Int J Adv Manuf Technol (2017) 92:1365–1370
DOI 10.1007/s00170-017-0182-8

ORIGINAL ARTICLE

# An effective method for fabricating microchannels on the polycarbonate (PC) substrate with $CO_2$ laser

Xueye Chen [1] · Zengliang Hu [1]

Received: 25 July 2016 / Accepted: 20 February 2017 / Published online: 11 March 2017


**Abstract** This paper proposes an effective processing method for fabricating microchannels on the polycarbonate (PC) substrate with $CO_2$ laser. The width of microchannel has close relationship with $CO_2$ laser parameters including laser power, laser moving velocity, and length of microchannel. In order to optimize the width of the microchannel, the orthogonal experiment method is successfully applied in this experiment with $L_9(3^3)$ orthogonal test table. Then, the optimal machining parameters are obtained and a verified experiment is confirmed. Finally, the optimal microcahnnels on the PC can be obtained with the presented process parameters.

**Keywords** $CO_2$ laser · Polycarbonate substrate · Microchannel · Orthogonal experiment method

## 1 Introduction

The technique of laser machining is popular and convenient in the modern processing technology. $CO_2$ laser machining plays an important role in laser technology application. Many materials have been successfully processed. El-Taweel et al. studied the Kevlar-49 composite materials which were processed using $CO_2$ laser with the Taguchi technique [1]. Ghosal et al. optimized penetration depth of $CO_2$ LASER-MIG hybrid welding used for 5005 Al–Mg alloy [2]. Antończak et al. described the influence of organobentonite clay on grooving of polycaprolactam using $CO_2$ laser [3]. Wang et al. produced three-dimension hard metal functional parts from commercial available powders using the selective laser sintering technology [4]. Teixidor et al. studied the effects of nanosecond laser processing parameters on depth and width of microchannels fabricated from PMMA [5]. Rahmani-Monfard et al. presented a newly developed pre-defined three-dimensional PMMA scaffold fabricated via $CO_2$ laser drilling technique [6].

Microfluidic chip technology is a kind of miniaturized total analysis system and one of the most active areas. $CO_2$ laser machining is a key important fabrication method and polymer substance is the main material in the microfluidic devices. Li et al. described a method which $CO_2$ laser fabricated polystyrene molds for PDMS microfluidic devices [7]. The influence of the quality of PMMA with different processing parameters was evaluated [8]. Eltawahni et al. optimized the $CO_2$ laser cutting quality parameters for PMMA [9]. Sun et al. produced a novel hybrid PMMA-PC microchip by bonding a PC cover plate with a PMMA substrate containing microchannel which is fabricated by $CO_2$ laser ablation [10]. A passive three-dimension mixers with PMMA and PDMS were fabricated with $CO_2$ laser machining [11]. Toossi et al. studied a novel approach that thin metal electrode prototypes were patterned using a low-power $CO_2$ laser cutter [12]. In order to lucubrate the microfluidic devices, Chen et al. studied a review about fractal design of microfluidics and nanofluidics [13]. Chung et al. demonstrated the fabrication of flexible light guide plate with $CO_2$ laser LIGA-like technology which included the laser ablation of micro-groove PMMA master mold, pouring PDMS to the mold and casting the micro-groove microstructure for flexible light guide plate application [14]. Li et al. studied the fabrication of droplet microfluidic devices on polystyrene substrate using a $CO_2$ laser system [15]. Prakash et al. proved the PMMA

✉ Xueye Chen
xueye_chen@126.com

Zengliang Hu
hzl1170329696@163.com

1 Faulty of Mechanical Engineer and Automation, Liaoning University of Technology, Jinzhou 121001, China

microchannel of two-pass laser processing is smoother than that of single-pass laser processing [16]. Yang et al. studied a prediction model of a $CO_2$ laser cutting experiment using the progressive Taguchi neural network mode [17]. In recent years, we have carried out a series of studies on $CO_2$ laser machining technology [18–22].

As early as 2009, Qi et al. have processed the PC using $CO_2$ laser direct-writing ablation [23]. But after them, the research of PC is less in microfluidic devices. This paper studies a method of application of PC in the microfluidic chip technology. In the study, in order to optimize the width of microchannels, some microchannels are processed on PC sheet using $CO_2$ laser with orthogonal experiment method. The orthogonal experiment method is more convenient and efficient than the traditional experimental methods. The optimal parameters of $CO_2$ laser machining which include laser power, laser moving velocity, and length of microchannel are obtained. The parameters can make the width error of microchannel becoming smaller.

