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Microhole Creation in FDM-Printed Sheet Polymers: A Punching Process Approach

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ABSTRACT

Fused deposition modeling (FDM) 3D printing is one of the additive manufacturing processes that can make components with complex shapes, require no tools, are cheap, safe, and have minimal waste. Despite all the advantages of the FDM process, the inability of this technique to create holes on a micro scale can be a problem and limits its application. In this research, a combination of FDM and machining processes was carried out, where micro holes in FDM printed components were created using a punching process. The punching process is carried out by varying pressure and speed. Furthermore, the diameter of the hole and the quality of the sheared edge of the hole resulting from the punching process were evaluated through observation using an optical microscope. The results show that the holes resulting from the punching process have a better shape and diameter than the FDM process. Then, the analysis of the sheared edge from punching shows that pressure and speed significantly affect the surface quality of the resulting sheared edge, where the quality increases with increasing pressure and speed. In the end, the punching process was proven to create micro-scale holes in FDM-printed polymer, especially at minimum thickness.

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1. INTRODUCTION

Fused deposition modeling (FDM) is a manufacturing technique that uses polymer filament spools as raw materials and is widely known as three-dimensional printing (3D printing). Contrary to machining techniques, which are generally subtractive, where the material is reduced gradually until it becomes the desired shape, FDM adopts an additive technique where the material is added gradually in layers, making this technique known as additive manufacturing or layer manufacturing process (Gurr and Mülhaupt, 2012; Pratama *et al.*, 2021). This additive processing method makes FDM reliable, especially in polymer processing. This is shown by several advantages that FDM has, such as no tools required, thus making this process cheaper, safer, and have minimal waste (Cantı and Aydın, 2018; Cheng *et al.*, 2017; Jami *et al.*, 2013; Masood and Song, 2004; Sood *et al.*, 2010).

In addition, the FDM technique has also been proven to be able to create complex shapes without using a mold (Adib *et al.*, 2024). Given the advantages offered by FDM-based additive manufacturing, this technique has the potential for the fabrication of micro parts, particularly for Microelectromechanical Systems (MEMS) applications using polymers (Aronne *et al.*, 2024; De Pasquale, 2021; Petersen *et al.*, 2020; Sun and Velasquez-Garcia, 2017). On the other hand, this technique also has several disadvantages, such as low mechanical properties of printed components (Ivey *et al.*, 2017; Keleş *et al.*, 2017; Pratama *et al.*, 2024a; Pratama *et al.*, 2024c) as well as poor dimensional accuracy and surface quality. (Garg *et al.*, 2016; Krolczyk *et al.*, 2014; Pratama *et al.*, 2022; Akande, 2015).

Another weakness that was rarely discussed or even researched was the inability of the FDM process to produce micro-scale printed components, especially circular shapes or holes, as shown in **Figure 1**. This is caused by the use of a stepper motor as the nozzle driver, thereby having low accuracy in the micro-scale motion. On the other hand, printing components with minimum thickness can also cause geometric failure due to warping (Kusuma *et al.*, 2022).

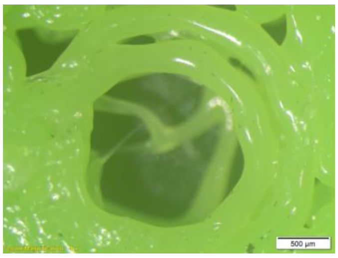

Figure 1. FDM printed micro holes (1.7 mm diameter)

Literature discussing the issue on micro-scale feature creation using FDM are scarce. One previous study stated that subtractive methods like drilling could overcome this problem. This research proves that holes in FDM-printed components can be made with various hole dimensions, which shows the machineability of FDM-printed components (Gómez-Gras *et al.*, 2021).

Moreover, previous research focused on solving this problem by optimizing printing parameters. Research conducted by Chang and Huang shows that the profile error is mainly caused by the lack of contour and dimensions, which could be optimized during the slicing (Chang and Huang, 2011). However, this technique may not be suitable for overcoming the contour shape failure shown in **Figure 1**, making the machining process a promising method for solving this problem. The drilling technique can be promising if the component has adequate thickness. However, this process may be less efficient in thin components due to a cushion required under the workpiece. Based on several considerations, punching may be an appropriate technique for hole-making in printed components with a minimum thickness.

