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Exploring the Manufacturability and Quality of Small-Scale Hole via Fused Deposition Modeling Technology

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Abstract

Fused Deposition Modeling (FDM) is a 3D printing process that builds parts layer by layer by selectively depositing melted material in a predetermined path. FDM has gained popularity due to its low cost, ease of use, and wide material availability. However, there are still challenges to overcome, especially when it comes to producing small-scale features with high precision and quality. Small-scale features are essential in many applications such as microfluidics, microelectronics, and biomedical devices. The ability to produce high-quality small-scale features with FDM can significantly expand its potential applications. This paper aims to assess the manufacturability of small holes using 3D printing-FDM Technology. Benchmarking specimens contained holes with varied sizes are designed and fabricated with different parameters (layer height and building direction). The results of this study provided an insights into the limitations and capabilities of FDM technology for small-scale holes fabrication and help to identify potential areas for improvement.

Keywords
3D printing, Fused Deposition Modeling, Design for 3D printing, Small features, Small holes.

1. Introduction
Additive manufacturing, also known as 3D printing, has revolutionized the way we produce objects, enabling the fabrication of complex geometries with ease and precision. Among the various 3D printing technologies available, Fused Deposition Modeling (FDM) has gained significant popularity due to its low cost, user-friendly nature, and wide range of compatible materials (Rajan, Kumaresan, et al,2022). FDM works by selectively depositing melted material layer by layer to build a part according to a predetermined path. FDM also known as Fused Filament Fabrication (FFF). The FDM process begins with a 3D model of the desired object, which is sliced into thin layers by specialized software. The 3D printer then heats a filament of thermoplastic material, typically ABS (Acrylonitrile Butadiene Styrene) or PLA (Polylactic Acid), to its melting point. The melted material is extruded through a nozzle and deposited onto the build platform or previous layers, following the pre-determined path specified by the sliced model. As the deposited material cools down, it solidifies and adheres to the previous layers, gradually building up the object. The printer moves the nozzle along the X, Y, and Z axes to create the desired shape. Support structures may be added during printing to provide stability for overhanging or complex features, and these supports can be removed after the printing process is complete. The ability to manufacture small-scale holes using FDM technology is an area of interest and research. Understanding the manufacturability and quality of small holes is crucial for expanding the applications of FDM and improving its capabilities. This exploration involves assessing the effects of different parameters, such as layer height and building direction, on the fabrication of small holes using FDM.

2. Literature Review

Serval researchers gave attention to the features manufacturability and the quality of the objects produced via FDM. For instant For example, Mwema, F. M etal 2020 used dimensional and microscopy in quality assessments of home-made 3D printed products. Some of the common elements (shapes) were created. These shapes include circular, diamond, hollow, square, and S-shapes. The dimensions of the printed elements were measured and compared to the CAD models. Significant inaccuracies were noted on diamond tips, corners, and S-shape thickness. Optical microscopy demonstrated that dimensional variations were primarily due by insufficient filament material fusion during printing. Sudin et al 2016 studied the dimensional accuracy of components manufactured using the Fused Deposition Modelling (FDM) additive manufacturing technology. An investigation of sixteen different dimensions of the part feature revealed that the dimensions of the parts had a substantial effect on the dimensional correctness of the FDM model. Furthermore, it was discovered that the FDM machine is less accurate when making circular form parts such as cylindrical, sphere, and hole since the bulk of them are outside of the machine's tolerance. For the evaluation of the FDM process, a benchmark part with diverse shapes, features, and geometries was used by Abdulrahman Al-Ahmari et.al 2021. Wadea Ameen et al. (2018) investigated the fabrication of overhang round holes with and without support. The experiments were carried out with Ti6Al4V powder and electron beam melting (EBM). A large number of overhanging holes, both with and without support, were made and evaluated. Geometrical precision, mechanical properties, and microstructures were used to assess process performance. It was demonstrated that up to a specific dimension (18mm) overhanging elements can be successfully created without support. Knoop, F., and Volker Schöppner 2017, Studied the geometrical precision of the holes and cylinders of the cylindrical elements. Different test specimens with inner and exterior diameters ranging from 3 to 80 mm were created. To analyze deviations from the nominal size and form deviations, all specimens were measured with a coordinate measuring machine (CMM). The method of measurement includes scanning the surface to record the path of dimensional deviations over the diameter. This paper focuses on exploring the manufacturability and quality of small-scale holes using FDM technology. The primary objective is to assess the capabilities and limitations of FDM in fabricating small holes.