In this paper, we study the influence of laser parameters on the PC microchannels. The microchannels are processed by $CO_2$ laser LCJG-1290 and a set of optimal parameters are successfully obtained with the orthogonal experiment method. This paper provides an important method for researching the application of PC sheet in the microfluidic devices. The study procedure is as follows: First, an answer which width error of microchannel is found with a set of laser parameters. Secondly, a $L_9(3^3)$ orthogonal test table is performed by orthogonal experiment method. Thirdly, the experiment datum is processed and the optimal machining datum was obtained. Finally, making a microchannel with optimal machining datum verifies the authenticity of optimal datum.

## 2 Materials and methods

### 2.1 $CO_2$ laser machine system

The $CO_2$ laser (LCJG-1290, Nanjing Latron laser Technology Co., Ltd. Jiangsu province) with a programming system (NC system) is used in this study. Figure 1 shows the profile of $CO_2$ laser machine system. The $CO_2$ laser has a wavelength of 10.6 μm and sets the operating voltage of 220 V. The predicted substrate is flat on the Z-plantform and the machining process is completed with different laser parameters. The different laser parameters are controlled by the laser programming system which combines computer and CAD technology. The $CO_2$ laser beam from the laser head which includes a mirror, a focusing lens and the outlet of auxiliary gas, is irradiated to the surface of the predicted substrate.

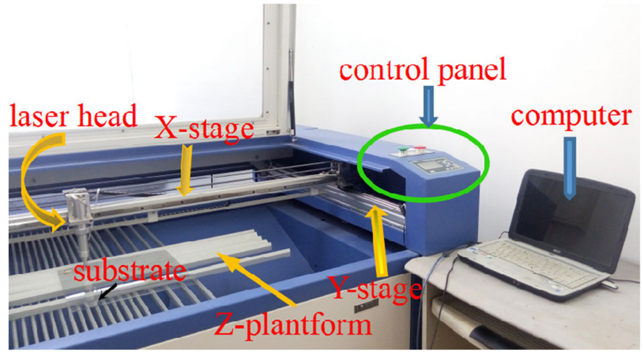


**Fig. 1** $CO_2$ laser machine system

A predicted graphics is drawn by the CAXA software and then it is imported into the software which controls laser machining. The relevant machining parameter is set in the controlled system and the processes of trajectory data extraction, trajectory planning, simulation and interference check are completed automatically. The control plane of laser shows the power control device, machining speed button, total power indicator, emergency stop button, and servo power button.

### 2.2 Material details

PC is one of organic polymer materials which widely used the fabrication of microfluidic chip. It is a kind of strong thermoplastic resin and possesses the characteristics of high transparency, excellent toughness, and very good dimensional stability. The density of PC is 1.2 g/cm$^3$ and the temperature of the glass transition is 148 °C. The transmittance of PC is about 89% in infrared spectral range. The surface of PC has the adust phenomenon and generates tan fume in the process of $CO_2$ laser machining. The PC decomposes into carbon dioxide gas, phenol, and other components in the high temperature.

### 2.3 The temperature field model

Laser is a kind of electromagnetic wave with high energy and good monochromaticity. When the laser beam irradiates to the material surface, a part of energy of laser beam is absorbed and another energy is reflected by the material. The material produces thermal effect with materials absorbed the laser energy. With increase of temperature of material surface, the material will present the decomposed phenomenon which includes molten, gasification, and evaporation. Finally, the hole and channel are generated on the material surface. According to the principle of conservation of energy, the equation is defined as follows:

$$E = E_{absorption} + E_{reflection} \quad (1)$$

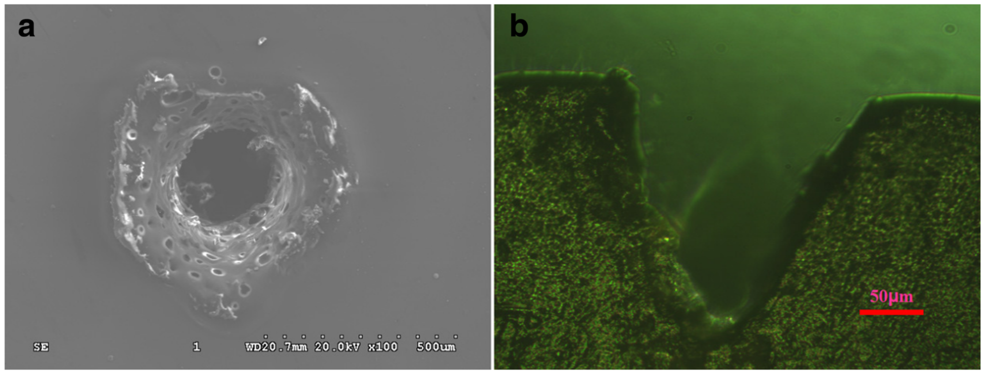


**Fig. 2** The shape of laser beam irradiates to the material surface. **a** The laser spot using laser burst firing. **b** The shape of processed microchannel

where $E$ is the energy of laser, $E_{absorption}$ is the energy of material absorption and $E_{reflection}$ is the energy of material reflection.

