Analysis of Passive Mixing Microchannel Fabrication of Microfluidics Device on Acrylic Material Using Low Power CO_2 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 microfabrication process consists of design, microstucturing 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 CO_2 laser was used for microstucturing 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, CO_2 laser, acrylic material

1. 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 $CuSO_4$ 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 ethacrylate (PMMA), polycarbonate and poly dimethysiloxane (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 CO_2 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 CO_2 lasers for biomedical applications with observations on CO_2 laser cutting of gypsum material [12]. Another research was conducted to analyze the effect of laser

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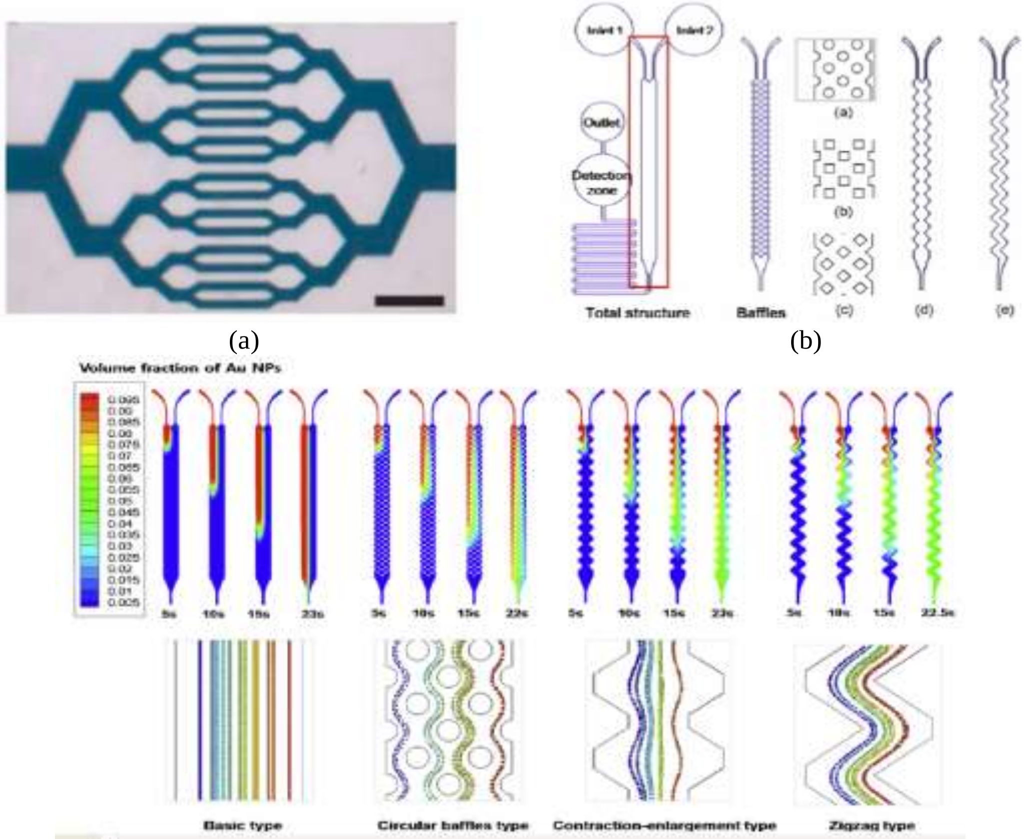
power, cutting speed and number of pass to the depth of cut in acrylic materials using CO_2 laser [13].

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 design.



(a) (b)

(c)

Figure 1. (a) Channel resemble capillaries [1], channel for flow analysis of: (b) Au NPs dan (c) $CuSO_4$ [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	Wedged shaped inlest	1	1	0.9
	90^0 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

2. Experiments

2.1. Material and processing

In this study, the channel was manufactured to have size of microchannel of 200µm > D> 10µm, according to Table 3

Table 3. Classification of channel dimensions [16]

Conventional channels	*> 3mm*
Minichannels	*3mm ≥ D > 200µm*
Microchannels	*200µm ≥ D > 10µm*
Transitional microchannels	*10µm ≥ D > 1µm*
Transitional nanochannels	*1µm ≥ D > 0.1µm*
Nanochannels	*0.1µm ≥ D*
D : smallest channel dimension	

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/^{0}C
Thermal conductivity	0.000729	W/m.^{0}K
Specific heat	5.344	J/kg.^{0}K

Melting temperature	1103.15	° K
Density	1190	Kg/m3

The cutting process was used a CO_2 laser machine where the machine has specifications as shown in Table 5.

