

Analysis of Passive Mixing Microchannel Fabrication of Microfluidics Device on Acrylic Material Using Low Power CO₂ Laser

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Abstract

Microfluidics device has been applied in the biomedical fields to manipulate fluids in a channel network with the dimensions between 5-500 μm . Microfluidics device is manufactured by micro fabrication process consists of design, micro structuring and back-end process. One of microfluidics application is passive mixing microchannel. In this device, the fluids will flow through the channel without any moving part and pressure from outside to produce mixing fluid. It is important to design the form of channel to produce a good passive mixing microchannel. In this study, the process of channel design was performed. Low power CO₂ laser was used for microstructuring process as a cutting tool to produce microfluidic device on acrylic material. The parameters affect the output of the cutting process are the laser power, cutting speed and the design of channel. Surface roughness of designed channel was observed. Finally, back-end process was performed by joining process using thermal bonding method. From the experimental results, the design of channel 1 has an influence on all parameters to the surface roughness compared to design of channel 2.

Keywords: Microfabrication, microfluidics, passive mixing microchannel, CO₂ laser, acrylic material

Introduction

Recently, in biomedical applications there are many concepts to solve the problems on the fields. One of the concepts is microfluidics fabrication, such as by making channel of capillary-like networks [1], biochemical observations of flow characteristics for Au NPs and CuSO₄ using varied channel [2], and many other models as shown in Fig. 1.

Previously, silicon [3] and glass [4] materials were used widely for microfluidics fabrication, because of the good physical, electrical and optical properties, but the material cost was high. While the use of polymer materials for microfluidics fabrication can reduce costs and be able to use a simple manufacturing process when compared to silicon and glass materials.

Comparison of some material for microstructuring for microfluidics fabrication is shown in Table 1. Some examples of material are included polymer material which are polymethyl methacrylate (PMMA), polycarbonate and poly dimethylsiloxane (PDMS).

Several techniques for microfluidics fabrication have been conducted by using etching and photolithography for silicon and glass material [6]. And for the polymer material, several forming techniques can be used such as hot embossing [7], injection molding [8], soft lithography [9] and laser ablation [10].

Laser has been used since 40 years ago for cutting, drilling and welding. In biomedical applications, the use of laser machining is widely used because the laser cutting process is carried out precisely, less carbonization and good results of cutting compared to conventional cutting processes.

Microfluidics fabrication using laser has been carried out with various types of laser, particularly using CO₂ laser machine [11].

In this study, the use of laser is to study further from the previous research that has been conducted, such as the use of diode lasers for the sintering and cutting process on acrylic material and the use of CO₂ lasers for biomedical applications with observations on CO₂ laser cutting of gypsum material [12]. Another research was conducted to analyze the effect of laser power, cutting speed and number of pass to the depth of cut in acrylic materials using CO₂ laser [13].

One of the microfluidics application is fluid mixing in microscale. There are 2 types of mixing process which are active and passive mixing. Active mixing is the process of fluid mixing where the pressure from the outside like a pump is used to move the fluid through the channel with high mixing efficiency. While the passive mixing is the process of mixing where the fluids flow through the channel without any moving part and pressure from outside to produce mixing fluid [14].

In microfluidics applications for chemical and biological fields, active mixing is not popularly used compared to passive mixing because it uses pressure/high pressure while. [14]. Therefore in this study, it is important to determine good passive mixing method. Various forms of microchannel design has been developed, producing many different profiles with different quality. This study will design Y-channel model with lamination category. This model is used to produce quick fluid mixing in simple

