euspen's 23rd International Conference & Exhibition, Copenhagen, DK, June 2023
www.euspen.eu

Characterization of Digital Light Processing and Two-Photon Polymerization 3D printing technologies for micro-manufacturing

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Abstract
Additive manufacturing technologies are continuously pushing the boundaries to deliver parts with higher resolution and more convoluted shapes. In the present study, different test geometries were 3D printed using different cutting-edge commercial machines. Machine working principles are based on Digital Light Processing (DLP) and Two-Photon Polymerization (2PP) additive manufacturing. The aim of the study was to investigate the printing capabilities of the selected technologies for product applications with critical dimensions ranging from 150 µm to 500 µm. The characterization was carried out by quantifying the printed parts' dimensional compliance with the specified dimensions. The parts were examined using a 3D laser confocal microscope. Critical dimensions were measured for each printed part, and the results were compared to the nominal values. The studied parts have outer dimensions ranging from 2 mm to 6 mm, while they contain features with sizes varying from 130 µm to 500 µm. The results were categorized into two groups: (i) with information about relatively large (>2 mm) outer dimensions and (ii) data about relatively small features (<500 µm) on the test geometries. The above categorization facilitates the measurement process and separates the shape dimensions from the internal features. The overall comparison of the measured dimensions demonstrated a minimum deviation of 0.4 % and a maximum deviation of 6.8 % from the CAD files' nominal values.

Additive manufacturing, 3D printing, Digital Light Processing, Two-Photon Polymerization

1. Introduction

The rapid advancement in the field of additive manufacturing has resulted in the widespread use of 3D printing as a cost-effective and energy-saving alternative to traditional manufacturing processes. 3D printing involves the digital description of an object using a dot array called voxels, which sizes ranging from the nanoscale to the macroscale. Using various materials and complex 3D microstructures in new micro products makes AM processes more beneficial than traditional methods like lithography-based or micromachining approaches [1].

Among the different 3D printing technologies, micro-additive manufacturing, or micro-3D printing, has gained significant attention due to its capability to fabricate various micro products with resolution in the micrometer down to the sub-micrometer scale. These micro products have potential applications in sensing, medicine, and communications [2] or oral drug delivery [3]. A review of 3D µAM techniques by Vaezi et al. [1] presented Vat Photopolymerization (VP) methods, such as Stereolithography (SLA) and Digital Light Processing (DLP), as scalable AM methods that can be applied in both standard and micro size manufacturing. In two separate studies, Vaut et al. [4, 5] investigated the capabilities of SLA and DLP for oral drug delivery micro devices and micro micro mechanical components respectively.

In addition to DLP, several other 3D printing technologies are available, including 2PP (Two-Photon Polymerization). [6] DLP uses a digital projector to cure a photopolymer resin layer by layer, while 2PP uses a focused laser beam to polymerize a photopolymer resin in a 3D space. One key advantage of DLP 3D printing is its high resolution and accuracy, which allows for creation of detailed and precise parts and products. In addition, DLP 3D printers are generally faster and more efficient than other technologies, with some models able to print multiple objects simultaneously. However, DLP 3D printing can be limited by the types of materials that can be used, and it is not suitable for large or complex objects due to the size of the printing bed. [7]

On the other hand, 2PP 3D printing has the advantage of being able to print complex and highly detailed objects with a high level of accuracy and resolution without the need for support structures. However, 2PP 3D printing is generally slower and more expensive than other technologies. [7, 8, 9, 10]

In 3D printing, objects are created and represented digitally as a grid of dots, known as voxels, which function as the smallest printing unit, similar to pixels in image creation. The voxel size in 3D printing can range from very small, at the nanoscale level (sub-µm dimensional scale), to very large, at the macroscale level (mm dimensional scale and above). [11]

The present study aimed to examine specific machines' printing abilities with down to nanoscale printing-level capabilities for products with critical dimensions ranging from 150 µm to 500 µm. These machines operate on the two different principles of DLP and 2PP. The evaluation was done by measuring the dimensional accuracy of the printed parts compared to the nominal dimensions. The parts were examined by means of a 3D laser confocal microscope for both dimensional measurements and high-resolution scanning of the micro features. Through the metrological comparison of the micro-printed parts, this study provides an assessment of the DLP and 2PP techniques' performance. It lays forward information that illustrates the recent advancements in the field of micro additive manufacturing. Such information will help incorporate more intricate designs while using these micro-manufacturing technologies.