Punching is a machining process generally used for sheet metal shearing (Kurniawan *et al.*, 2020b). In this technique, the success of the cutting process is mainly supported by pressure, speed, and the effective distance between the tool and the die, known as clearance (Kurniawan *et al*., 2022). Fast processing is the main advantage of this technique; thereby, it is widely used in making components for electronic, automotive, aerospace, and even medical applications (Duan *et al.*, 2021; Engel and Eckstein, 2002; Vollertsen *et al.*, 2006; Zeidi *et al.*, 2021). Although it is commonly used in metal processing, the simplicity of the punching process may be an appropriate and efficient solution for micro-hole making in FDM-printed thin components.

Based on various considerations, the punching process could be an effective technique for creating micro-scale holes in printed components with minimal thickness, warranting further investigation. This research aims to evaluate and identify the most suitable manufacturing method for producing micro-features, such as holes, in FDM-printed components, focusing on developing the fabrication of micro-components for MEMS applications using the FDM process. This study assessed the punching technique by varying parameters such as pressure and speed to determine its efficacy and precision in producing accurate micro-holes.

2. RESEARCH METHODOLOGY

This research aims to evaluate the effect of punching parameters on the resulting hole, such as dimensional accuracy and sheared edge quality. The outcomes must be compared with the holes manufactured using the FDM process. FDM samples with holes were printed with a Creator Pro 3D printer (Flashforge, China) using PLA filament (eSun, China).

Figure 2 (a) shows the dimensions of the sample, which has a thickness of 0.6 mm. As can be seen in the illustration of **Figure 2** (b), the FDM process makes components by printing the outer contour first (1), then the inner circle contour (2), and finally, the empty area is filled with infill (3). During the process, shape failure occurs when making the inner circle, resulting in an imperfect shape, as shown in **Figure 1**.

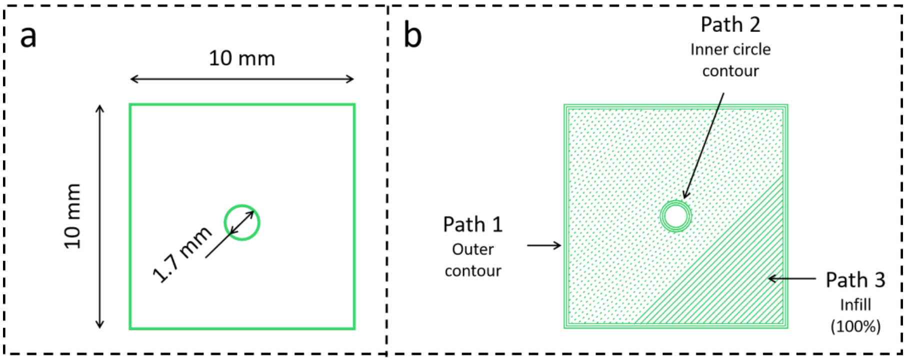

Figure 2. (a) specimen dimensions, and (b) sequence of the hole-making process in FDM

Table 1. Design of Experiment (DoE) in this research

Run	Air Pressure	Punch Speed	Sample code	Number of samples
Control	-	-	FDM	3
1	4	30	A1	3
2	4	40	A2	3
3	4	50	A3	3
4	5	30	B1	3
5	5	40	B2	3
6	5	50	B3	3
7	6	30	C1	3
8	6	40	C2	3
9	6	50	C3	3
Total number of samples				30

Table 2. Printing parameters

No	Parameters	Unit
1	Temperature	200 ºC
2	Raster angle	Default (45°/-45°)
3	Printing speed	30 mm/min
4	Printing orientation	Horizontal
5	Layer height	0.2 mm
6	Infill percentage	100%

After the FDM sample with holes had been made, several other samples were printed without holes as a sample for the punching process. The varied parameters in the punching process are pressure and punch speed, so the design of the experiment (DoE) is shown in **Table 1**, where samples with FDM printed holes are used as controls. All variations of the group sample were printed three times using the same printing parameters, as shown in **Table 2**. Based on the printing parameters used, namely a layer height of 0.2 mm, each FDM printed sample consists of 3 layers.

(a) (b)

Figure 3. (a) micro punch machine, and (b) tools and dies used

The punching process was carried out using a micro punch machine specially designed for making micro-scale holes, as shown in **Figure 3** (a). Either tool and die were made using high-speed steel (HSS) with a tool dimension of 1.70 mm and a die hole dimension of 1.725 mm, as shown in **Figure 3** (b). Since the micro punch machine used was explicitly designed for titanium processing, the force generated by pneumatics as a machine driver can certainly process polymer materials. The machine has a length, width, and height of 350 mm, 350 mm, and 659 mm, respectively, and the component specifications are provided in **Table 3.** The punching machine can generate force up to 1 kN.