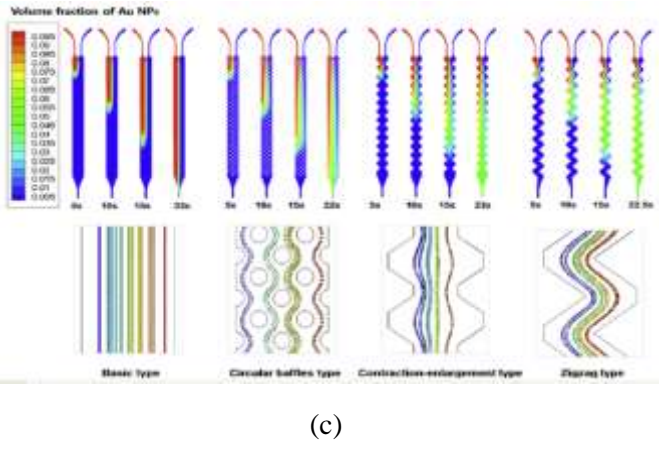
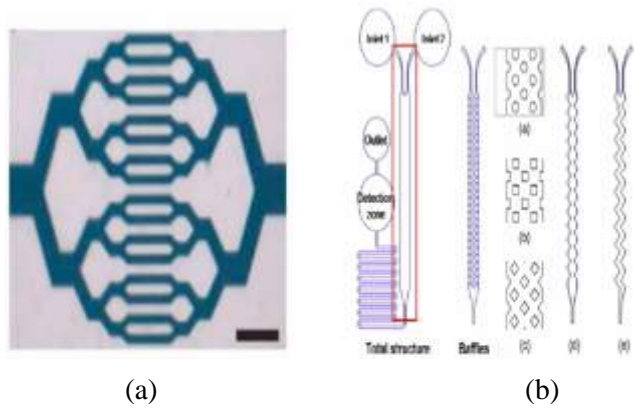


Figure 1. (a) Channel resemble capillaries [1], channel for flow analysis of: (b) Au NPs dan (c) CuSO₄ [2]

Table 1. Comparative material for microstructuring [5]

	Silicon	Glass	Technical thermoplastics (e.g. PMMA, PC, PEEK)	Thermoset polymers	Elastomers
Microfabrication	Easy-medium	Easy-medium	Easy	Medium	Easy
Structuring processes	Wet and dry etching	Wet etching, photostructuring	Injection molding, hot embossing, thermoforming, laser ablation	Casting, lithography, etching	Casting
Possible geometries	Limited, 2D	Limited, 2D	Many, 2D, 3D	Mostly 2D, 3D possible	Mostly 2D, 3D possible
Assembly	Easy	Medium	Easy	Medium	Easy
Interconnections	Difficult	Difficult	Easy	Easy	Easy-medium
Mechanical stability	High	High	Low-medium	High	Very low
Temperature stability	High	High	Low-medium	Medium	Low
Acid stability	High	High	High	High	High
Alkaline stability	Limited	High	High	High	High
Organic solvent stability	High	Medium-high	Low-medium	Medium-high	Low
Optical transparency	No	High	Mostly high	Partly	High
Material price	Medium	Medium-high	Low-medium	Medium	Low

Table 2. The development of passive mixing in the last 6 years [15]

Categories	Mixing Technique	Mixing Time (ms)	Mixing Length (µm)	Mixing Index
Lamination	Wedge shaped inlets	1	1	0.9
	90° rotation	-	-	0.95
Zigzag channels	Elliptic-shape barriers	-	-	0.96
3-D serpentine structure	Folding structure	489	10,000	0.01
	Creeping structure	-	-	0.015
	Stacked shim structure	-	-	-
	Multiple splitting, stretching and recombining flows	-	-	-
	Unbalanced driving force	-	815	0.91
Embedded barriers	SMX	-	-	-
	Multidirectional vortices	-	4255	0.72
Twisted channels	Split-and-recombine	730	96,000	~1
Surface-chemistry	Obstacle shape	-	1000	0.98
	T-/Y- mixer	-	1000	0.95

Experiments

Material And Processing

In this study, the channel was manufactured to have size of microchannel of $200\mu\text{m} > D > 10\mu\text{m}$, according to Table 3

Table 3. Classification of channel dimensions [16]

Conventional channels	$> 3\text{mm}$
Minichannels	$3\text{mm} \geq D > 200\mu\text{m}$
Microchannels	$200\mu\text{m} \geq D > 10\mu\text{m}$
Transitional microchannels	$10\mu\text{m} \geq D > 1\mu\text{m}$
Transitional nanochannels	$1\mu\text{m} \geq D > 0.1\mu\text{m}$
Nanochannels	$0.1\mu\text{m} \geq D$
<i>D : smallest channel dimension</i>	

The material properties used in this study was acrylic as shown in Table 4.