It is an assumption which an instantaneous point heat source with irradiates on the surface of material. The initial temperature is assumed as *0* °C, when the distance which is from one point to heat source is $R$ after the time $t$, the temperature field $T$ is shown:

$$T = \frac{2Q}{c\rho(4\pi at)^{3/2}} \exp\left(-\frac{R^2}{4at}\right) \quad (2)$$

where the circle radius of temperature field is $R = (x^2 + y^2 + z^2)^{1/2}$, $a$ is the thermal diffusivity of material, $\lambda$ is the wavelength, and $Q$ is the thermal energy [24].

Equation (2) calculates the change of material temperature and shows the circular temperature field with radius $R$. The temperature of center of laser beam is the highest. The temperature reduces with increase of the distance from the center. Figure 2 shows the profile of $CO_2$ laser processed PC. The shape which $CO_2$ laser beam irradiates to PC surface produce is cone, as shown in Fig. 2a. With the movement of $CO_2$ laser beam, the processed microchannel presents U-shape or V-shape, as shown in Fig. 2b.

A combination of photochemical and photothermal processes is the main role of $CO_2$ laser machining mechanism. When $CO_2$ laser beam irradiates on PC surface, a part of energy of laser beam is absorbed and another energy is reflected by PC. The temperature of PC is rapidly increased by the absorbed energy. With the increase of temperature, the material properties of PC begin to change due to some chemical bonds are broken. PC will first melt, decompose, and vaporize. The decomposed PC is converted to carbon dioxide gas, phenol, and other components with tan fume.

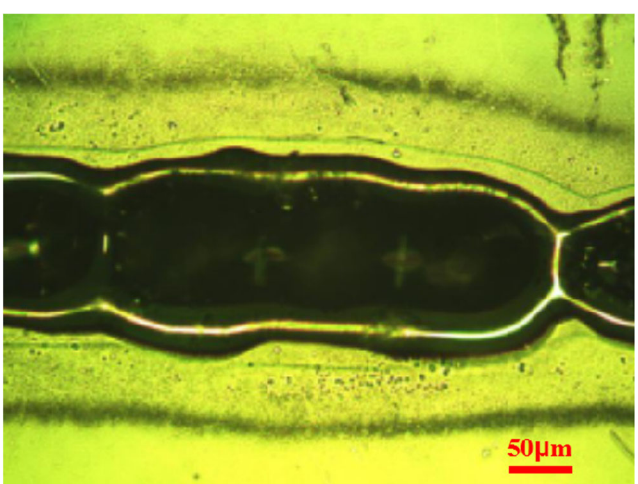


**Fig. 3** The micrographs picture of the PC sheet

## 3 Results and discussion

### 3.1 Effect of laser parameters setting on width of microchannel

A PC sheet is processed using $CO_2$ laser with laser power of 4 W, laser moving velocity of 15 mm/s, and length of microchannel of 100 mm. The widths of microchannel exist error. The metallographic microscope and scanning electron microscope (SEM) are applied to observe the datum of experiment. Figure 3 shows the micrograph picture of microchannel. In order to make the width error of whole microchannel decrease, some

**Table 1** Orthogonal levels and factors

| Level | Factor | | |
|---|---|---|---|
| | A (laser power) ( W) | B (laser moving velocity) (mm/s) | C (channel length) (mm) |
| 1 | 4 | 5 | 40 |
| 2 | 8 | 10 | 70 |
| 3 | 12 | 15 | 100 |

**Table 2** The corresponding parameters of experiment of each group

| No. | A | B | C |
|---|---|---|---|
| 1 | 1 | 1 | 1 |
| 2 | 1 | 2 | 2 |
| 3 | 1 | 3 | 3 |
| 4 | 2 | 1 | 2 |
| 5 | 2 | 2 | 3 |
| 6 | 2 | 3 | 1 |
| 7 | 3 | 1 | 3 |
| 8 | 3 | 2 | 1 |
| 9 | 3 | 3 | 2 |

experiments are completed. Compared with the results of these experiments, the most optimal laser machining parameters will be obtained.

For convenience, the orthogonal experiment method is applied in the experiment and was presented by Taguchi. The optimal conditions are obtained by a few of experiments with the method. Laser power, laser moving velocity, and length of microchannel are defined for the main factors to influence of the width error of microchannel in the experiment. A $L_9(3^3)$ $CO_2$ orthogonal array laser cutting experiment using orthogonal array experimental factors is performed. Table 1 shows orthogonal levels and factors. Table 2 shows the corresponding parameters of experiment of each group.

### 3.2 $CO_2$ laser machining experiment

Next, the optimal experiment was completed with the above orthogonal parameters. The predicted schematic of microchannel of PC sheet in three dimensions was drawn by Solidworks 2012 with the different laser parameters. Figure 4 shows the predicted schematic of microchannel.