3. Methods

The methods include three stages, the first stages is designing the benchmarking specimens for the holes with different sizes, the second stage is fabrication the designed specimens with different orientations and layer thickness, the third stage is evaluation the fabricated specimens using the appropriate instruments.

3.1 Design the Benchmarking specimens

To evaluate the manufacturability of small scale holes, benchmarking specimen is designed using SolidWorks CAD software as shown in Figure.1.

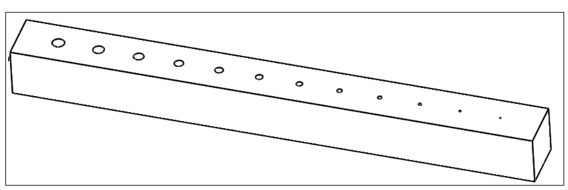


Figure1. Designed holes benchmarking specimen

The round holes are designed with a variety of sizes ranged from 0.1 mm to 1.2 mm with increment of 0.1 mm as shown in Figure.2. The specimen is designed with height 5mm and 5mm thickness.

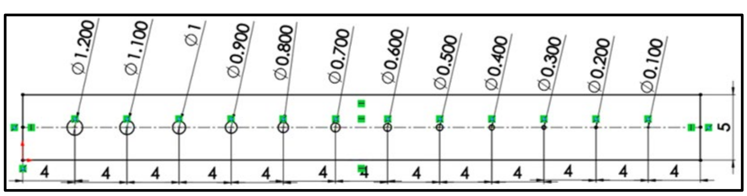


Figure 2. Dimensions of designed round holes

3.2. Fabrication the Benchmarking specimens

The benchmarking specimens models are prepared for printing using ideaMaker software. In this stage the models are placed in the platform, the selected building direction and layer height are adjusted. Tow layer heights (0.1 and 0.2mm) and two building directions (Horizontal and Vertical) are consider in this study as shown in Figure 3.

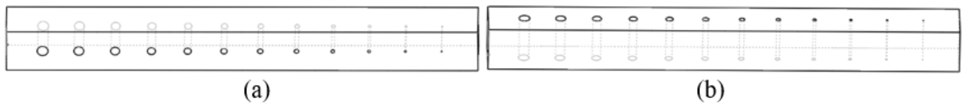


Figure 3. Designed specimens a) Horizontal building direction b) Vertical building direction

Also 0.4mm nozzle diameter, and 100% infill density are used as a fixed printing parameters. Support structures are generated only in the bottom of the models (in touch platform). RAISE3D E2 (FDM) printers are used to fabricate the designed specimens. Figure 4 shows the used RAISE 3D E2 printers and Figure 5 and Figure 6 shows the fabricated specimens. Also PLA filament materials having a diameter of 1.75 mm have been used.

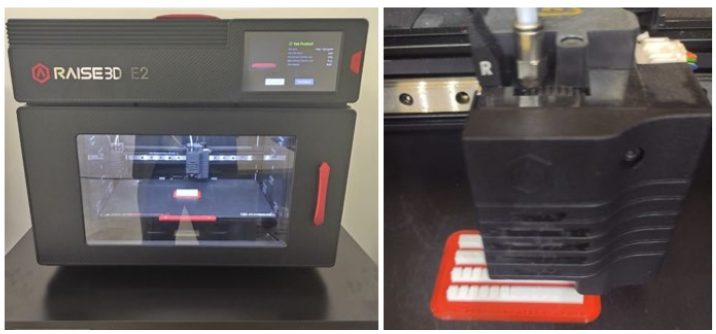


Figure 4. RAISE 3D E2 printer

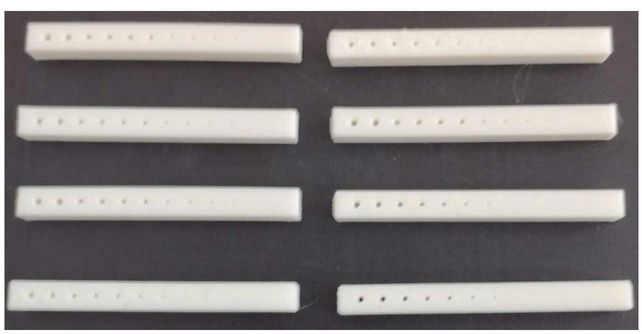


Figure. 5. sample of fabricated specimens

3.3 Manufacturability and quality evaluation

Before evolution the manufacturability and the quality of the small scale features the effect of the layer height and the build direction on the building time is evaluated. To evaluate the manufacturability and the quality of the small features visual inspection, USP microscope and light projector are use. The first step of the evolution is to evaluate the manufacturability (existing of the feature) of the features where the second step is to evaluate the quality of the features though evaluate the dimensions errors.

