Polydimethylsiloxane Microchannel Fabrication from 3D Printed Mold

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ABSTRACT

3D printing has a great effect in microfluidics field of study due to fastest and cheapest way in producing a microchannel. In this work, replication, characterization and testing of PDMS microchannel have been demonstrated by using 3D printed mold technique. The characterization of the 3D printed mold and replicated PDMS microchannel is performed using an optical and scanning electron microscope (SEM). From the 3D printed microchannel mold characterized, it is observed that as the design width increases, the accuracy of the 3D printer increases for the width but decreases for thickness. Finally, PDMS microchannel and PDMS base were successfully bonded using a plasma cleaner set for 12 seconds at 200 mTorr. A functional test was then conducted using flowing colour dyed water with a maximum volumetric flow rate of 9 ml/min from a syringe pump into the PDMS microchannel. No leakage was observed during the testing due to the strong bond between the flat PDMS surfaces. Replication of PDMS microchannel using 3D printed mold technique has proven to save time and more economically. Therefore, 3D printed mold technique is proven as latest solution and a viable option to expedite and mass produce PDMS microchannels for the market.

Keywords: *3D Printed mold, microchannel, PDMS, functional test*

1.0 INTRODUCTION

A polydimethylsiloxane (PDMS) microchannel is being recognized in the medical field due to the numerous possible applications in diagnostics, biological cell studies and therapeutics. PDMS material has extraordinary properties such as its nontoxic properties and convenience to produce a final product. To date, there are numerous techniques in fabricating PDMS microchannel i.e. glass and silicon etching, polymer replica and injection molding. Each of the technique brings their own advantages and disadvantages.

In the medical field, microchannel can act as a supplementary technology to a microfluidic system commonly termed ‘lab on a chip’ or ‘MicroTAS’ (Micro Total Analysis System). Microchannel can deliver fluid samples to the MicroTAS, in which the MicroTAS can analyze the fluid samples down to the smallest picolitre [1]. The market and demand for microchannels are there and and increasing. Hence, to cater for these potential demands, microchannel must be fabricated quickly and inexpensively as a way to reduce the cost and maximize profit.

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The popular technique in fabricating microchannel is using SU-8 mold replication technique. However, these technique is inconvenient without microfabrication facilities and expensive for mass production. Thus, the 3D printed mold technique might be the solution due to its fast and cheap replication process.

Present 3D printers are able to print products in a wide range of geometrical dimensions. Accuracy of a 3D printer in printing small dimension down to micrometre will greatly influence the final design of the PDMS microchannel. A common technology that is used by many researchers to print the 3D printed mold is the Fused Deposition Modelling (FDM) which is a rapid prototyping 3D printing technology that was used in this research [2]. FDM melts and extrude thermoplastic filaments through a nozzle and deposited on the built platform to solidify and finally attain the desired shape, layer by layer [3]. To date, works on 3D print PDMS microchannel using PDMS directly has been initiated. However, this technique can only be done by adding an orange dye in the resin which sacrificed the optical advantage of the PDMS [4].

Even with the capability of a high-end 3D printer specifications that has the ability to print features down to several tens of micrometre, the actual printing capability of the printer is still doubtful [5]. In fact, some researchers suggested that only microchannel with dimension above 300 μm × 300 μm (in width and depth) can actually be printed using 3D printer [6].

With reference to Figure 1, in order to replicate a PDMS microchannel, a 3D printed mold as shown in Figure 1(a) was used as a master to allow the liquid PDMS to take shape and solidify as illustrated in Figure 1(b) resulting in a solid PDMS microchannel in Figure 1(c) which can be easily peeled and tested after bonding to a PDMS base as depicted in Figure 1(d). In between the replication, a characterization was performed to check the accuracy of the dimensions. Finally, at the end of the study, a bonded PDMS microchannel was tested with dye colored water to check for any leakage.