Table 4. Properties of acrylic [17]

Mechanical Properties		
Properties	Value	Unit
Young Modulus	3.2	Gpa
Tensile strength	35-62	Mpa
Elongation	5-7,2	%
Compressive strength	28-97	Mpa
Yield strength	48-97	Mpa
Physical Properties		
Properties	Value	Unit
Thermal expansion	48-80	$e-6^{\circ}\text{C}$
Thermal conductivity	0.000729	$\text{W/m}^{\circ}\text{K}$
Specific heat	5.344	$\text{J/kg}^{\circ}\text{K}$
Melting temperature	1103.15	$^{\circ}\text{K}$
Density	1190	Kg/m^3

The cutting process was used a CO₂ laser machine where the machine has specifications as shown in Table 5.

Table 5. Specification of CO₂ laser machine

Power	0 ~ 100 % (max. 60 Watt)
Wavelength	10.6 μm
Frequency mode	PWM (200 Hz - 200 KHz)
Laser head move	Pulse unit (0.1 mm/s -)
Output voltage MPC 6535	0 ~ 5 Volt
Power Laser Output	0 ~ 30 mA
Frequency	1~ 999
Beam diameter	0,002 m or 2 mm

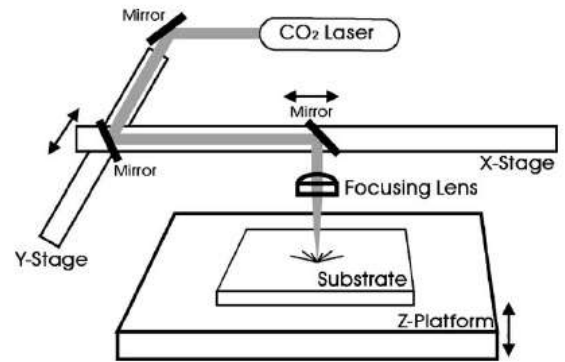


Figure 2. The concept of process CO₂ laser cutting machine

The concept of the CO₂ laser cutting machine is shown in Figure 2. In this study, some of the parameters used in this study is shown in Table 6.

Table 6. Parameters of experiment

Parameter	Value	Unit
Laser power	6, 6.6, 7.2, 7.8, 8.4	Watts
Cutting speed	5, 10, 15, 20, 25	mm/s
Size of channel (the width of the peak x the width of the valey)	0.3 x 0.3 mm, 0.5 x 0.5 mm, 0.7 x 0.7 mm, 0.3 mm x 0.7, and 0.7 x 0, 3 mm	
Design of channel	2 type of design (1 & 2)	

Design of Channel

In this study, there are two channel designs were created with a CO₂ laser machine. It has 2 lines, the straight line and the dashed line. Straight line shows the laser cut the path continuously, while the dashed line shows that laser cut the line in discrete distance.