Table 5. Specification of CO_2 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

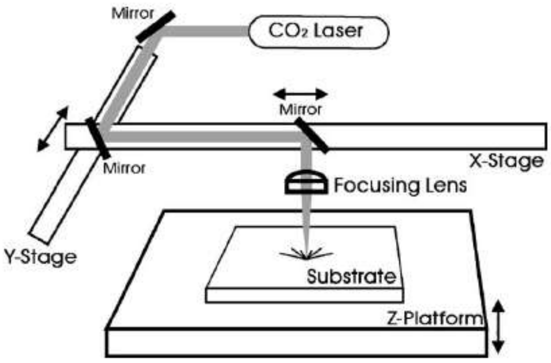


Figure 2. The concept of process CO_2 laser cutting machine

The concept of the CO_2 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)*	

2.2. Design of Channel

In this study, there are two channel designs were created with a CO_2 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.

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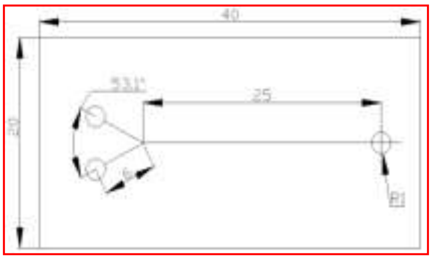


Figure 3. Design of Channel

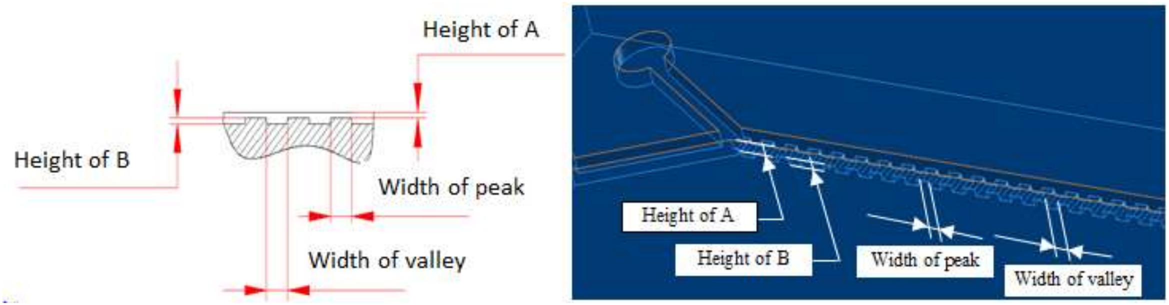
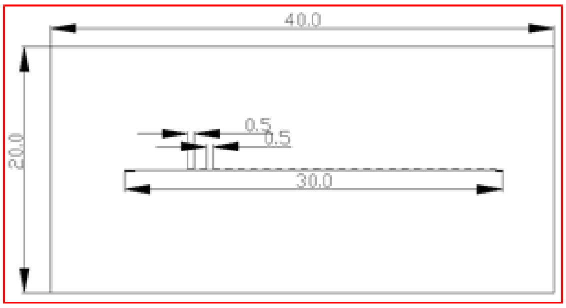