4. Results and Discussion

4.1Building time

Table 1 and fig. 6 present the time of fabrication the specimens with the variety of building direction and layer height. The same specimen has been used the difference only in the building direction and layer height. Both parameter have effect on the building time and the horizontal building diction and high layer height resulted with the minimum building time. High layer height reduce the number of layers and the horizontal building diction avoid the shifting from liner to rotational motion of the nozzle in each layer which resulted in shorter fabrication time.

Table1. Building time of the specimens

Experiment number	Building direction	Layer Height (mm)	Building time (min)
1	Horizontal	0.1	30.61
2	Horizontal	0.2	18.55
3	Vertical	0.1	35.8
4	Vertical	0.2	20.88

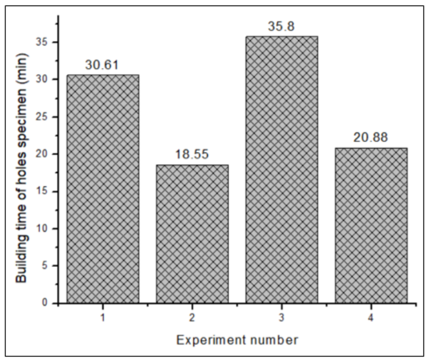


Figure 6. Building time of the specimens

4.2 Manufacturability and quality of the fabricated holes

To evaluate the manufacturability and quality of the fabricated holes profile projector is use as shown in Figure 7. Manufacturability of the holes are assessed in two cases, manufacturable holes and unmanufacturable holes. A through holes that appear in the profile projector are considered as manufacturable holes, while the designed holes that weren't made on the specimens or made as a blind holes are considered as unmanufacturable holes.

The quality (roundness) of the holes are evaluated only for the manufacturable holes where the table cells of unmanufacturable holes are kept empty as presented in Table 2.

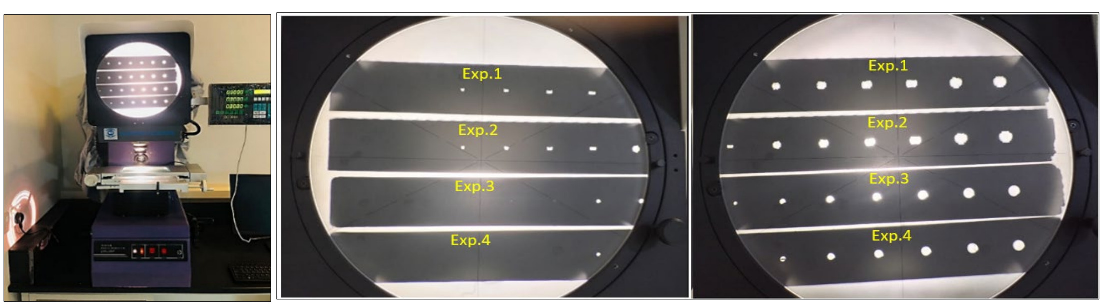


Figure 7. The used profile projector

To confirm the repeatability of the printing process each experiment has been conducted twice times and two specimens has been printed and evaluated for each experiment. Figure. 8 shows how the produced holes of experiment 1 are completely identical.

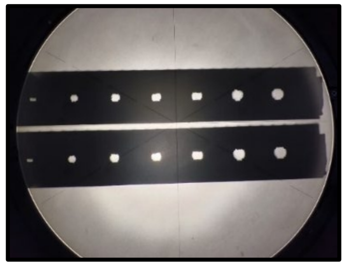


Figure 8. The used profile projector

The results of manufacturability evaluation showed that the minimum printable hole that fabricated horizontally with layer heights 0.2mm and 0.1mm is 0.3mm and the minimum printable hole that fabricated vertically with layer heights 0.2mm and 0.1mm is 0.6mm and the holes that had diameters less than these limits didn't appear the fabricated specimens as shown in table.

