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Design of Printing Parameter Settings Methodology for FFF Printing of Waterproof Samples from a Flexible Material

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Abstract: 3D printing technology plays a key role in the design of prototypes and final parts. The ability to quickly and easily produce almost any shape using the Fused Filament Fabrication (FFF) method is used in almost every industrial sector, science and research. Materials for the FFF method can be divided into two groups, namely rigid and flexible. Flexible materials, in combination with pneumatics or hydraulics, offer a wide range of applications. However, in the FFF method, where individual fibers are stacked on each other and side by side, the question arises of whether the fibers will bond sufficiently to prevent water or air from passing through. This paper aims to design a methodology for the printing parameters of an FFF printer when printing from flexible materials to ensure that the filaments bond sufficiently for the printed part's water and air tightness. The proposed methodology is verified on printed samples by two tests, namely waterproof and airtightness tests. Two of the most commonly used highly flexible materials, namely TPU 30D and TPE 88, were selected for testing. The results of the work are intended to help the designers and technologists to calibrate the printing parameters for the printing of flexible materials for use in pneumatics or hydraulics.

Keywords: FFF; TPU; TPE; additive manufacturing; waterproof; airtightness; print settings

1. Introduction

Additive manufacturing technology has revolutionised the design of prototypes and final functional parts in various industries, science and research. Additive technology allows the creation of shapes and assemblies that would be impossible to produce with other currently available technologies or would be too time-consuming or costly to produce [1, 2]. Fused Filament Fabrication (FFF) is one of the most widespread 3D printing methods due to its ability to produce almost any shape of part or assembly quickly, efficiently, easily and inexpensively [3, 4]. Combined with currently available materials, this technology is used, for example, in robotics to print robotic grippers [5], jaws [6], FinRay fingers [7], snake robots [8], topology-optimized robotic arms [9], flexible wheels of mobile robots [10], parts of chimney weeping robot [11], end effectors [12], or for holders of many kinds of sensors [13, 14].

The materials for this method can be divided into two basic types: rigid and flexible. Flexible materials combined with pneumatics or hydraulics offer a wide range of applications, for example, soft pneumatic actuators and grippers [15] or pneumatic artificial muscles [16]. For these applications, however, achieving the necessary airtightness or water tightness is necessary. However, the process of the FFF method, which involves

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laying individual fibers side by side, raises the question of whether these fibers bond sufficiently to provide the necessary water or air tightness. Figure 1 shows a microscopic view of the bottom of a printed sample produced by FFF technology from TPU 30D flexible material. It is visible the gaps through which water and air can flow or leak.

The sample in Figure 1 was printed with the default print parameters for the material. It can be seen that these parameters are not correct for sufficient bonding of the layers together. Whether the filaments bond together depends primarily on print parameters such as extrusion width or infill/perimeter overlap. The extrusion width parameter indicates how wide the filament should be deposited and depends on the diameter of the nozzle, which is most often 0.4 mm. With the extrusion width parameter, the actual width of the filament to be deposed can be controlled by up to several tens of per cent. The second influential parameter leading to the bonding is the infill/perimeters overlap parameter. This parameter determines how far into the perimeter the infill will be printed.

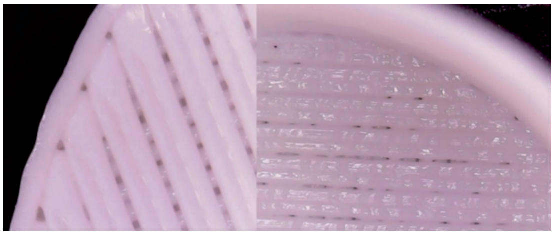

Figure 1: Printed sample before calibration. (left) bottom side. (right) top side of the bottom.

This paper proposes a methodology for the printing parameters of an FFF printer when printing from flexible materials to ensure that the filaments bond sufficiently for the printed part's water and air tightness. It highlights the need for essential first layer calibration and presents tests to validate the proposed methodology. The materials chosen for the tests represent the two most commonly used highly flexible materials for FFF technology, thermoplastic elastomer (TPE) and thermoplastic polyurethane (TPU), which is a specific type of TPE. Specifically, TPU 30D [17] and TPE 88 [18] were used. The results of this study are intended to help designers and technologists calibrate printing parameters for flexible materials and subsequently use them in applications involving pneumatics or hydraulics.