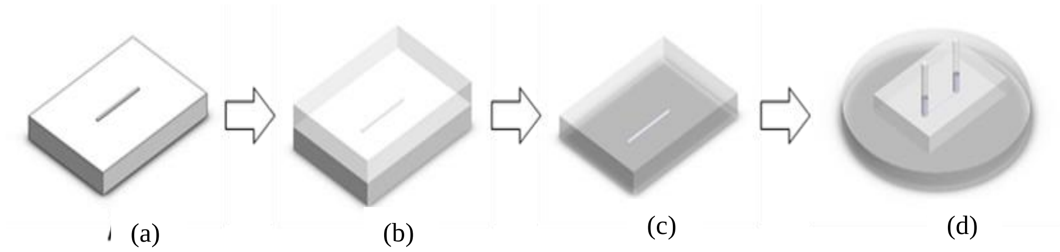

Figure 1: Fabrication of the PDMS microchannel from 3D printed mold

2.0 METHODOLOGY

A 3D printed mold was drawn with a base of length, width and thickness of 35 mm, 25 mm and 5 mm, respectively and a microchannel on top of the base of various widths and thicknesses and a length of 14 mm as shown in Figure 2 for Model E. Numerous models were printed and alphabetically labeled as shown in Table 1.

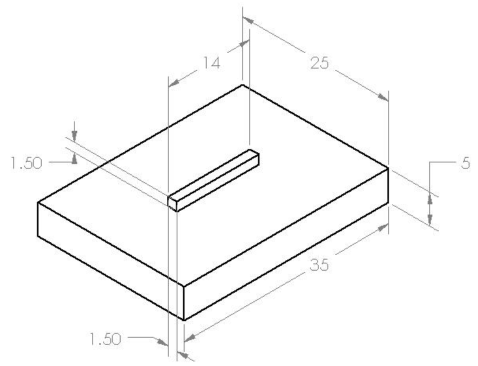

Figure 2: Geometry of the microchannel mold E (in mm)

Table 1: Microchannel models

Model	Width (mm)	Thickness (mm)
O	0.55	0.55
D	1.0	1.0
F	0.1	0.55
G	0.2	0.55
H	0.3	0.55
J	0.5	0.55

Two types of 3D printers were used which are *ANYCUBIC DIY Kossel* 3D printer and *Double Nozzle 3D Printer Creator Pro*. The 3D printed microchannel molds were subsequently printed and compared. The specifications of the 3D printer used in this work are shown in Table 2.

Table 2: Specifications of the 3D printers

Name	ANYCUBIC DIY Kossel	Double Nozzle 3D Printer Creator Pro
Printing Technology	Fused Deposition Modeling	Fused Deposition Modeling
Layer Resolution	0.1 – 0.4 mm	0.1 – 0.5 mm
Positioning Accuracy	X/Y/Z 0.0125 mm	X/Y/Z 0.011/0.11/0.0025 mm
Print Speed	20 ~ 80 mm/s	40 mm/s
Nozzle Diameter	0.4 mm	0.4 mm
Extruder Quantity	Single	Double
Build Size	Ø180 × 320 mm	320 × 467 × 381 mm
Max. Print Bed Temp.	100^{o}C	120^{o}C

In this work, the width and thickness of the microchannel were measured to act as data in order to compare the printed mold with the drawn 3D mold. The models were examined under an optical microscope and only Model G was examined under a scanning electron microscope. An optical microscope uses light to show the microscopic feature whereas a scanning electron microscope uses a beam of electrons to measure the microscopic features. Since SEM uses electrons, heat is subjected to the 3D printed mold and it causes the mold to slightly melt. Because of this issue, the mold was first coated with thin gold layer using a specialized gold coater.

The 3D printed mold was baked in a furnace at 75°C for 45 minutes and later washed using a normal dish washer soap [7]. The 3D printed mold was then wiped dry using a dust-free cotton cloth to safeguard a clean surface and ensuring the mold is completely dry. The cleaning step is crucial as the process was done without dust control environment or without clean room facilities. The cleanliness of the mold surface will ensure good PDMS microchannel structure will be replicated. Next, the mold was wrapped using an aluminium foil. High viscosity liquid PDMS was poured into this folding to ensure PDMS microchannel fixed thickness. Finally, the molds were coated with a *CYCLO* silicon spray sprayed 10 cm away with two passing [8].

