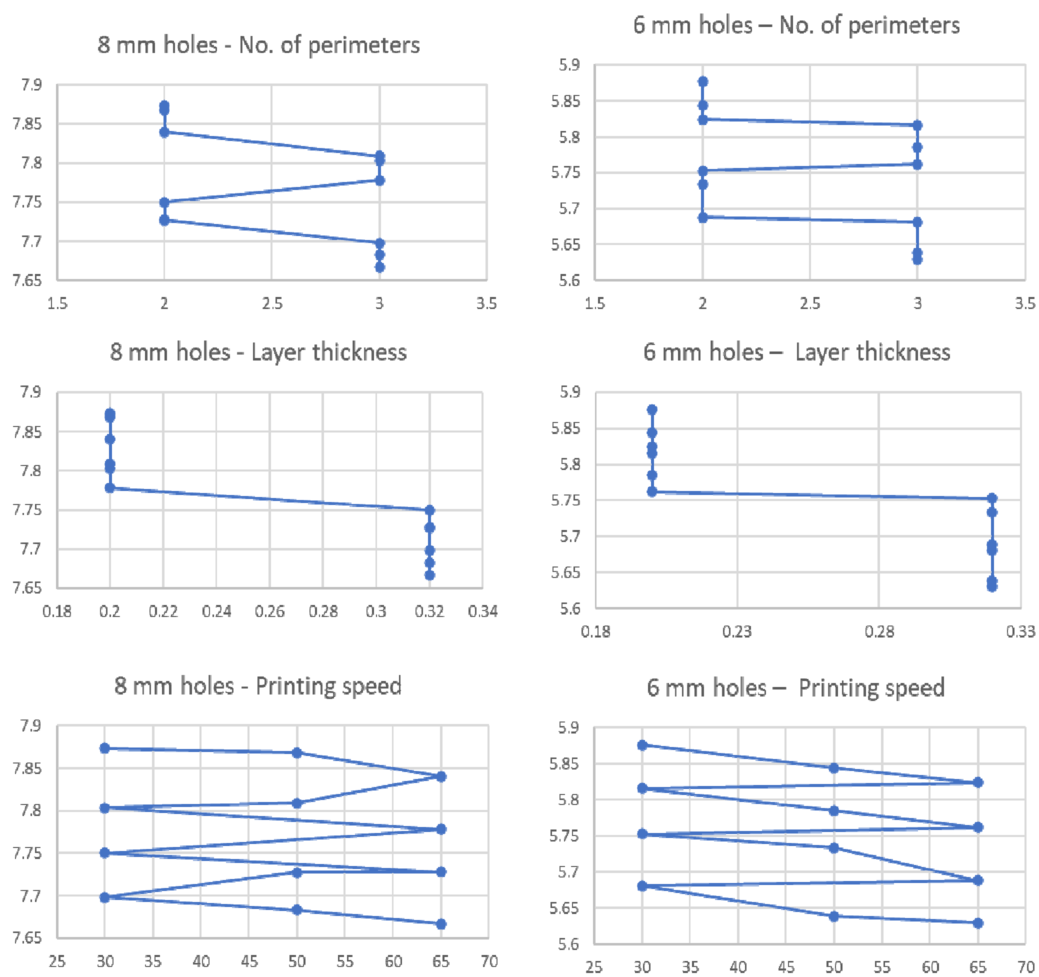


Fig. 5. Diagrams for 8 mm and 6 mm diameters holes.

Table 5

Results: process parameters effect on dimensional accuracy

Specimen	Layer thickness (mm)	10 mm ($\varnothing_n$)	8 mm ($\varnothing_n$)	6 mm ($\varnothing_n$)
		$\varnothing_p$ (mm)		
Avg. diameter ($\varnothing_a$)	0.2	9.834	7.829	5.818
	0.32	9.746	7.709	5.688
Error $\Delta\varnothing$ ($\varnothing_n - \varnothing_a$)	0.2	0.166	0.172	0.182
	0.32	0.254	0.291	0.313
Specimen	**No. of perim.**	**10 mm ($\varnothing_n$)**	**8 mm ($\varnothing_n$)**	**6 mm ($\varnothing_n$)**
		$\varnothing_p$ (mm)		
Avg. diameter ($\varnothing_a$)	2	9.814	7.798	5.787
	3	9.766	7.740	5.719
Error $\Delta\varnothing$ ($\varnothing_n - \varnothing_a$)	2	0.186	0.202	0.214
	3	0.234	0.260	0.281
Specimen	**Print speed (mm/s)**	**10 mm ($\varnothing_n$)**	**8 mm ($\varnothing_n$)**	**6 mm ($\varnothing_n$)**
		$\varnothing_p$ (mm)		
Avg. diameter ($\varnothing_a$)	30	9.796	7.781	5.782
	50	9.792	7.772	5.751
	65	9.782	7.753	5.726
Error $\Delta\varnothing$ ($\varnothing_n - \varnothing_a$)	30	0.204	0.219	0.219
	50	0.208	0.228	0.250
	65	0.218	0.247	0.274