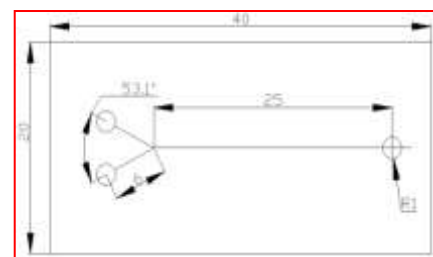


Figure 3. Design of Channel

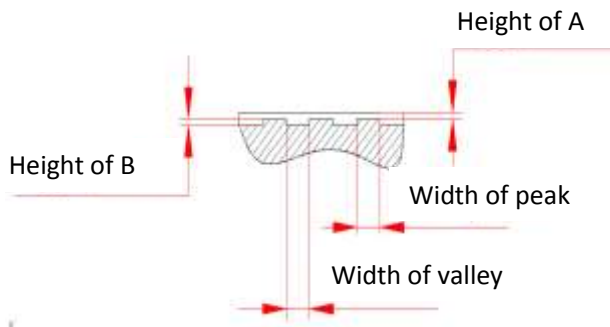


Figure 4. Design of the channel

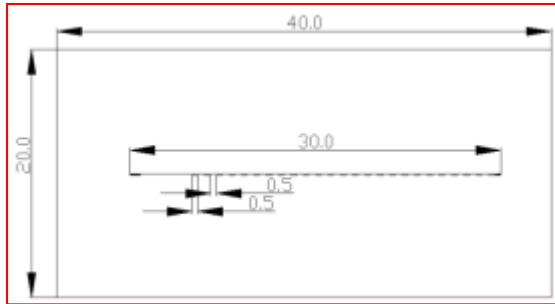


Figure 5. Design of Channel 1

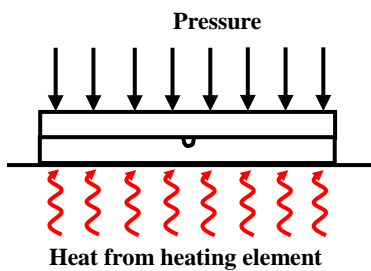


Figure 6. Design of Channel

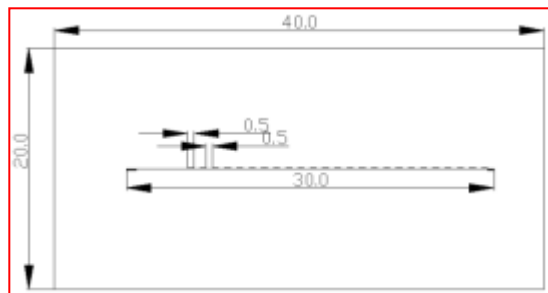
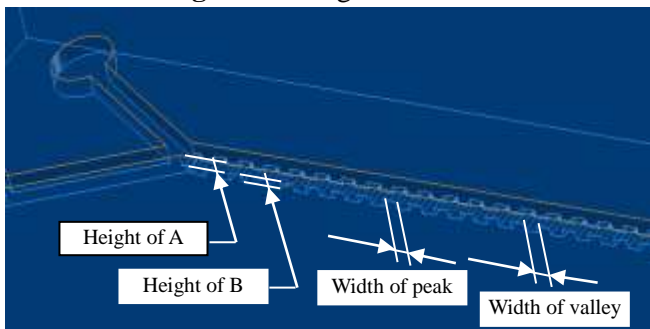


Figure 7. Process of thermal bonding [18]

Design of Channel 1

The design of channel 1 shows that the laser cutting process is conducted by a straight line followed by a dashed line.

Design of Channel 2

The design of channel 2 shows that the laser cutting process is conducted by a dashed line followed by a straight line.

Back-end Processing

In this stage, the process of joining acrylic materials was conducted using thermal bonding method. Figure 7 shows that the important parameters in joining the materials are given pressure, temperature and holding time in joining process.

Results and discussion

Distance Laser Focus Machine

Based on data obtained from previous studies, it is shown that the distance of 29 mm in Z-axis during the cutting process will generate deepest depth and smallest width of cutting product.

Cutting Results

Figure 8 and 9 shows the cutting result of design of channel 1 and 2, respectively. The observed results are surface roughness, height of A and B and error of peak and valley. The observation was conducted on the same size of peak and valley with 0.3 x 0.3 mm, laser power of 6 Watt and cutting speed of 5 mm/s.