A standard weight mixture ratio of 10:1 elastomer and curing agent was mixed using a glass rod. The mixture was initially riched with air bubbles but after degassing, the mixture was cleared of bubbles. By degassing using a refrigerator at 4°C, it took about 2 hours for the mixture to degas. However, for a self-made centrifuge rotating at 435 rpm, it took only 20 minutes to completely degas. The PDMS was then poured and treated in the *LT Furnace L6-1200* at 80°C for 50 minutes [7]. The resulting PDMS was then peeled by hand. However, there are models that either were not coated with silicon or left in the furnace overnight as shown in Table 4. The observation on the replicated microchannel is shown in Table 5.

Models O and D which completely follow the recipe were taken to the next step for bonding and testing. For bonding, the microchannel was first punctured using a biopsy puncture at the two ends of the channel for the fluid inlet and outlet. Then, the two surfaces were exposed for plasma treatment in oxygen plasma PE-50 XL. In this oxygen plasma, the plasma was created as a high frequency voltage that ionised the low pressure gas inside the system. The purpose of this plasma treatment is to further clean the surfaces and activated the PDMS surfaces from hydrophobic to hydrophilic. The hydrophilic surfaces will facilitate the smooth fluid flow in the microchannel. The two PDMS surfaces were then placed upon each other and a weight was applied to secure the bonding. After the bonding process, a flexible silicon tubing of 2 mm in external diameter was installed through the punctured holes. Dye colored water was flown into the microchannel with a volumetric flow rate of 1 mL/min to 9 mL/min using *Legato™ 180* dual syringe picoliter infuse/withdraw pump. The pump can provide precise and stable flow delivery into the microchannel. The bonded PDMS structure was also observed for any sign of leakages.

3.0 RESULTS AND ANALYSIS

3.1 Printed 3D Printed Molds

The 3D printed molds produced from two different 3D printers were shown in Figure 3. It was observed that the first 3D printer (ANYCUBIC DIY Kossel 3D printer) was able to completely print the small structure microchannel down to micrometre dimension.

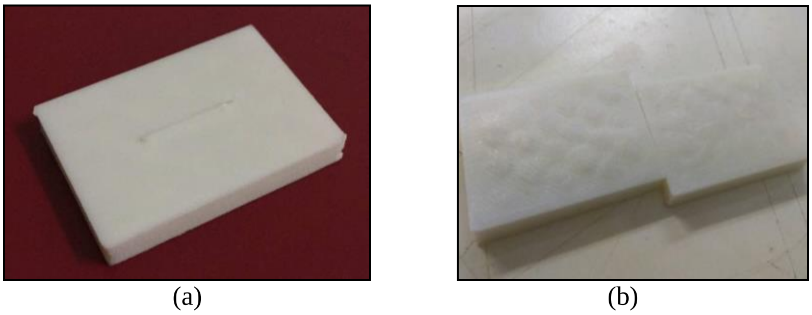

Figure 3: 3D printed microchannels produced using different two 3D printers: (a) *ANYCUBIC DIY Kossel* (b) *Double Nozzle 3D Printer Creator Pro*

For all the 3D printed molds, there were no obvious defects. On the other hand, the second 3D printer (*Double Nozzle 3D Printer Creator Pro*) only printed bumps and failed to print the microchannel. Although the second 3D printer has a better specifications, the problems in the settings caused the printer failed to print the molds. It is recommended that the settings to be reset to allow single extrusion walls. The second solution is to install a nozzle with smaller tip size such as one equipped with a 0.3 mm nozzle.

3.2 Characterization Result of The 3D Printed Molds

The thickness and width of the 3D printed molds were repeatedly measured using an optical microscope. The averaged dimension was calculated and tabulated in Table 3. It can be observed that as the design width increases, the accuracy of the 3D printer correspondingly increases in width but decreases in thickness. This is due to the spreading of the droplet as suggested by [9] and the small size of the nozzle. One can imagine from a small nozzle, to print a larger width the nozzle would have to pass multiple times and this total high release of resin from multiple passes would pile up that in turn subsequently forming a larger thickness. A smaller width would require fewer passes of the nozzle. However, since the nozzle is larger than the width, the expelled width of the resin is larger than the microchannel and since it requires fewer passes, the thickness is more accurate.