Table 6

Results: quality vs. printing time and cost

Specimen (S)	% of 10 mm	% of 8 mm	% of 6 mm	Printing time
1	98.66	98.41	97.93	2h 44 min
2	98.64	98.35	97.40	2h 26 min
3	98.37	98.00	97.07	2h 25 min
4	98.00	97.54	96.93	3h 7 min
5	98.12	97.61	96.42	2h 42 min
6	98.26	97.23	96.03	2h 36 min
7	97.84	96.88	95.88	2h
8	97.74	96.59	95.57	1h 51 min
9	97.58	96.60	94.80	1h 48 min
10	97.34	96.23	94.68	2h 12 min
11	97.18	96.04	93.98	1h 58 min
12	97.08	95.84	93.83	1h 54 min
Difference ($S_1 - S_2$)	0.02	0.06	0.53	−18 min (−10.97%)

According to the diagrams and computations, the specimen with the best dimensional accuracy is the one with a layer thickness of 0.2 mm and 2 shells/perimeters. For all the diameters, the printing speed has not a significant influence on their dimensional accuracy, but it does affect the manufacturing time and cost.

The best specimens in terms of accuracy are no. 1 and 2, but in terms of time, the best specimen is 9 (Table 6).

Thus, the best compromise between the dimensional accuracy and the printing time is specimen 2, which has 0.02% higher dimensional accuracy for 10 mm diameters, 0.06% higher for 8 mm diameters, and 0.53% higher for 6 mm diameters but is 18 minutes faster (with 10.97% faster than first specimen). Because the difference between the two specimens for the 6 mm holes is 0.53%, it can be concluded that speed has a greater impact for the small size holes, and a higher speed can introduce larger dimensional errors.

3.2. 405 nm light exposure effect on holes dimensional accuracy

Table 7 shows the average diameters of the through holes after 48 hours of exposure to violet-blue light (Fig. 6).

According to the results, there is a difference in the diameters of the holes before and after the exposure. Table 8 shows the values obtained after computing the dimensional error (calculated as the difference between the diameter of the holes before and after the light curing process). Thus, all the holes diameters were reduced after 48 h of violet-blue light exposure.

The accuracy of the holes decreased after the light curing process by approximately 2.5% (the highest dimensional error), equivalent to 0.143 mm, being recorded for the specimen 8 and the 6 mm diameter holes. As a result, it can be said that small diameters are more affected by light curing (approximately 1.68% average error for 6 mm diameter) compared to holes with larger diameters (approximately 0.74% average error for 10 mm diameter).

Table 7

Results: Diameters mean values after light curing

Specimen	10 mm ($\varnothing_n$)	8 mm ($\varnothing_n$)	6 mm ($\varnothing_n$)
	$\varnothing_{cured}$ (mm)		
1	9.820	7.821	5.816
2	9.818	7.792	5.739
3	9.804	7.760	5.708
4	9.773	7.757	5.748
5	9.733	7.707	5.657
6	9.739	7.683	5.675
7	9.692	7.683	5.675
8	9.669	7.613	5.591
9	9.649	7.604	5.594
10	9.654	7.626	5.602
11	9.644	7.600	5.554
12	9.623	7.576	5.518

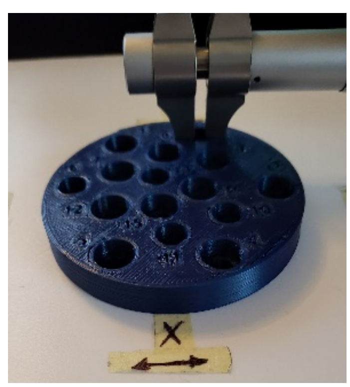


Fig. 6. Measuring the holes after the 405 nm light curing.