2. Methods and materials

The CAD files were prepared and designed in the Solidworks software environment and prepared in STL format for being printed by each of the machines. For each file, an appropriate number of pillars (i.e., supporting structures) were incorporated into the design so the printers could print the part layer by layer. Three designs were used for this study, along with three commercially available printers. Each of the printed specimens was then examined through optical and confocal microscopy.

2.1. 3D printers

Three different state-of-the-art machines were used for 3D printing the parts. Two machines operated with Digital Light Processing (DLP) Technology, and one used Two-Photon Polymerization (2PP). It should be noted that all three machines operate with specific patented UV-sensitive resin materials for the printing process. Technical details of each machine can be seen in Table 1, where the printers are distinguished with DLP1, DLP2, and 2PP. This nomenclature will be used throughout the study to examine the details of different parts corresponding to each machine.

Table 1. The technical details of the three different 3D printing machines used in this study.

Technical information	DLP1	DLP2	2PP
XY Resolution	1.9 µm	10 µm	400 nm
Layer thickness	1 µm	10-40 µm	0.3-5.0 µm
Build volume	50×50×100 mm^3	94×52×45 mm^3	100×100×8 mm^3
Material	UV Sensitive Resin	UV Sensitive Resin	UV Sensitive Resin

2.2. Microscopy measurement process

In order to inspect the quality of the printed parts and measure their dimensional compliance, the 3D laser confocal microscopy technique was used. Confocal microscopy was carried out using the LEXT OLS 4100, a laser-scanning confocal microscope produced by Olympus (Tokyo, Japan). With the help of confocal microscopy, the outer dimensions of the parts were measured. Subsequently, the small features on the parts were closely examined using fine-step scanning along the Z-axis to measure the depth in selected cases.

For each case study, three parts were printed, and during the microscopy inspection process, the measurements were repeated three times for each feature of interest. The measurement repeatability was estimated considering the standard deviation.

2.3. Printing materials

Considering that the machines are commercially availbale, the materials used for each are patented, and their specific details are protected. However, the specifications for the geometries selected as case studies dictate that the photopolymeric resins used for the different micro additive manufacturing processes are of relatively high tensile strength (>50 MPa) making them suitable for the parts to be later tested in their individual applications.

3. Quality assurance

Three geometries were selected to be printed by the 3D printers, as illustrated in Figures 1, 2, and 3. These parts were selected due to the importance of their functionality and tolerances in the context of micro production and micro assembly processes. They all have micro-sized features, and each had their respective challenges, making them suitable for use as a case study. Hence their investigation will reveal the challenges ahead.

3.1. Part number 1 – Cylindrical beam

As shown in Figure 1, the first test specimen encompasses a small orifice of 270 µm and two concentric holes with diameters of 250 µm and 130 µm, respectively. From the back side, only the 130 µm hole is visible. The cylindrical geometry of the part, along with its micron-sized feature, qualified it as a suitable case study.