Figure 4. Design of the channel



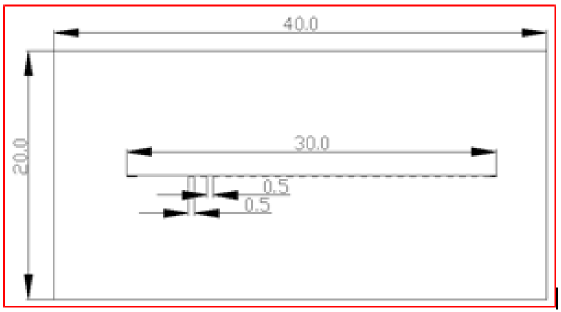


Figure 5. Design of Channel 1

Figure 6. Design of Channel 2

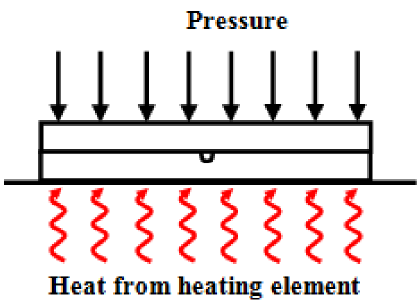


Figure 7. Process of thermal bonding [18]

2.3. 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.

2.4. 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.

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2.5. 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.

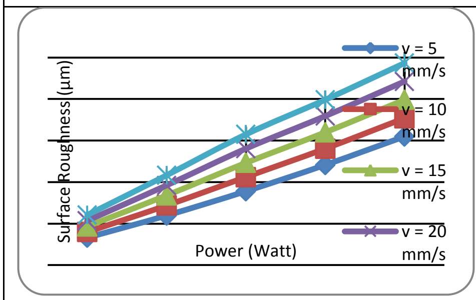
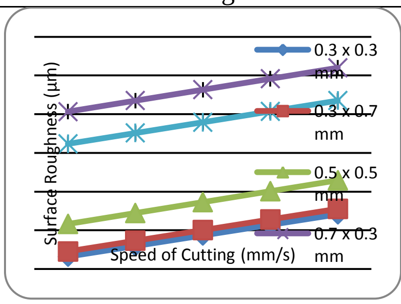
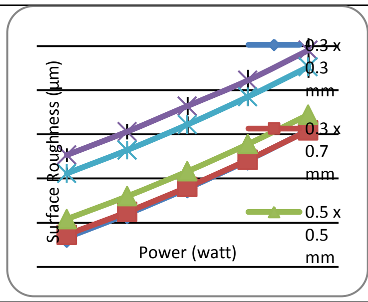
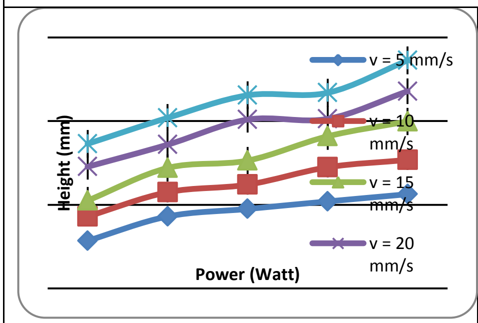
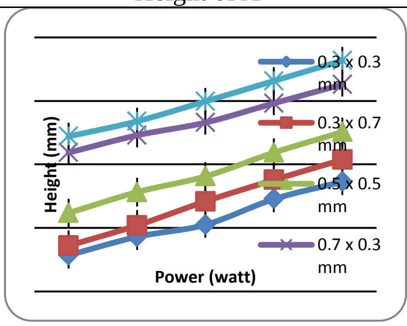
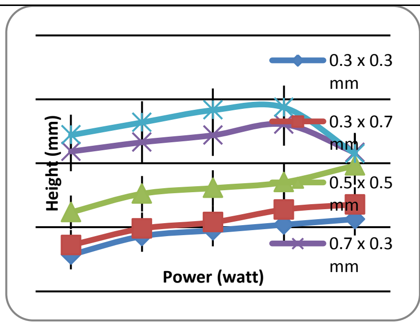
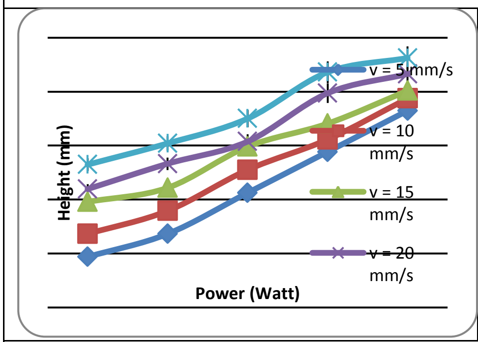
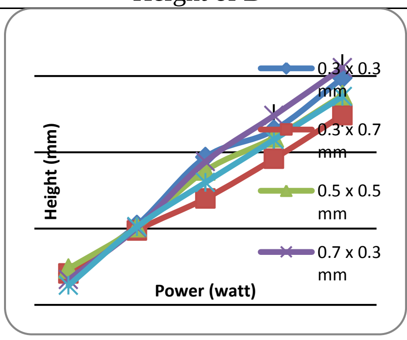
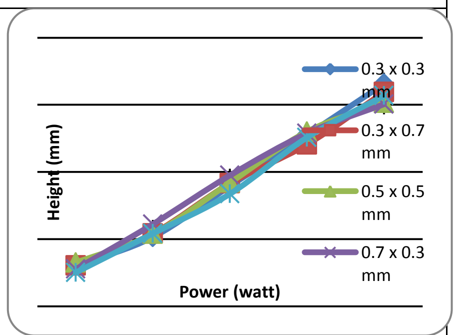
3. Results and discussion