Table 3: 3D printed molds specifications

Model	Designed (mm)		Average Printed (mm)		Percentage (%) Difference	
	Width	Thickness	Width	Thickness	Width	Thickness
F	100	550	121.08	539.45	21.08	-1.92
G	200	550	237.67	544.15	18.83	-1.06
H	300	550	354.26	537.20	18.09	-2.33
I	400	550	417.04	575.00	4.26	4.55
J	500	550	502.24	636.85	0.45	15.79

3.3 PDMS Microchannel

In fabricating the PDMS microchannel, only the molds presented in Table 4 were used for replicating and this table also shows the steps taken by each of the molds for the 3D printed mold treatment.

Table 5 shows the observations on the replicated PDMS microchannel. It is therefore concluded that silicon coating facilitates peeling [8] and for better replication, it is suggested to take out the PDMS microchannel immediately after the furnace is cooled down. This is to prevent the PDMS material to become too ‘flowy’ and too thin. The thin PDMS microchannel will result in peeling difficulty from the 3D printed mold. From the optical microscope observation, the PDMS microchannel surface is indeed rough [10] as there are rough edges seen on the walls of the molds. Note that the roughness measurement was not done. However, the roughness is expected to be not significant in contributing to the bonding failure and microchannel flow problem.

Table 4: Steps taken on the PDMS microchannel

Step		Model					
		O	D	F	G	H	J
Bake in a furnace	Yes, at 80°C for 50 minutes	✓	✓	✓	-	✓	×
	No, left at room temperature	×	×	×	-	×	✓
If in furnace	Left overnight	×	×	✓	-	✓	-
	Collect after cooled	✓	✓	×	-	×	-

Coated with Silicon	✓	✓	✓	-	×	✓

Table 5: Observation on the PDMS microchannel

Model	Observation
O	A thick PDMS microchannel with visible air bubbles
D	A thick PDMS microchannel with visible air bubbles
F	A thin microchannel that is easy to peel
G	PDMS microchannel was not replicated
H	A thin microchannel that is difficult to peel and torn
J	A thin microchannel

3.4 Bonding and Functional Testing

For both PDMS microchannels based on Models O and D, there were no leakage to have occurred when subjected to maximum volumetric flow rate of 9 mL/min as shown in Figure 4. This confirms that plasma bonding is a strong type of bonding to bond the two PDMS surfaces. It is reported that this bond is due to the strong covalent bonds created between the two surfaces.

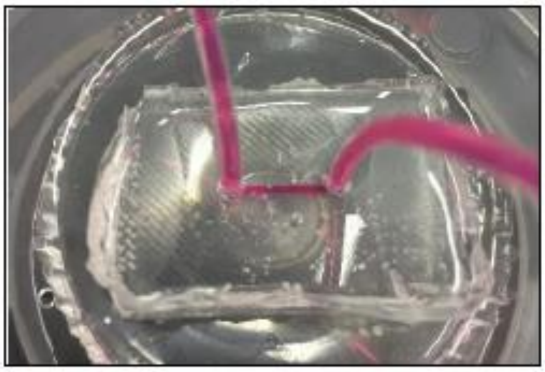

Figure 4: PDMS microchannel during functional testing

Table 6: Leakage with different flow rates

Model	Flowrate of dye colored water (mL/min)								
	1	2	3	4	5	6	7	8	9
O	×	×	×	×	×	×	×	×	×
D	×	×	×	×	×	×	×	×	×

4.0 CONCLUSION

The fabrication of a PDMS microchannel using a 3D printed mold technique has been successfully demonstrated and proven to be a viable technique. This technique is deemed largely inexpensive and the fact that the fabrication of the microchannel is rapid. Furthermore, the technique is also inexpensive with the total price for all of the molds is less than RM 20.00. In addition, it took less than four hours to print 11 microchannel molds. However, despite the many advantages of using this technique, there is a drawback. This includes a rough surface PDMS microchannel was produced as proven from the microscopic images and the large percentage differences between the replicated PDMS microchannel and drawn microchannel due to the spreading of the droplet.

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