Table 2. Manufacturability of the fabricated holes

#	Design diameter (mm)	Horizontal building direction		Vertical building direction	
		Layer height 0.1 mm	Layer height 0.2 mm	Layer height 0.1mm	Layer height 0.2 mm
1	0.1	Unmanufacturable	Unmanufacturable	Unmanufacturable	Unmanufacturable
2	0.2	Unmanufacturable	Unmanufacturable	Unmanufacturable	Unmanufacturable
3	0.3	Manufacturable	Manufacturable	Unmanufacturable	Unmanufacturable
4	0.4	Manufacturable	Manufacturable	Unmanufacturable	Unmanufacturable
5	0.5	Manufacturable	Manufacturable	Unmanufacturable	Unmanufacturable
6	0.6	Manufacturable	Manufacturable	Manufacturable	Manufacturable
7	0.7	Manufacturable	Manufacturable	Manufacturable	Manufacturable
8	0.8	Manufacturable	Manufacturable	Manufacturable	Manufacturable
9	0.9	Manufacturable	Manufacturable	Manufacturable	Manufacturable
10	1	Manufacturable	Manufacturable	Manufacturable	Manufacturable
11	1.1	Manufacturable	Manufacturable	Manufacturable	Manufacturable
12	1.2	Manufacturable	Manufacturable	Manufacturable	Manufacturable

Manufacturable hole (green) Unmanufacturable hole (red)

It was observed that the least printed hole in the horizontal direction is 0.3mm in diameter and 0.8mm in vertical detraction. Lower hole diameters do not appear at all on the profile projector. Minimum Zone circle (MZC) method is used to assess the roundness of the fabricated through holes. The MZC method uses the minimum zone circle as the reference circle to evaluate the roundness as shown in the Figure 9 (Knoop, F., and Volker Schöppner,2012, Elerian, F. A etal 2021).

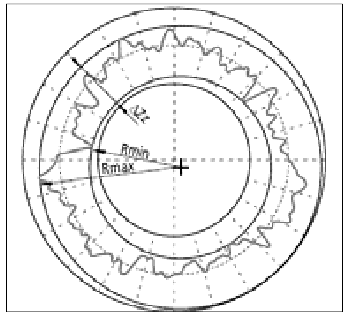


Figure 9. The Minimum Zone Circle (MZC) method

The roundness error is expressed as follows:

$$\Delta Zz = R\ max - R\ min \qquad (1)$$

Where R max and R min is the maximum and minimum distance between the MZC circle and the measured profile. Table 3 presents the roundness of the horizontally and vertically fabricated holes with different layer heights

Table 3. Manufacturability (ΔZz) and the roundness of the fabricated holes

#	Design diameter (mm)	Horizontal building direction		Vertical building direction	
		Layer height 0.1 mm	Layer height 0.2 mm	Layer height 0.1mm	Layer height 0.2 mm
1	0.1				
2	0.2				
3	0.3	0.159	0.133		
4	0.4	0.206	0.122		
5	0.5	0.207	0.133		
6	0.6	0.236	0.255	0.113	0.035
7	0.7	0.167	0.148	0.179	0.090
8	0.8	0.176	0.208	0.023	0.080
9	0.9	0.182	0.250	0.121	0.041
10	1	0.435	0.381	0.114	0.039
11	1.1	0.275	0.257	0.062	0.118
12	1.2	0.228	0.229	0.093	0.105

The results show that the building dedication has significant effect on the roundness of the fabricated holes and building of the holes in vertical building direction result on better quality. The layer thickness has no clear effect on the roundness of the fabricated holes. The roundness errors of the fabricated holes are decreased as the holes dimeters are increased.

The percentages of roundness errors to the designed holes dimeters also calculated by dividing the hole roundness error on designed hole dimeter as presented in Table 4.

$$P\Delta Zz = \Delta Zz/D \qquad (2)$$

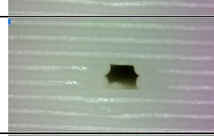
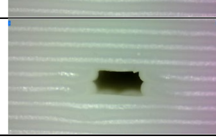
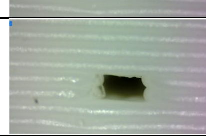
Where the PΔZz is the percentages of roundness errors and the D is the designed hole dimeter.