3.1. 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.

3.2. 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.

a. Size of 0.3 x 0.3 mm	**b. Power of 6 watt**	**c. Cutting speed of 5 mm/s**
Surface roughness		
		
Height of A		
		
Height of B		
		
Error of width of peak		

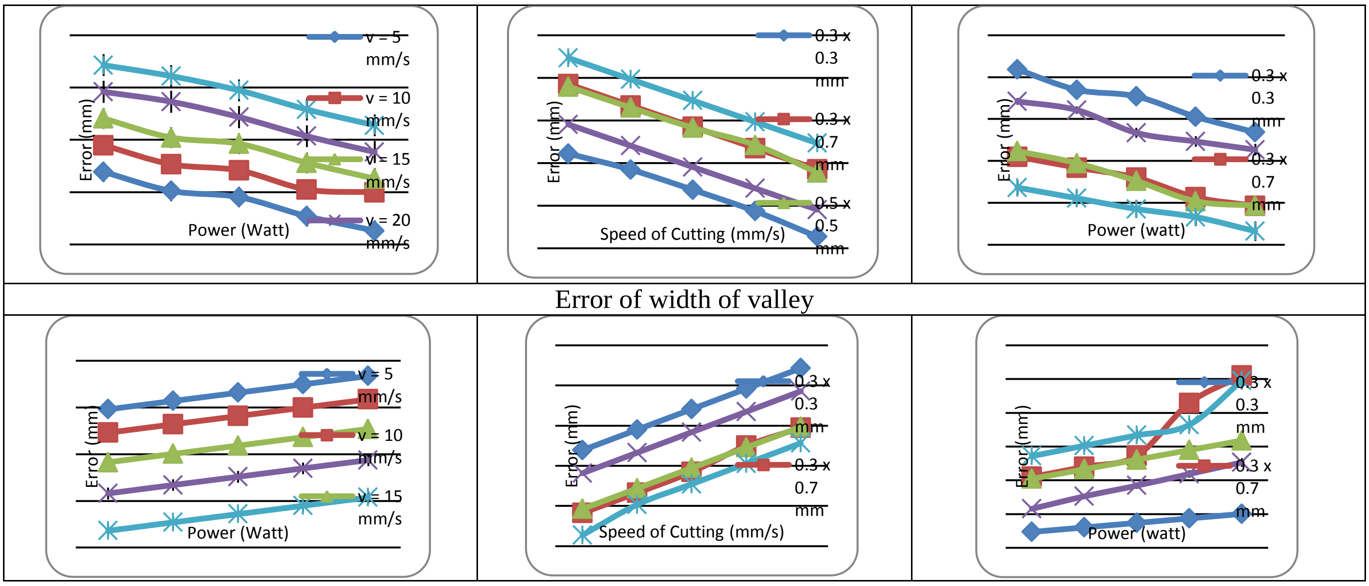
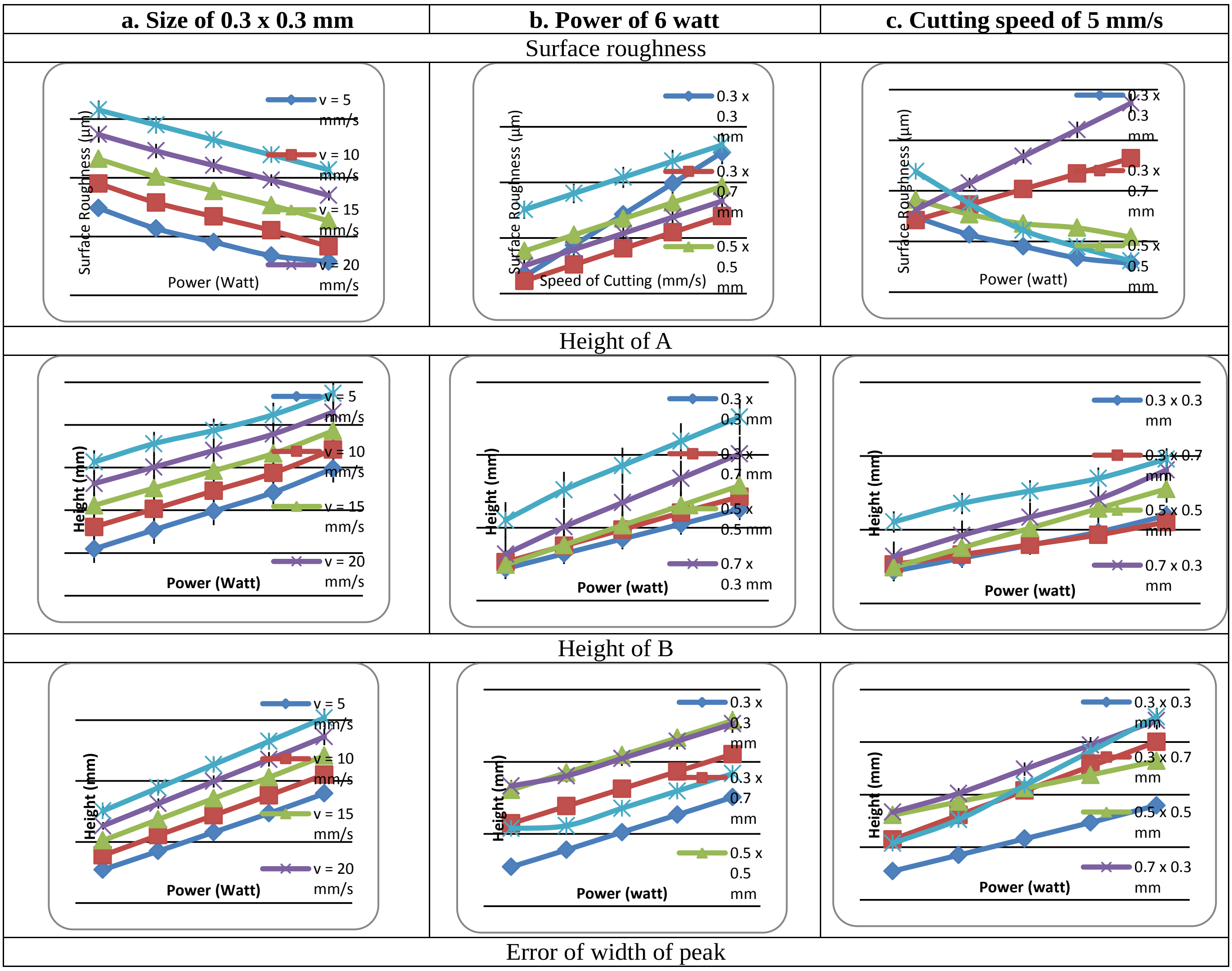