After punching, the hole dimensions (top and bottom) of all group samples from FDM, A, B, and C were captured under an optical microscope Olympus with 4× zoom magnification. The specimens were sectioned in the middle to evaluate the sheared edge of the punched samples, as shown in **Figure 4.** The sheared edge was captured using an Olympus optical microscope with 11.5× magnification, with one sample from each group selected as a representative for observation.

The measurement of diameter and sheared edge is carried out using image processing techniques using the open-source software ImageJ. In general, the sheared edge resulting from punching consists of 3 main areas, namely roll-over, burnish, and fracture and burr (F&B), as shown in **Figure 5**. Eventually, the best quality is determined by the highest percentage of burnish, which is the smoothest part of the cut (Kibe *et al.*, 2007; Kurniawan *et al.*, 2019).

Table 3. Specifications of the punch machine components

Component	Model
Hydraulic actuators	KAIYUAN SC160-100R
Load Cell	Zemic L6E 50 tons capacity
Velocity sensor	LJ12A3-4-Z/B

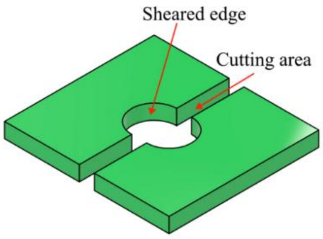

Figure 4. Cutting position and sheared edge of the sample

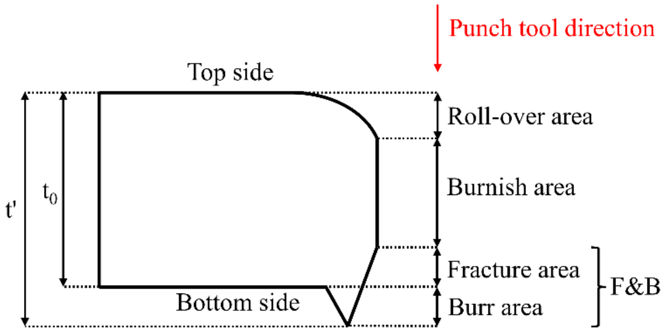

Figure 5. The sheared edge area resulting from the punching process

3. RESULTS AND DISCUSSION

3.1. Hole diameter of FDM and punched samples

The results of the observations on the shape of the holes produced by FDM and punching are shown in **Figure 6**. As shown in the figure, the resulting holes from the punching process have a perfect circle shape, unlike FDM holes. This shows the potential for using the punching process on polymer materials, especially FDM-printed components.

The hole diameter measurements from each sample group are shown in **Figure 7**. It should be noted that the expected hole diameter is 1.7 mm or 1700 µm. Based on the graph shown in **Figure 6**, the hole diameter in the FDM sample has significantly smaller dimensions than the expected diameter. The hole diameter on the top side of the FDM sample is 1440.67 ± 117.5 µm, while the bottom side has a larger diameter, i.e., 1559.43 ± 41.64 µm. This might occur due to the process of depositing material in layers, which ultimately causes a staircase and overlapping phenomenon, shifting the deposited material on the top position towards the inside of the hole and reducing the diameter on the top side.

In contrast to the punched PLA, the hole diameters in sample groups A, B, and C have a contradictory phenomenon, where all the upper diameters are larger than the lower diameters. Several factors may cause this: (1) polymer materials are more elastic than metal, resulting in an imperfect shearing process but partly tension. As shown in **Figure 6** (b), (c), and (d), the area around the hole turns white, indicating a crazing phenomenon caused by excessive tensile load; (2) this phenomenon could also occur due to tool wear and misalignment during the punching process (Kurniawan *et al.*, 2020a). Nonetheless, the diameter of the punched PLA in all sample groups had good results and was close to the desired diameter. None of the diameters in the punched PLA sample group were <1600 µm, especially in the top hole.