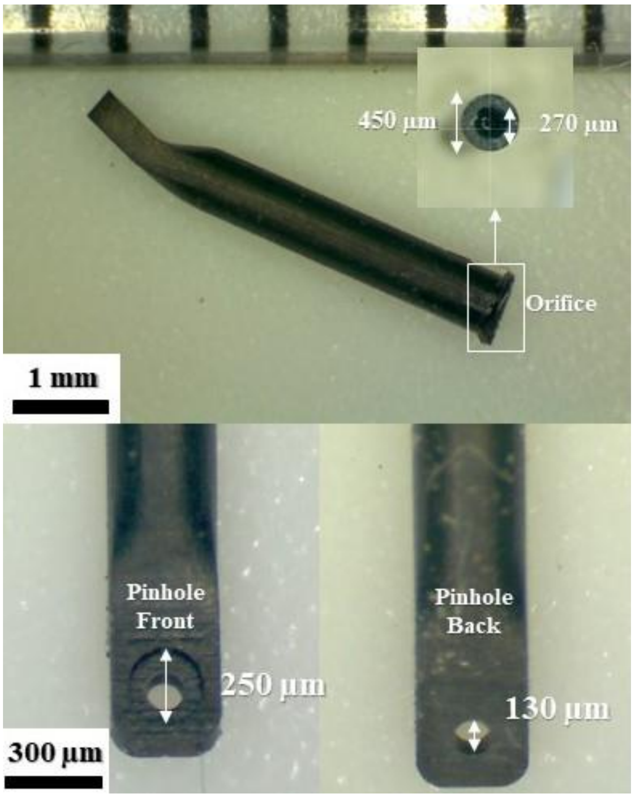

Figure 1. The first case study with a relatively simple cylindrical shape and two small holes within. The orifice is 270 µm, and the hole on the tail has two concentric circles with diameters of 250 µm and 130 µm.

This part was printed by two different machines: DLP1 and DLP2. Table 2 shows the dimensions for the overall features and the hole measured with a confocal microscope for the two printers. A challenge in printing this part was the angled configuration of the cylindrical segment shown in Figure 1. As a result of this angle, the part needed to be stabilized over the printing stage with the assistance of a temporary pillar (only for the part printed by DLP1) that would be snipped in the post-processing phase after the print. The orifice showed defects in some printed parts, hinting that a slight alteration in the printing conditions could affect the final quality.

Table 2. The measurement data from the first case study. This part was printed by DLP1 and DLP2.

Part 1 Cylindrical beam	Target	DLP1	DLP2
Pinhole – Front [µm]	250	240 ± 5	242 ± 6
Pinhole – Back [µm]	130	122 ± 5	121 ± 6
Orifice – Inner Diameter [µm]	270	269 ± 5	268 ± 6
Orifice – Outer Diameter [µm]	450	446 ± 5	445 ± 6
Length [mm]	5.60	5.57 ± 0.05	5.59 ± 0.06

3.2. Part number 2 – Microfluidic channel

Contrary to the first specimen, part two has larger outer dimensions. This part was chosen as a case study to inspect the machines' performance in printing a straight and relatively long channel with small features, as summarised in Table 3. The part was a simple design that resembles a lab-on-a-chip micro channel, and printing it could shed light on some of the challenges for future microfluidics developments. This part was only printed by DLP2.

Table 3. The measurement data from the second case study, the microfluidic channel. This part was printed by DLP2.

Part 2 Microfluidic channel	Target	DLP2
Chip width [mm]	4.50	4.48 ± 0.02
Channel width [µm]	375	373 ± 2
Channel depth [µm]	150	148 ± 2