Figure 8. Cutting results in design of channel 1

Design of Channel 2



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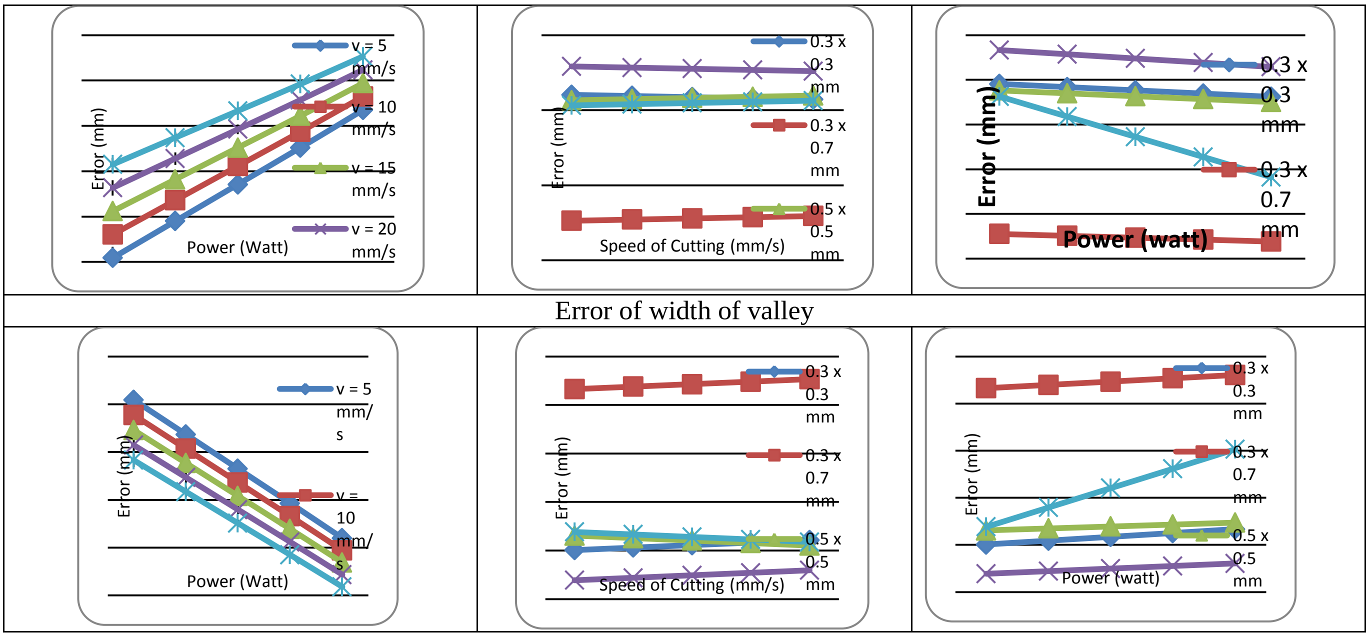

Figure 9. Cutting results in design of channel 2

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.

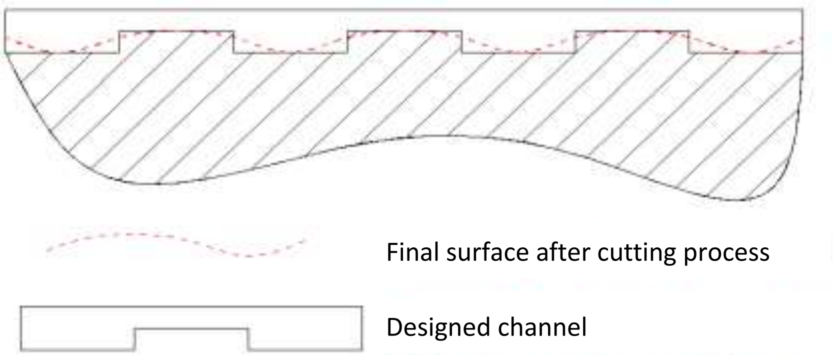

Figure 10. Comparison between designed channel and final surface after cutting process

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

	Laser power (Watt)				
Cutting speed (mm/s)	**6**	**6.6**	**7.2**	**7.8**	**8.4**
5	23.225	33.906	45.587	58.268	71.949
10	25.955	38.748	52.429	66.110	80.791
15	28.685	43.590	59.271	73.952	89.633
20	31.415	48.432	66.113	81.794	98.475
25	34.145	53.274	72.955	89.636	107.317

Table 8. Analysis of variance from Table 7

Factor	**Sum of square**	**Degree of freedom**	**Estimated variance**	**Fcalc**	**Ftable**
Cutting speed	1934.17	4	483.542	32.2743	3.01
Laser power	11592.40	4	2898.1	193.4353	3.01
Error	239.72	16	14.9823		
Total	13766.29	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)