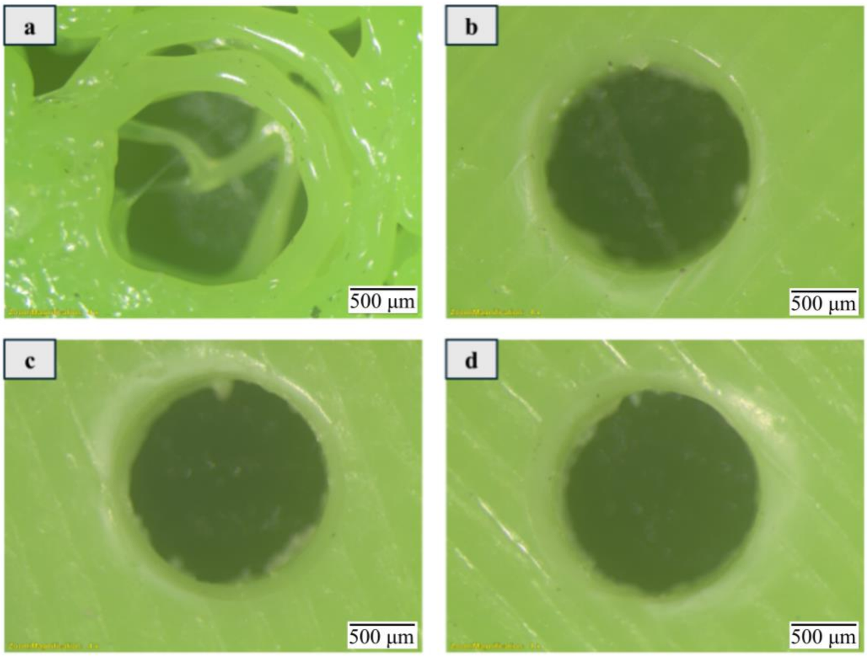

Figure 6. Holes (top side): (a) FDM, (b) group A, (c) group B, and (d) group C

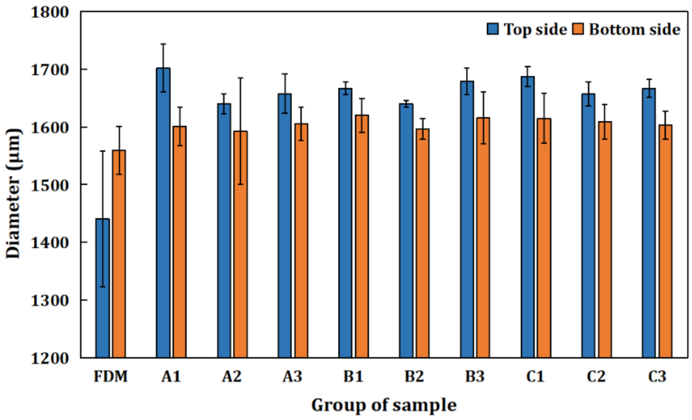

Figure 7. Graphical comparison of hole diameters for each sample group

3.2. Sheared edge of punched samples

Observations on the sheared edge of sample groups A, B, and C are shown in **Figure 8**. In the figure, each area of roll-over, burnish, as well as fractures and burrs from each punched sample were indicated by the area with a yellow line. Then, the cross-sectional of each area was calculated and shown in **Figure 9**. The graph shows that air pressure and speed significantly affect the edge quality of punched PLA, which is indicated by an increase in the burnish area. In area A, when compared to the burnish areas A1, A2, and A3, it can be seen that the burnish area increases as the speed increases, even though the same air pressure was used. This pattern then repeats in group samples B and C.