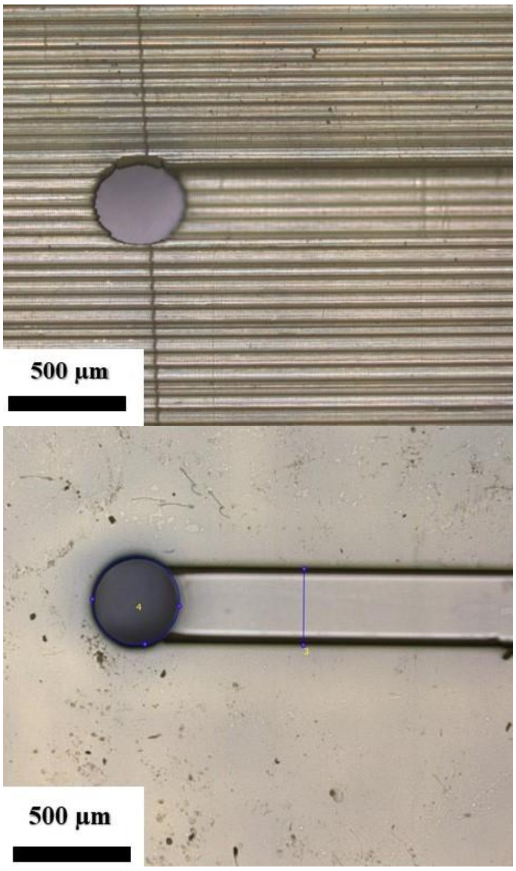

Figure 2. The second case study with a design resembling a lab-on-a-chip system which incorporates a channel having a width of 375 µm and a depth of 150 µm. This part was only printed by DLP2 and in two different printing-stage orientations, which resulted in two post-print conditions.

Two different stage orientations were chosen to investigate the difference that such change will cause. In the first condition, the part was printed while having been placed on a narrower side of 2 mm × 44 mm. The part printed with this condition showed visible printing lines that would compromise the transparency for applications such as lab-on-a-chip systems.

In the second condition, the part was placed on its wide side of 4.5 mm × 44 mm. As seen in Figure 2, the resulting part was a chip with less visible printing lines and improved aesthetics. The downside was that the channel surface was covered by a layer of resin printed over the channel as the first layer.

3.3. Part number 3 – Micro-mechanical part

A more complex geometry was selected as a part to be 3D printed with all three available machines, as seen in Figure 3. In addition to including small features, this part's relatively more intricate design provides a comparison reference for all three printers.

The overall dimensions of the part and the features within it can be seen in Table 4. The table includes measured data from components produced by all three machines.

A closer look at the part printed by DLP1 in Figure 3 reveals small dents on the surface, which are traces of the cut-out printing pillars. The pillars, which were only used in DLP1, provide support for the overhang during the printing stage.

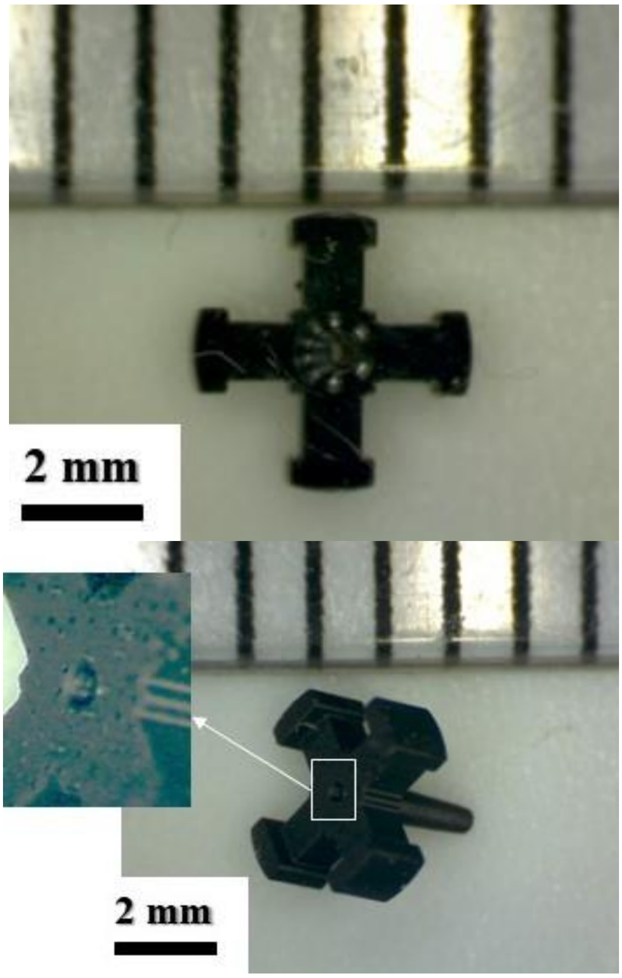

Figure 3. Micro-mechanical products printed by all three machines. A close inspection of the part shows minor dents on the surface, which are the traces from the pillars that were later cut in the post-printing process. These pillars provided stability and ensured the alignment of the part during the print and were only used during the printing process with DLP1.