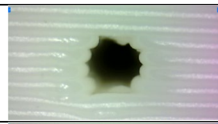
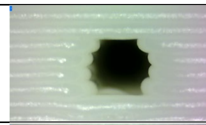
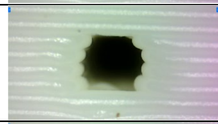
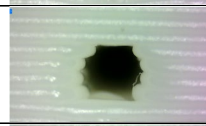
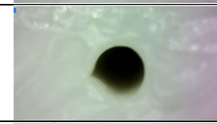
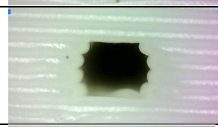
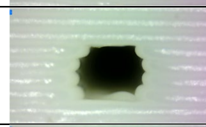
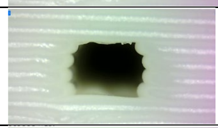
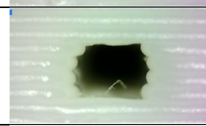
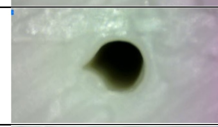
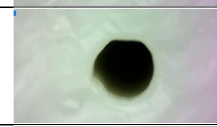
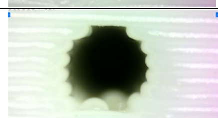
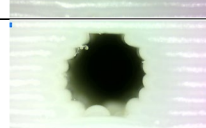
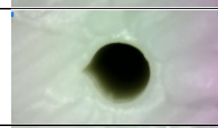
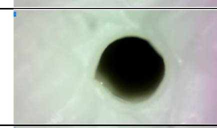
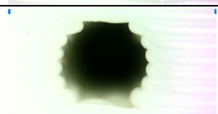
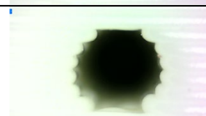
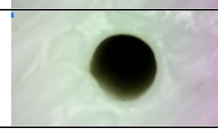
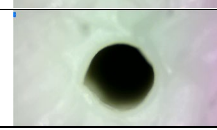
Table 4. Percentages of roundness error to the designed holes dimeters (ΔZz/D)

#	Design diameter (mm)	Horizontal building direction		Vertical building direction	
		Layer height 0.1 mm	Layer height 0.2 mm	Layer height 0.1mm	Layer height 0.2 mm
1	0.1				
2	0.2				
3	0.3	0.530	0.442		
4	0.4	0.398	0.331		
5	0.5	0.318	0.265		
6	0.6	0.265	0.221	0.188	0.058
7	0.7	0.227	0.189	0.161	0.050
8	0.8	0.199	0.166	0.141	0.044
9	0.9	0.177	0.147	0.126	0.039
10	1	0.159	0.133	0.113	0.035
11	1.1	0.145	0.120	0.103	0.032
12	1.2	0.133	0.110	0.094	0.029

It's clear that in general as the hole diameters are decreased the percentages of roundness error are increased and that return to the difficulty that the printer head to rotate in very small space. Also, printing in narrow spaces generates vibration for the entire printer, which results in printing errors. USB-Digital-Microscope-attached with Camera (Model B011) is used to evaluate the micro features. Table 5 shows the microscopic images for the fabricated holes.

Table 5. Optical microscopy images for the fabricated holes

Design diameter (mm)	Horizontal building direction		Vertical building direction	
	Layer height 0.1 mm	Layer height 0.2 mm	Layer height 0.1mm	Layer height 0.2 mm
0.1				
0.2				
0.3				
0.3				
0.4				
0.5				
0.6				

0.7				
0.8				
0.9				
1				
1.1				
1.2				

The microscopy images confirm the printed holes in vertical direction have better roundness compared with those fabricated in horizontal direction. Also it's clear that the roundness are improved as the hole dimeters are increased.

5. Conclusion

The aim of this study is to evaluate the manufacturability and the quality of small holes via FDM 3D printing technology with different layer heights and building directions. The following conclusions are drawn based on the results:

- The minimum printable hole in the horizontal direction is 0.3 diameter mm and 0.8mm in vertical detraction.
- The minimum printable diameter pin is 0.9mm and any diameter less than 0.9mm didn't appear in the fabricated part.
- The printing direction has a significant effect on the hole manufacturability and quality and the vertical build direction perform well better than the horizontal build direction.

More studies can be conducted in the effect of printer parameter on the process capability on fabrication the other small features and. Also different materials can be used and the rules can be developed for each materials.

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Biography

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