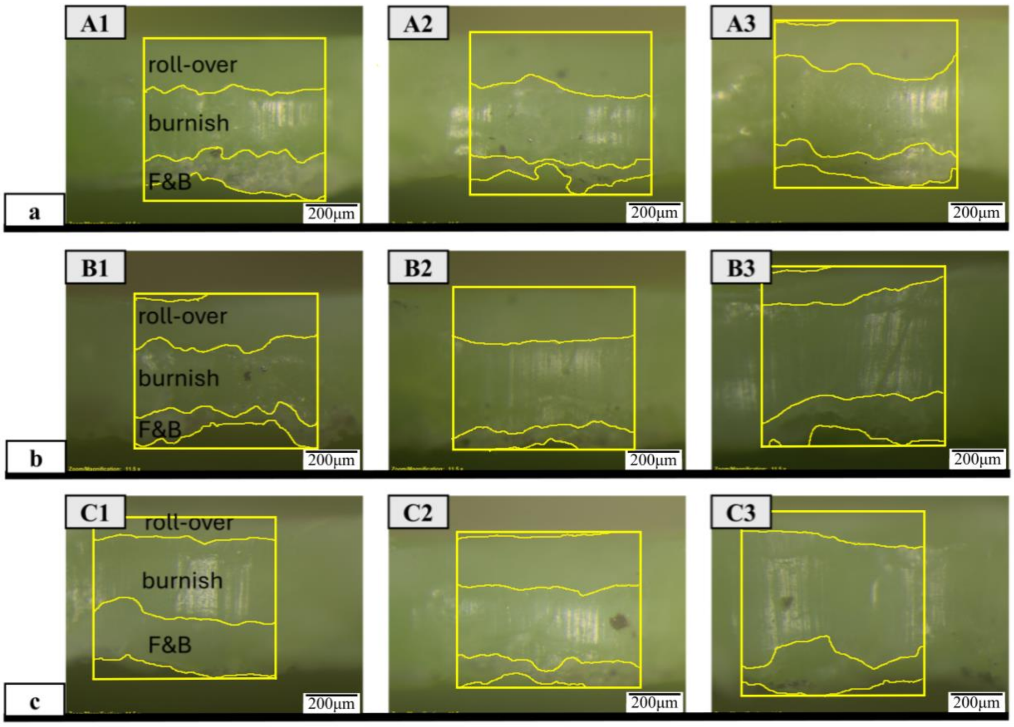

Figure 8. Observation of the sheared edge of (a) group A, (b) group B, and (c) group C

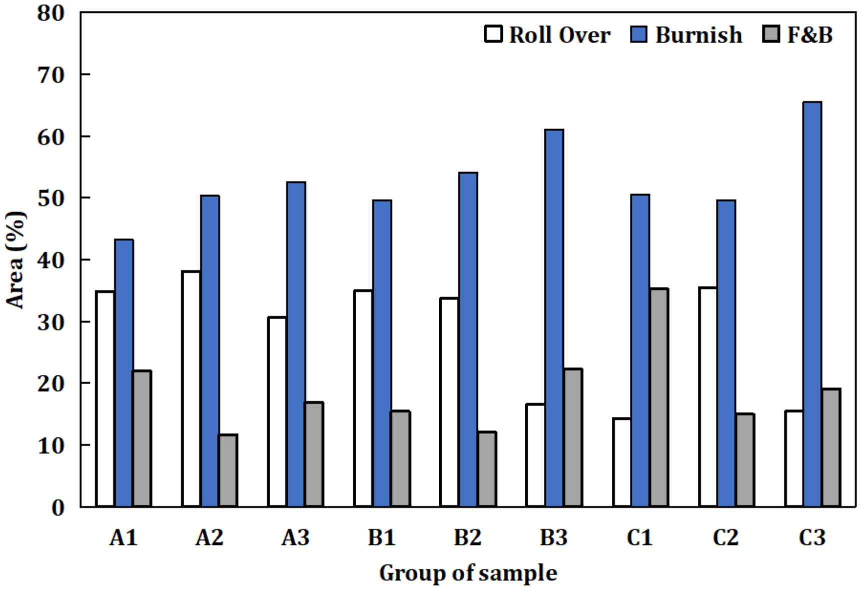

Figure 9. Comparison graph of sheared edges from each sample group

On the other hand, if sample groups are compared with different pressures, for example, A1, B1, and C1, it can also be seen that the burnish area increases. However, the increase in the percentage of burnish area is not as high as with speed variations. A significant increase is visible in sample groups A3, B3, and C3, where the burnish area increases significantly along with increasing pressure at high speed, i.e., 50 mm/min.

This finding shows that speed has a more significant effect on the sheared quality compared to pressure. After going through the punching process, the phenomena that occur in FDM-printed PLA samples ultimately have a similar pattern to metal (Joo *et al.*, 2005). However, an exciting thing emerged in this research, where the layer boundaries of the FDM printed polymer were no longer visible after the punching process, as shown in **Figure 8**.

4. CONCLUSION

This research successfully demonstrated the application of the punching process for creating micro-holes in FDM-printed thin sheet components. The punched holes exhibited superior shape and dimensional accuracy compared to those produced by FDM printing, with diameters closer to the desired dimensions. Both pressure and speed significantly influenced the sheared edge quality of the punched PLA, with speed being the more critical factor, particularly at higher pressures. Additionally, the punching process improved bonding between layers by eliminating the visibility of interlayer lines. These findings suggest that the micro-punching process is a promising method to produce accurate micro-scale holes in polymer sheets, which has great potential to improve Microelectromechanical Systems (MEMS) fabrication using FDM technology, especially for applications that require precise micro-holes.

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