2. Experimental Section

First, a calibration methodology is proposed for setting the printing parameters to ensure watertight samples. Subsequently, the designed samples are tested for waterproofness and pressure endurance tests.

2.1. Methodology for setting printing parameters for FFF printing of waterproof samples

The proposed methodology for achieving sufficient bonding of deposited fibers to ensure both waterproofing and airtightness is based on changing the printing parameters in slicing software PrusaSlicer 2.5.0 [19] for the Original Prusa i3 MK3S [20] printer with Flexion flexible materials extruder [21]. The methodology is experimental and is evaluated by visual inspection of the printed sample. Using these visual checks, the printing parameters are subsequently adjusted, a new sample is printed with these parameters, and the whole process is repeated until the layers sufficiently bond (no visible gaps and pores).

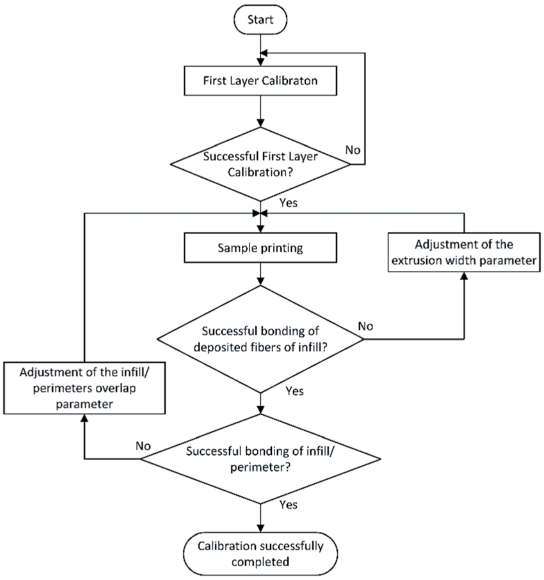

Figure 2: Methodology diagram for print calibration.

The methodology consists of three steps. The first step is to calibrate the first layer. This calibration setup is sufficiently explained in the Prusa Research printer manufacturer's instructions [22] and thus needs to be detailed described in detail further in this paper. The second step is to check the bonding of deposited fibers of the infill. If the gaps are visible under the microscope, the value of the parameter extrusion width parameter is changed. If the deposited fibers are sufficiently bonded, then comes the final step. The success of bonding infill fibers to perimeters fibers is checked. If there are also visible gaps, the value of the parameter infill/perimeters overlap is changed. Each adjustment of the printing parameters results in a new sample being printed. The entire methodology is illustrated in Figure 2.

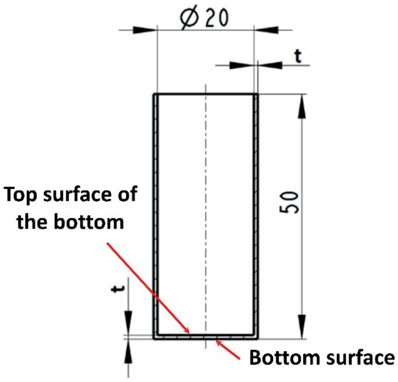

Figure 3: The drawing of the sample.

A cylinder with an inner diameter of 20 mm and a wall thickness of 0.4 mm (one perimeter) was selected as the printed sample. The drawing of the sample is shown in Figure 3. The underside of the base and the top of the base were visually inspected under a microscope.

The basic print parameters settings for printing a sample are shown in Table 1.

Figure 4 shows a printed sample before the calibration of the first layer and with default settings for printing.

2.2. Watertightness test method

To prove the proper bonding of the fibers according to the presented methodology, another set of samples was printed and checked for water tightness. The samples were printed from two materials at different wall thicknesses t (see Figure 3). Table 2 shows the variations of the printed samples.

Table 1: Printing parameters.

Parameter	Value	Parameter	Value
Filament diameter	1.75 mm	Perimeter speed	45 mm/s
Nozzle diameter	0.4 mm	Speed for infill	80 mm/s
Layer height	0.2 mm	Speed for first layer	20 mm/s
Infill	100 %	Speed for top layer	40 mm/s
Number of perimeters	10	Width parameters	0.45 mm
Nozzle temperature	210 °C	Infill/perimeter overlap	25 %
Bed temperature	60 °C		

Table 2: Printed samples for water tightness test.