	Cutting speed (mm/s)				
Size	**5**	**10**	**15**	**20**	**25**
0.3 x 0.3 mm	23.225	25.955	28.685	31.415	34.145
0.3 x 0.7 mm	24.562	27.312	30.062	32.812	35.562
0.5 x 0.5 mm	31.647	34.467	37.287	40.107	42.927
0.7 x 0.3 mm	60.665	63.495	66.325	69.155	71.985
0.7 x 0.7 mm	52.342	55.132	57.922	60.712	63.502

Table 10. Analysis of variance from Table 9

Factor	**Sum of square**	**Degree of freedom**	**Estimated variance**	**Fcalc**	**Ftable**
Size	5830.49	4	1457.62	310132.226	3.01
Cutting speed	387.53	4	96.8832	20613.447	3.01
Error	0.0752	16	0.0047		
Total	6218.09	24			

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)

	Laser power (Watt)				
Size	**6**	**6.6**	**7.2**	**7.8**	**8.4**
0.3 x 0.3 mm	23.225	33.906	45.587	58.268	71.949
0.3 x 0.7 mm	24.562	34.876	46.190	58.504	71.818
0.5 x 0.5 mm	31.647	41.976	53.304	65.633	78.961
0.7 x 0.3 mm	60.665	71.291	82.917	94.543	108.169
0.7 x 0.7 mm	52.342	62.922	74.503	87.083	100.664

Table 12. Analysis of variance from Table 11

Factor	Sum of square	Degree of freedom	Estimated variance	Fcalc	Ftable
Size	5798.80	4	1449.70	16226.597	3.01
Laser power	715.91	4	1787.976	20012.958	3.01
Error	1.43	16	0.0893		
Total	12952.13	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)

	Laser power (Watt)				
Cutting speed (mm/s)	**6**	**6.6**	**7.2**	**7.8**	**8.4**
5	29.651	22.674	18.084	13.494	11.405
10	37.999	31.491	26.774	22.058	16.589
15	46.347	40.308	35.463	30.618	25.273
20	54.695	49.125	44.152	39.179	33.956
25	63.043	57.942	52.842	47.741	42.640

Table 14. Analysis of variance from Table 13

Factor	Sum of square	Degree of freedom	Estimated variance	Fcalc	Ftable
Cutting speed	3596.50	4	899.13	1755.0261	3.01
Laser power	1275.47	4	318.868	622.4069	3.01
Error	8.1970	16	0.5123		
Total	4880.17	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)

	Cutting speed (mm/s)				
Size	**5**	**10**	**15**	**20**	**25**
0.3 x 0.3 mm	29.651	37.999	46.347	54.695	63.043
0.3 x 0.7 mm	28.429	32.793	37.156	41.519	45.883
0.5 x 0.5 mm	36.459	40.822	45.186	49.549	53.912
0.7 x 0.3 mm	32.520	36.884	41.247	45.611	49.974
0.7 x 0.7 mm	47.628	51.992	56.355	60.718	65.082

Table 16. Analysis of variance from Table 15

Factor	Sum of square	Degree of freedom	Estimated variance	Fcalc	Ftable
Size	1030.32	4	257.58	32.45	3.01
Cutting speed	1331.45	4	332.86	41.93	3.01
Error	127.02	16	7.94		
Total	2488.79	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)

	Laser power (Watt)				
Size	**6**	**6.6**	**7.2**	**7.8**	**8.4**

0.3 x 0.3 mm	29.651	22.674	18.084	13.494	11.405
0.3 x 0.7 mm	28.429	34.544	40.659	46.774	52.889
0.5 x 0.5 mm	36.459	30.706	27.046	25.386	21.725
0.7 x 0.3 mm	32.520	43.051	53.582	64.112	74.643
0.7 x 0.7 mm	47.628	34.981	24.425	17.881	12.315

Table 18. Analysis of variance from Table 17.

Factor	**Sum of square**	**Degree of freedom**	**Estimated variance**	**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	6250.88	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.