Table 4. The measurement data from the third case study. This part was printed by all three machines.

Part 3 – Micro Mechanical Part	Target [µm]	DLP1 [µm]	DLP2 [µm]	2PP [µm]
Front Orifice – Outer Diameter	200	196 ± 4	195 ± 4	190 ± 7
Front Orifice – Inner Diameter	150	149 ± 4	149 ± 4	148 ± 7
Back Orifice – Outer Diameter	500	498 ± 4	498 ± 4	497 ± 7
Back Orifice – Inner Diameter	150	149 ± 4	147 ± 4	147 ± 7

4. Discussion

As summarized in Tables 2, 3, and 4, the features were measured for each case study. The results laid the ground for understanding the obstacles in printing complex geometries that incorporate micro-sized components. A helpful way of characterizing the measurement data is to categorize them based on the size of the features. Figure 4 provides a visual overview of the measurements where the data was separated into two categories including features larger or smaller than 500 µm.

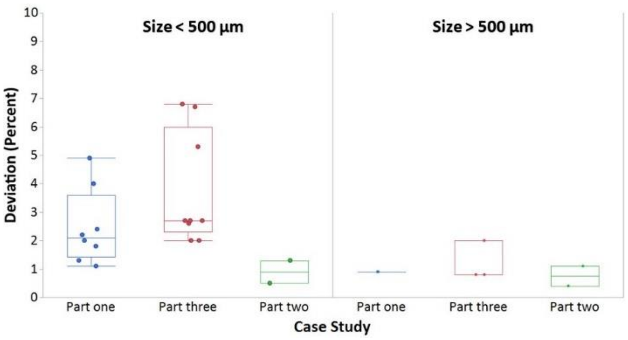

Figure 4. Percentage deviation based on a categorization of the measurement data into two sets of features with a size larger than 500 µm and those with a size smaller than 500 µm.

As illustrated in Figure 4, all the data points corresponding to the measured dimension's deviation from the nominal values were visualized in two separate categories. The Y-axis shows the deviation in percentage for each of the parts printed with all three machines. The minimum recorded throughout the measurements was 0.4 % (chip width belonging to part two printed by DLP2), and the maximum was 6.8 % (back orifice for part three printed by the 2PP).

5. Conclusion

The study aimed at assessing the printing accuracy and precision of three commercial state-of-the-art 3D printers for products with dimensions ranging from 150 µm to 500 µm. The evaluation was done by performing thorough quality assurance on these parts to determine how closely the printed parts matched their designed dimensions. The challenges in printing each of the parts due to their small features were discussed.

Additionally, for the quality assurance process, a 3D laser confocal microscope was used to inspect the parts, and their critical dimensions were measured and compared to the expected values. The parts had outer dimensions from 2 mm to 6 mm and features with sizes from 150 µm to 500 µm. in order to simplify the evaluation process; the results were divided into two groups based on size: larger outer dimensions (>2mm) and smaller features (<500 µm). The comparison of the measured dimensions showed a minimum deviation of 0.4% from the designed values and a maximum deviation of 7%. This study revealed some of the limitations and pitfalls to be avoided in manufacturing similar geometries. Finally, it laid the foundation to establish a methodology for further investigations of micro additive manufacturing technologies. This will be instrumental to understand current process developments, their performances and challenges, and eventually, the opportunities they offer for future applications.

Acknowledgment

This work is part of the Eureka Eurostars-2 E!113461 AcouPlast project funded by Innovation Fund Denmark, grant no. 9046-00127B, and Vinnova, Sweden's Innovation Agency, grant no. 2019-04500.

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