Sample	Material	Wall thickness t
XA1	TPE 88	0.4 mm
XA2	TPE 88	0.8 mm
XA3	TPE 88	1.2 mm
XA4	TPE 88	1.6 mm
XB1	TPU 30D	0.4 mm
XB2	TPU 30D	0.8 mm
XB3	TPU 30D	1.2 mm
XB4	TPU 30D	1.6 mm

The samples are tested as follows. Each sample is filled with 13 ml of water, weighed and placed in the measuring device. The measuring system consists of a glass container, temperature sensor and humidity sensor. The samples are placed in a glass container. There is also a container of water in the glass container to ensure a faster increase of 100% humidity inside the glass container (some

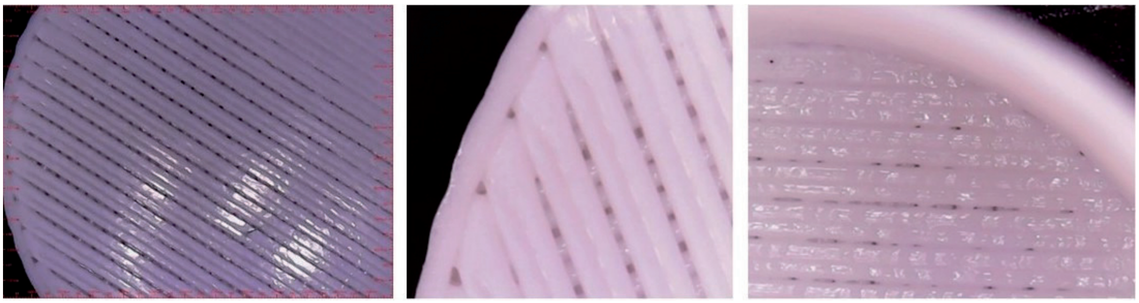

Figure 4: Printed sample before calibration. (left) Bottom surface, middle. (middle) Bottom surface zoomed at edge. (right) Top surface of the bottom.

decrease in the amount of water in the samples due to evaporation was assumed). The progress of the test is monitored by two cameras, one taking images every 30 minutes and the other used to monitor the liquid levels online. Figure 5 shows the measuring system.

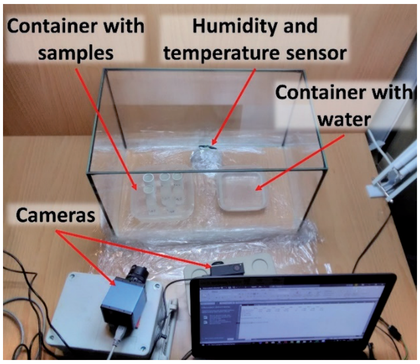

Figure 5: Measuring system.

Measuring was conducted over 15 days. Afterwards, the samples were removed from the glass container, and the water leakage was checked visually, and the loss of the weights was measured.

2.3. Pressure endurance testing method

The second test is the pressure endurance of the printed samples. In addition, the TPU 30D and TPE 88 materials are examined in this test. Figure 6 shows the basic dimensions, shape, and assembly of the specimen.

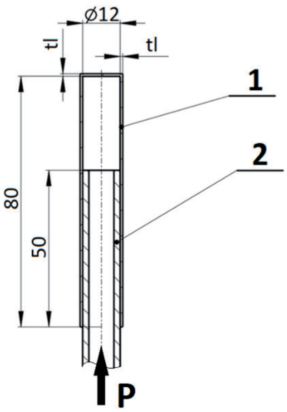

Figure 6: Drawing of the assembly.

The printed sample (element 1 in Figure 6) is inserted into a standardized pneumatic hose (element 2) with an outer diameter of 12 mm. The samples are printed with a thickness (thickness) of 0.8 and 1.2 mm, i.e., 2 and 3 perimeters. The pneumatic hose is inserted into the printed sample to a depth of 50 mm and is secured against ejection by adhesive tape and tightening strips. An image of the measurement system is shown in Figure 7.