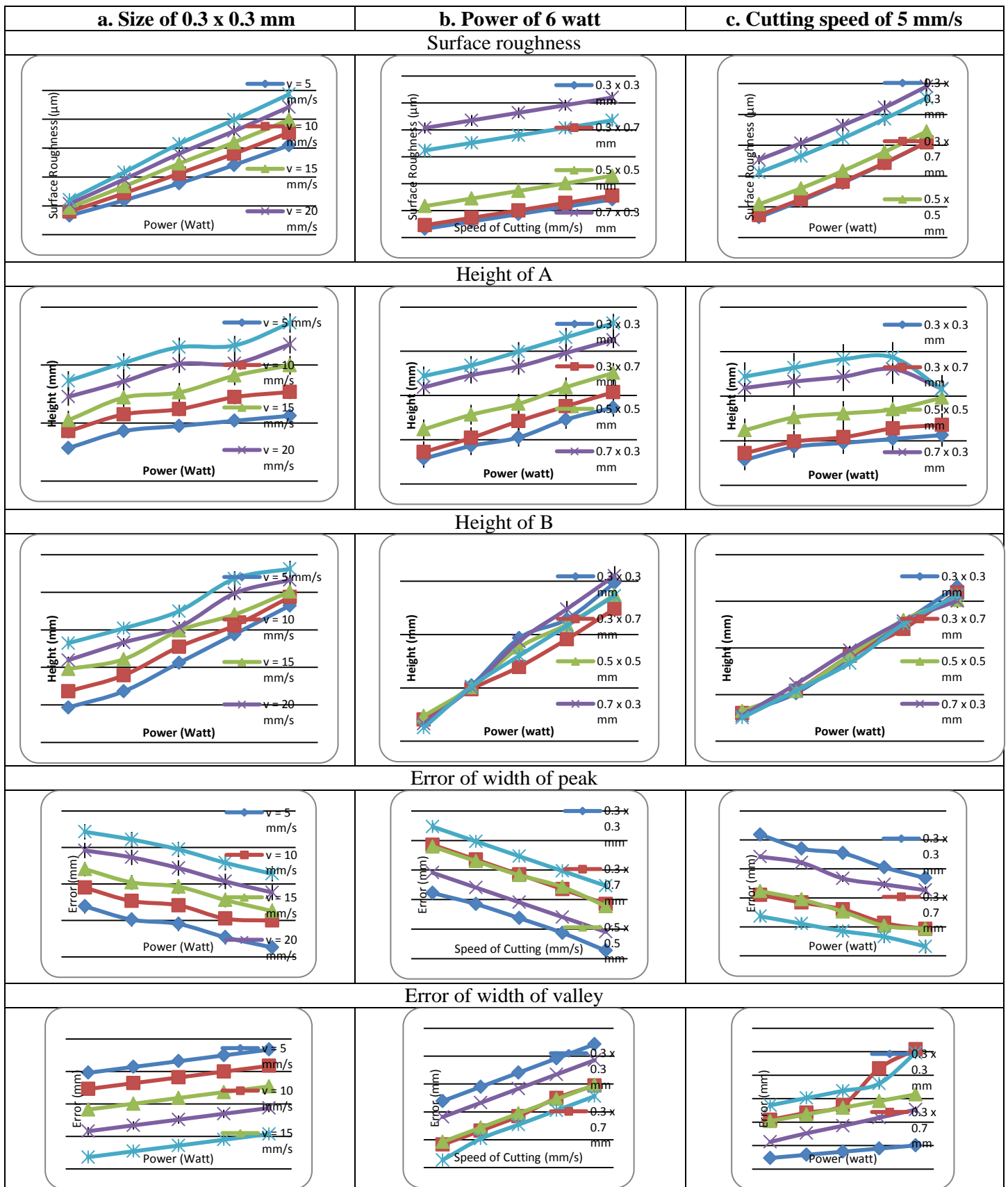


Figure 8. Cutting results in design of channel 1

Design of Channel 2

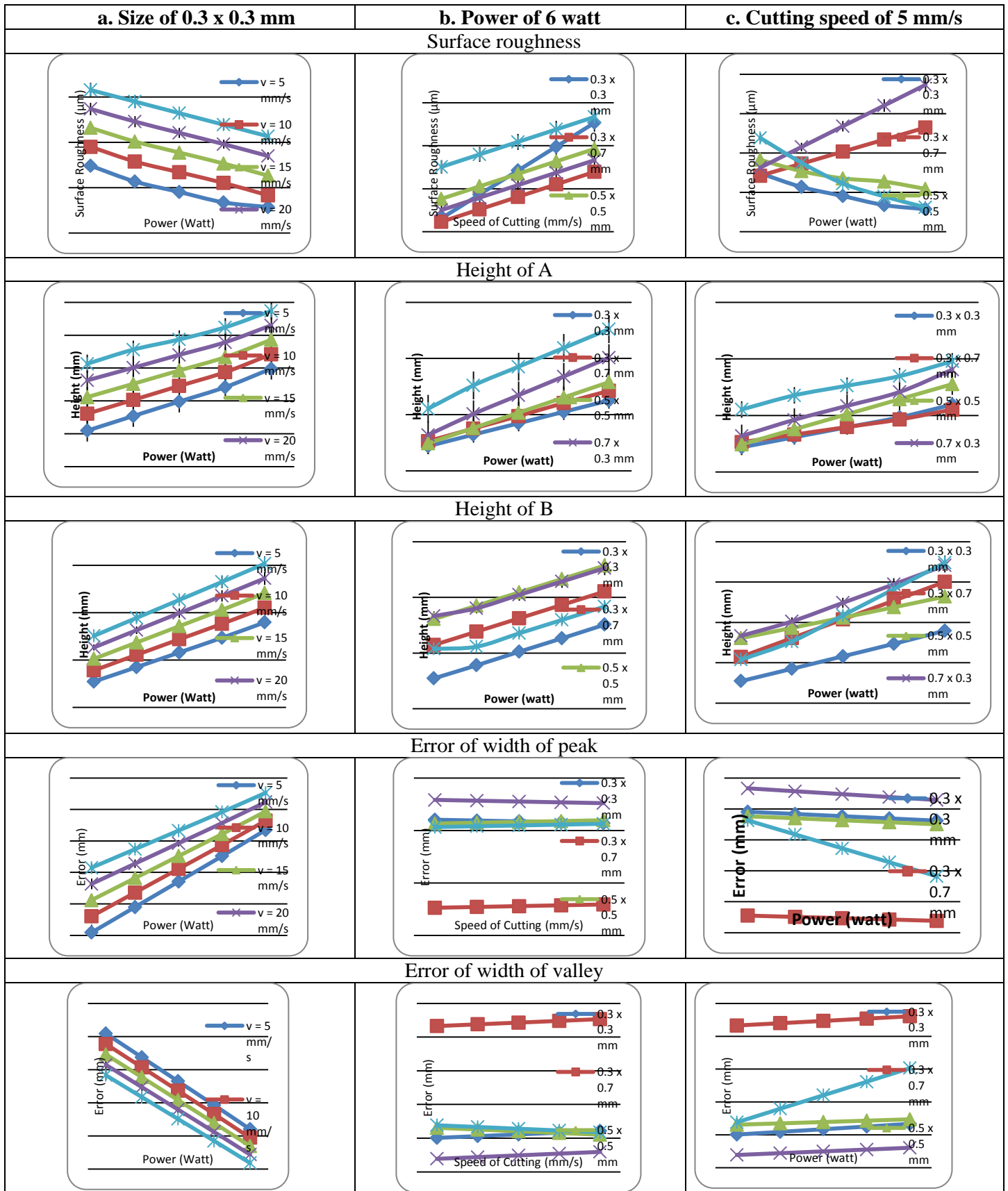


Figure 9. Cutting results in design of channel 2

In design of channel 1, for the width of peak x valley of 0.3 x 0.3 mm, the higher power of the laser and laser cutting speed, the higher surface roughness as shown in Fig. 8.a. In contrary, in design of channel 2, the surface roughness decreases as shown in Fig. 9.a. In constant laser power of 6 Watt, it is shown that the higher welding speed, the higher surface roughness for both design of channel as shown in Fig. 8.b and 9.b, respectively. In constant cutting speed of 5 mm/s, the higher laser power, higher surface roughness. In design of channel 2, some of surface roughness shows some decreasing in value during the increasing of the laser power.

The results of height of A and B for both design of channel show that the higher laser power and cutting speed, the higher height of A and B. In design of channel 1, the errors of width of peak decrease when the laser power and cutting speed increase, in contrary, the errors of width of valley decrease. In design of channel 2, with the increasing of laser power and cutting speed, the errors of width of peak and valley tend to increase. Some of errors of width of valley decrease during the increasing of the laser power. From the results, it is shown that the final surface after cutting process has the curvature form compared to the design of channel which has square form as shown in Fig. 10.

To determine the effect of the design of channel on surface roughness, data analysis using analysis of variance (ANOVA) was conducted. Table 7 – 12 show the data analysis of the effect of the parameters which are laser power, cutting speed and size of peak and valley to the surface roughness in design of channel 1. It is concluded that the effect of laser power, cutting speed and size of peak and valley have influenced the surface roughness as shown in Table 8, 10 and 12.