4. 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.

5. Reference

[1] Hou, H.H., Lee, W.C., Leong, M.C., Sonam, S., Vedula, S.R.K & Lim, C.T., *Microfluidics for applications in cell mechanics and mechanobiology*, Cellular and Molecular Bioengineering, Vol. 4, No. 4, 591-602 (2011)

[2] Jeon, W.J. & Shin, C.B., *Design and simulation of passive mixing in microfluidics systems with geometric variation,* Chemical Engineering Journal, Vol. 152, 575-582 (2009)

[3] Li, Y., Pfohl, T., Kim, J.H., Yasa, M., Wen, Z. Kim, M.W. & Safiya, C.R., *Selective surface modification in silicon microfluidics channels for micromanipulation of biological macromolecules*, Biomedical Microdevice Vol. 3, No.3, 239-244 (2001)

[4] Chen, Q., Chen, Q., Sacco, G.M.A., Scaltrito, L., Ferraris, M. & Ferrero, S., *Fabrication of large-area microfluidics structures on glass by imprinting and diode-pumped solid state laser writing techniques,* Microsyst Technol Vol. 17, 1611-1619 (2011)

[5] Becker, H. & Gärtner, C., *Polymer microfabrication technologies for microfluidics systems,* Anal Bioanal Chem Vol. 390, 89-111 (2008)

[6] Hnatovsky, C., Taylor, R.S., Simova, E., Rajeev, P.P., Rayner, D.D., Bhardwaj, V.R. & Corkum, P.B., *Fabrication of microchannels in glass using focused femtosecond laser radiation and selective chemical etching,* Appl. Phys. A Vol. 84, 47-61 (2006)

[7] Wu, C.H. & and Kuo, H.C., *Parametric study of injection molding and hot embossing in polymer microfabrication*, Journal of Mechanical Science and Technology Vol. 21, 1477-1482 (2007)

[8] Fu, G., Tor, S. B., Hardt, D. E. & Loh, N. H., *Effects of processing parameters on the micro-channels replication in microfluidics devices fabricated by microinjection molding*, Microsyst Technol Vol. 17, 1791-1798 (2011)

[9] Xia, Y. & Whitesides, G. M., *Soft lithography,* Annu. Rev. Mater. Sci., Vol. 28, 153-184 (1998)

[10] Devalckenaere, M., Jadin, A., Kolev, K., Laude, L.D., *Excimer laser ablation of polycarbonate-based plastic substrates*. Nucl Instrum Methods B, Vol. 151, 263-267 (1999)

[11] Li, J.M., Liu, C. & Zhu, L.Y., *The formation and elimination of polymer bulges in CO_2 laser microfabrication,* Journal of Materials Processing Technology Vol. 209, 4814-4821 (2009)

[12] Baskoro, A.S., Herwandi, Ismail, K.G.S., Siswanta, A., Kiswanto, G., *Analysis of cutting process of materials using low power laser diode and CO_2*, IJMME-IJENS, Vol. 11, No. 06, 13-18 (2011)

[13] Baskoro, A.S., Siswanta., A., Ismail, K.G.S., *Analysis of microchannels manufacturing of acrylic using low power CO_2 laser,* Advanced Materials Research, Vol. 789, 408-411 (2013)

[14] Nguyen, N. & Wu, Z., *Micromixers – a review*, J Micromech Microeng Vol. 15, R1 (2005)

[15] Lee, C.Y., Chang, C.L., Wang, Y.N. & Fu, L.M., *Microfluidic mixing: A review,* International Journal of Molecular Sciences, Vol. 12, No. 5, 3263-3287 (2011)

[16] Kandlikar, S.G., Garimella, S., Li, D., Colin, S. & King, M.R. *Heat Transfer and Fluid Flow in Minichannels and Microchannels,* Elsevier (2006)

[17] Kaysons, *Physical Properties of Acrylic Sheets,* Akrylik furniture dan accessories.

[18] Zhu, X., Liu, G., Guo, Y. & Tian, Y., *Study of PMMA thermal bonding*, Microsyst Technol Vol. 13, 403-407 (2007)