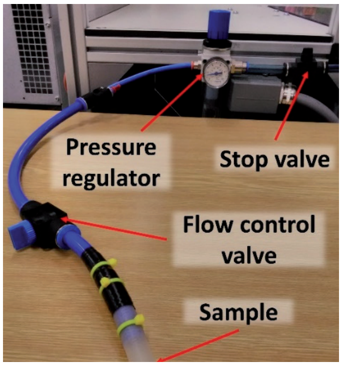

Figure 7: Pressure endurance measuring system.

Two methods were chosen for the pressure endurance testing. The first method tests the sample while gradually increasing the pressure. The pressure regulator valve is first set to atmospheric pressure. The stop valve and the flow control valve are open. Then the pressure is gradually increased to a relative value of 0.1 MPa by the pressure regulator. Subsequently, the air supply valve (stop valve) is closed, and the barometer on the pressure regulator is monitored for one minute to see if any air leaks from the printed sample. The stop valve is then opened, and the relative pressure increases by 0.05 MPa. The whole procedure is repeated until the sample is broken.

In the second method, the sample is tested by pressure impact. The pressure regulator valve is first set to atmospheric pressure while the flow control valve is open. Then the flow control valve is closed. The pressure regulator valve is set to a relative pressure of 0.1 MPa. The flow control valve is then rapidly opened to its full opening, causing a sharp increase (impact) in pressure in the printed sample. If the sample does not break, the flow control valve is closed, the relative pressure is increased by 0.05 MPa, and the measurement process is repeated. The pressure gradually increases until the sample breaks. A total of 10 samples from each test set were used.

3. Results and Discussion

First, the results of the calibration methodology for setting the print parameters are presented. Next, the results of watertight and pressure endurance tests are presented.

3.1. Results of the methodology for setting printing parameters for FFF printing of waterproof samples

Based on the presented methodology, after calibration of the first layer and several iterations of calibration of the extrusion width parameter value, the successful bonding fibers of the infill on the bottom and top side of the bottom was achieved, as shown in Figure 8.

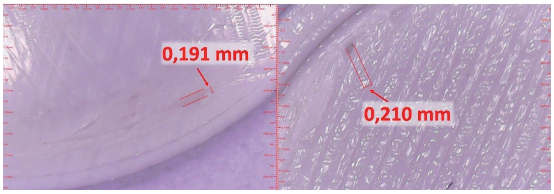

Figure 8: Printed sample after successful calibration of extrusion width parameters. (left) Bottom surface. (right) Top surface of the bottom.

The picture shows that the infill fibers are already sufficiently bonding. However, there are still visible gaps between the infill and perimeter (it has been experimentally verified that water leaks through these gaps). After the last step of the calibration process, namely setting the appropriate infill/perimeter overlap value, the fibers were bonded satisfactorily without gaps, as shown in Figure 9.

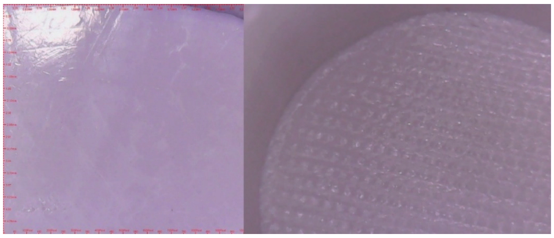

Figure 9: Printed sample after successful calibration process. (left) Bottom surface. (right) Top surface of the bottom.

Therefore, the calibration process is considered successful. The final print parameter constants are an extrusion width of 0.49 and an overlap for the fill and perimeters of 80%. However, it should be noted that these values may vary for other printers.

3.2. Results of the watertightness test method

During the water tightness measurement, the humidity in the glass container gradually increased to 100%, where it remained for the rest of the measurement. The average temperature during the measurement was 24.1°C, the minimum temperature 22.5°C and the maximum temperature 24.2°C. A record of the humidity and temperature measurements is shown in Figure 10.

After 15 days, the samples were removed from the glass container and checked for water leakage. Visually, no leakage of liquid was observed from any

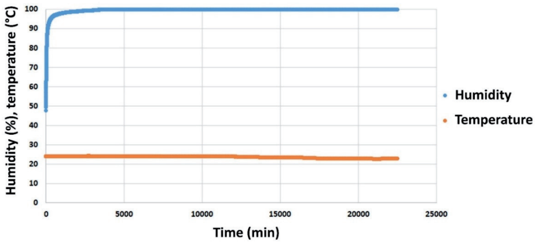

Figure 10: Humidity and temperature during the measurement time.

of the samples. The samples were then weighed, and their weight was compared with the weight before the measurements. Table 3 shows the measured values.