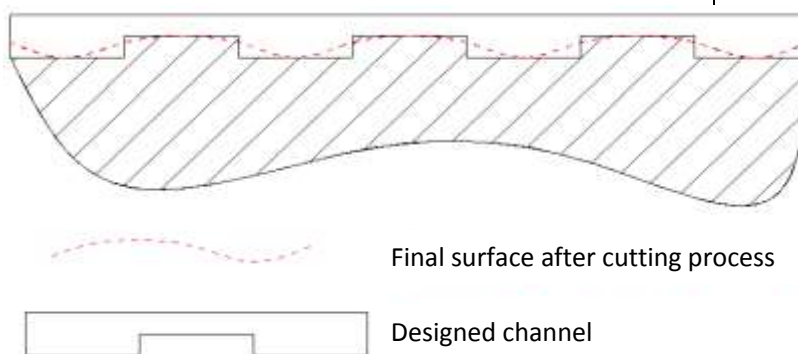


Figure 10. Comparison between designed channel and final surface after cutting process

Table 7. Effect of laser power and cutting speed to the surface roughness in size of 0.3 x 0.3 mm (design 1)

Cutting speed (mm/s)	Laser power (Watt)				
	6	6.6	7.2	7.8	8.4
5	23.2 25	33.9 06	45.5 87	58.2 68	71.949
10	25.9 55	38.7 48	52.4 29	66.11 0	80.791
15	28.6 85	43.5 90	59.2 71	73.9 52	89.633
20	31.4 15	48.4 32	66.11 3	81.7 94	98.475
25	34.1 45	53.2 74	72.9 55	89.6 36	107.31 7

Table 8. Analysis of variance from Table 7

Factor	Sum of	Degree of	Estimated	Fcalc	Ftable
Cutting	1934.1	4	483.542	32.27	3.01
Laser	11592.	4	2898.1	193.4	3.01
Error	239.72	16	14.9823		
Total	13766.	24			

Table 9. Effect of cutting speed and size of peak and valley to the surface roughness at laser power of 6 Watt (design 1)

mm	Cutting speed (mm/s)				
	5	10	15	20	25
23.2	25.9	28.6	31.4	34.1	
25	55	85	15	45	
24.5	27.3	30.0	32.8	35.5	
62	12	62	12	62	
31.6	34.4	37.2	40.1	42.9	
47	67	87	07	27	
60.6	63.4	66.3	69.1	71.9	
65	95	25	55	85	
52.3	55.1	57.9	60.7	63.5	
42	32	22	12	02	

Table 10. Analysis of variance from Table 9

Factor	Sum of	Degree of	Estimated	Fcalc	Ftable
Size	5830.4	4	1457.62	310132.2	
Cutting speed	387.53	4	96.8832	20613.44	7 3.01
Error	0.0752	16	0.0047		

Total	6218.	24
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Table 11. Effect of laser power and size of peak and valley to the surface roughness at cutting speed of 5 mm/s (design 1)

Size	Laser power (Watt)				
	6	6.6	7.2	7.8	8.4
0.3 x 0.3 mm	23.2 25	33.9 06	45.5 87	58.2 68	71.949
0.3 x 0.7 mm	24.5 62	34.8 76	46.1 90	58.5 04	71.818
0.5 x 0.5 mm	31.6 47	41.9 76	53.3 04	65.6 33	78.961
0.7 x 0.3 mm	60.6 65	71.2 91	82.9 17	94.5 43	108.16 9
0.7 x 0.7 mm	52.3 42	62.9 22	74.5 03	87.0 83	100.66 4

Table 12. Analysis of variance from Table 11

Factor	Sum of	Degree of	Estimated	Fcalc	Ftable
Size	5798.80	4	1449.70	16226.59	3.01
Laser power	715.91	4	1787.976	20012.958	3.01
Error	1.43	16	0.0893		
Total	12952.	24			

Table 13. Effect of laser power and cutting speed to the surface roughness in size of 0.3 x 0.3 mm (design 2)