Table 8

Results: Dimensional error after light curing

Specimen	10 mm (Øn)	8 mm (Øn)	6 mm (Øn)
	Øp – Øcured [mm]		
1	0.046	0.052	0.060
2	0.046	0.077	0.106
3	0.034	0.081	0.116
4	0.027	0.047	0.068
5	0.079	0.102	0.129
6	0.088	0.095	0.087
7	0.093	0.067	0.078
8	0.105	0.115	0.143
9	0.109	0.125	0.094
10	0.080	0.072	0.080
11	0.074	0.083	0.085
12	0.085	0.091	0.113

Table 9 presents the percentage values of the dimensional errors of the holes after light curing.

Table 10 provides information on the means of holes' diameters following 405 nm light exposure for each parameter. Even after this analysis, it can be noted that test parts with a layer thickness of 0.2 mm, 2 perimeters, and a speed of 30 mm/s produce the best results. Also, based on the mean values, the violet-blue light treatment affected more the parts with 3 perimeters than the parts with 2 perimeters.

Table 9

Results: Dimensional error after light curing (%)

Specimen	10 mm (Øn)	8 mm (Øn)	6 mm (Øn)
	Øp – Øcured [%]		
1	0.466	0.660	1.021
2	0.466	0.972	1.805
3	0.341	1.027	1.992
4	0.281	0.596	1.169
5	0.810	1.306	2.221
6	0.890	1.221	1.510
7	0.945	0.865	1.356
8	1.079	1.482	2.494
9	1.117	1.611	1.661
10	0.827	0.942	1.399
11	0.761	1.080	1.507
12	0.876	1.187	1.998
Avg. error	**0.738**	**1.079**	**1.678**

Table 10

Results: Mean diameters (mm) after light curing

	Process par.	10 mm (Øn)	8 mm (Øn)	6 mm (Øn)
Avg. diameter (Øa_cured)	No. of perimeters			
	2	9.742	7.712	5.687
	3	9.694	7.658	5.625
	Layer thickness (mm)			
	0.2	9.781	7.753	5.724
	0.32	9.655	7.617	5.589
	Print speed (mm/s)			
	30	9.734	7.722	5.710
	50	9.716	7.678	5.635
	65	9.704	7.656	5.624

One can conclude that the specimens can be manufactured at a speed of 50 mm/s for a quicker printing process and an accuracy that is close to the best part quality (−0.018 mm for 10 mm diameters, −0.054 mm for 8 mm diameters and −0.062 mm for 6 mm diameters).

According to the results after the light curing process, the specimen 2 has the best quality-time ratio, taking cost into account, and it has through-hole dimensional accuracy nearly identical to specimen 1 (approximately – 0.76%), while requiring less time to print.

4. CONCLUSIONS

This study examined the dimensional accuracy of directly 3D-printed holes in relation to a variety of variables, including the process parameters: layer thickness, the number of perimeters around the holes, printing speed, but also 405 nm light exposure.

The layer thickness is the process parameter with the largest impact on the dimensional accuracy of the holes, the printing speed having the smallest effect on holes' diameters value. A trade-off between the dimensional accuracy and the printing time and cost should be considered by the designer. Therefore, the optimal setting in this research was for the test parts printed at 50 mm/s, 2 perimeters and 0.2 mm layer thickness.

It should be also noted that, as discussed in the literature, the holes with a larger diameter are 3D printed more accurately than the holes with diameters around 5 mm.

For understanding how the violet-blue curing is influencing the dimensional accuracy, the same part were subjected to 48h of 405 nm wavelength light, the results showing a decrease in the diameters of all the test parts. The largest dimensional error between cured parts and the non-treated parts was 0.1 mm. Again, the holes with a small diameter (6 mm) were more affected by light curing than the holes with larger diameters. With a maximum diameter reduction value of 1.12% of the initial hole's diameter (0.109 mm) for the 10 mm holes, the effect of light curing is not significant noticeable. For the diameters of 8 mm, the 3D-printed holes have a maximum diameter decrease of 1.62%, or 0.125 mm. All these aspects should also be acknowledged by the designer when prescribing the holes' diameter values for parts used in medical applications and treated with 405 nm for sterilization.

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