Table 3: Measured values of the water tightness test method.

Sample	Weight before starting measurement	Weight after measuring	Weight difference
XA1	15.43 g	14.86 g	0.57 g
XA2	15.63 g	15.11 g	0.52 g
XA3	16.82 g	16.3 g	0.52 g
XA4	18.4 g	17.89 g	0.51 g
XB1	15.6 g	14.93 g	0.67 g
XB2	16.29 g	15.67 g	0.62 g
XB3	17.84 g	17.28 g	0.56 g
XB4	20 g	19.43 g	0.57 g

It can be seen from the table that all samples showed approximately similar values of the weight loss difference. This loss is probably due to the evaporation of water from the samples, corresponding to an increase in the measured moisture content inside the container to 100 %. In the container of water, which was also placed in a glass container, there was a weight loss of 8 g. It can therefore be assumed from the results that all samples were watertight.

3.3. Results of the pressure endurance testing method

All samples from the same test set broke at the same pressure value. In the first test method, no air leakage was observed in any of the cases (until the high pressure caused them to break). The measured values are shown in Table 4.

According to the results, it is evident that both materials are comparable in terms of the principle of this testing. Under impact loading, they withstood 0.5 MPa less pressure than under gradual increase. The specimens with 1.2 mm wall thickness also

Table 4: Measured values of pressure endurance testing method.

Material	Wall thickness	Testing method	Max pressure
TPU 30D	0.8 mm	Gradually increased	0.4 MPa
		Impact	0.35 MPa
	1.2 mm	Gradually increased	0.5 MPa
		Impact	0.45 MPa
TPE 88	0.8 mm	Gradually increased	0.5 MPa
		Impact	0.45 MPa
	1.2 mm	Gradually increased	0.5 MPa
		Impact	0.45 MPa

withstood 1 MPa more pressure than the specimens with 0.8 mm thickness. A broken sample is shown in Figure 11.

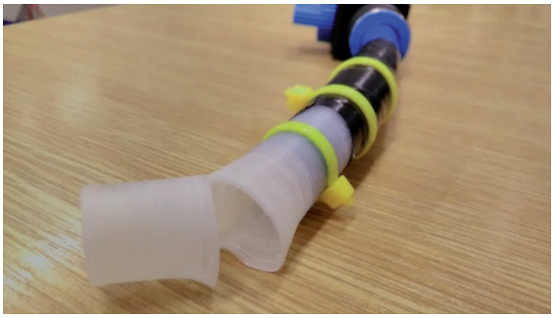

Figure 11: Broken sample.

All samples broke approximately halfway between the end of the inserted hydraulic hose and the end of the test sample. In all cases, the printed layers were torn apart (tear perpendicular to the sample axis).

4. Conclusions

A methodology for calibrating the printing parameters for FFF printing from flexible TPU 30D and TPE 88 materials was proposed. This method is based on microscope inspection, in which test prints samples are visually inspected for unfilled gaps and pores. On the basis of the inspection, the print parameters are adjusted. After adjusting the parameters, new samples are printed and the process is repeated until the result is satisfactory. For the test samples, the optimal values of the printing parameters were set to 0.49 for the extrusion width and 80% for the fill/perimeter overlap. However, it should be noted that these values may vary for different printers.

After successfully calibrating the print parameters, test samples were printed for the waterproof test. Even after 15 days, no water leakage was observed in any of the samples. Therefore, the printed samples were considered watertight at atmospheric pressure. The next test was a pressure test in which the test samples were subjected to two types of pressure: gradually increasing and impact. The results showed that both materials were comparable in terms of the principle of this testing. Under impact loading, they withstand 0.5 MPa less pressure than under gradual increase. The samples with 1.2 mm wall thickness also withstood 1 MPa more pressure in both tests than the samples with 0.8 mm wall thickness.

The proposed methodology was tested for selected flexible materials printed by the FFF method and confirmed as satisfactory according to the proposed tests. Because the methodology aims to avoid unfilled gaps and pores, it can void to increase the strength and stiffness of the printed parts [23], which could be the aim of further research. The results of this work are intended to help designers and scientists with further detailed testing and prototyping in the field of pneumatics or hydraulics.

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