Cutting speed (mm/s)	Laser power (Watt)				
	6	6.6	7.2	7.8	8.4
5	29.65 1	22.67 4	18.08 4	13.49 4	11.405
10	37.99 9	31.49 1	26.77 4	22.05 8	16.589
15	46.34 7	40.30 8	35.46 3	30.61 8	25.273
20	54.69 5	49.12 5	44.15 2	39.17 9	33.956
25	63.04 3	57.94 2	52.84 2	47.74 1	42.640

Table 14. Analysis of variance from Table 13

Factor	Sum of	Degree of	Estimated	Fcalc	Ftable
Cutting	3596.	4	899.13	1755.02	3.01
Laser	1275.	4	318.868	622.406	3.01
Error	8.197	16	0.5123		
Total	4880.	24			

Table 15. Effect of cutting speed and size of peak and valley to the surface roughness in at laser power of 6 Watt (design 2)

Size	Cutting speed (mm/s)				
	5	10	15	20	25
0.3 x 0.3 mm	29.6 51	37.9 99	46.3 47	54.6 95	63.0 43
0.3 x 0.7 mm	28.4 29	32.7 93	37.1 56	41.5 19	45.8 83
0.5 x 0.5 mm	36.4 59	40.8 22	45.1 86	49.5 49	53.9 12
0.7 x 0.3 mm	32.5 20	36.8 84	41.2 47	45.61 1	49.9 74
0.7 x 0.7 mm	47.6 28	51.9 92	56.3 55	60.7 18	65.0 82

Table 16. Analysis of variance from Table 15

Factor	Sum of	Degree of	Estimated	Fcalc	Ftable
Size	1030.3	4	257.58	32.45	
Cutting speed	1331.45	4	332.86	41.93	3.01
Error	127.02	16	7.94		
Total	2488.	24			

Table 17. Effect of laser power and size of peak and valley to the surface roughness in at cutting speed of 5 mm/s (design 2)

Size	Laser power (Watt)				
	6	6.6	7.2	7.8	8.4
0.3 x 0.3 mm	29.6 51	22.6 74	18.0 84	13.4 94	11.405
0.3 x 0.7 mm	28.4 29	34.5 44	40.6 59	46.7 74	52.889
0.5 x 0.5 mm	36.4 59	30.7 06	27.0 46	25.3 86	21.725
0.7 x 0.3 mm	32.5 20	43.0 51	53.5 82	64.11 2	74.643
0.7 x 0.7 mm	47.6 28	34.9 81	24.4 25	17.8 81	12.315

Table 18. Analysis of variance from Table 17.

Factor	Sum of	Degree of	Estimated	Fcalc	Ftable
Size	3632.95	4	908.24	5.59	3.01
Laser power	17.27	4	4.32	0.03	3.01
Error	2600.66	16	162.55		
Total	6250.8	24			

Table 13 – 18 show the data analysis of the effect of

the parameters which are laser power, cutting speed and size of peak and valley to the surface roughness in design of channel 2. It is concluded that the effect of laser power, cutting speed and size of peak and valley have influenced the surface roughness as shown in Table 14 and 16. However, according to Table 18, it is shown that laser power has less influence to the surface roughness at constant cutting speed. Therefore, based on data analysis by ANOVA it is shown that the design of channel 1 has an influence on all parameters to the surface roughness compared to design of channel 2. There are several parameters that have influence and some parameter has no effect on the surface roughness. Therefore, the design of channel 1 is more appropriate to be used than the design of channel 2.



Figure 11. Microfluidic device

Figure 11 shows the microfluidic device. From the microfluidic test for mixing two color of green and red, with the fluid discharge of 0.4 cc/mL, length of mixing of 29 mm and mixing speed of 0.031 mm/s, it was found that the mixing time was 928 sec.

Conclusions

Based on the results of passive mixing microchannel fabrication of microfluidic device, it is concluded that the design of channel 1 has an influence on all parameters to the surface roughness compared to design of channel 2. This shows that the design of channel 1 is more appropriate to be used than the design of channel 2. Analysis of experimental results show that the parameters determined in this research which are laser power, cutting speed and design of channel have a great influence to the surface roughness and influence the result of final product of microfluidic device.

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