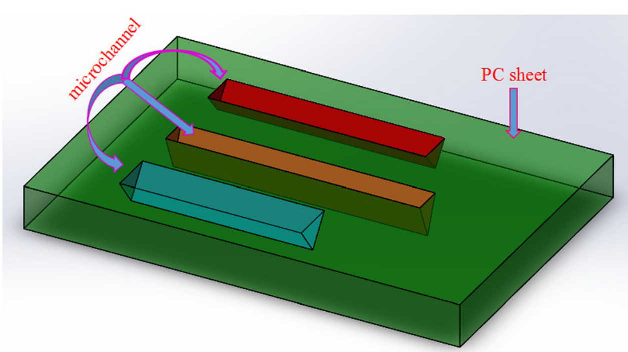


**Fig. 4** The predicted schematic of microchannel

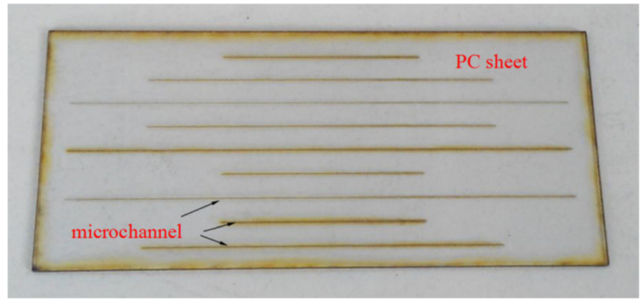


**Fig. 5** The schematic of microchannels of PC sheet

The nine microchannels of PC sheet were produced using $CO_2$ laser with the different laser parameters. Figure 5 shows schematic of microchannels. In the picture, the surface generated adust phenomenon and yellow material. The transmittance of PC was very high. The microchannels were processed by the parameters in Table 2. Three test points were selected in each microchannel in postprocessing. The method could ensure the accuracy of measurements. Next, some numerical methods were calculated for the microchannels of PC sheet.

### 3.3 Data analysis of the orthogonal method

Though the test of microscope, the datum of experiment is represented in Table 3. In order to accurately calculate the width error, processing stability $H$ is defined as follows:

$$H = \frac{S_{max} - S_{min}}{S_{mid}} \tag{3}$$

where $S_{max}$ is the maximum width of microchannel, $S_{min}$ is the minimum width of microchannel, and $S_{mid}$ is middle width of microchannel.

**Table 3** The factors response

| No. | A | B | C | Processing stability H (%) |
|---|---|---|---|---|
| 1 | 1 | 1 | 1 | 32.1 |
| 2 | 1 | 2 | 2 | 20.8 |
| 3 | 1 | 3 | 3 | 37.2 |
| 4 | 2 | 1 | 2 | 17.8 |
| 5 | 2 | 2 | 3 | 13.7 |
| 6 | 2 | 3 | 1 | 6.3 |
| 7 | 3 | 1 | 3 | 33.2 |
| 8 | 3 | 2 | 1 | 33.5 |
| 9 | 3 | 3 | 2 | 22.5 |
| $T_1$ | 30 | 27.7 | 23.9 | |
| $T_2$ | 12.6 | 22.6 | 20.3 | |
| $T_3$ | 29.7 | 22 | 28 | |
| $R$ | 17.4 | 5.7 | 7.7 | |

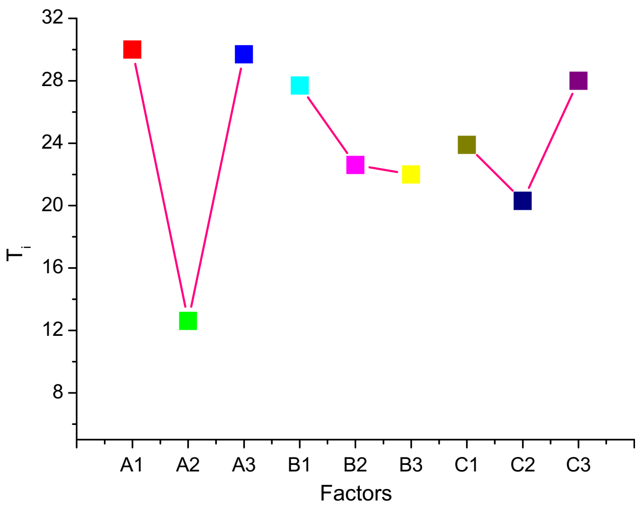


**Fig. 6** A factor response figure

In Table 3, $T_1$, $T_2$, and $T_3$ respectively indicate the average of factors in each level. The computational formula is defined as follows:

$$T^{\text{li}} = \frac{\sum H_{\text{li}}}{3} \tag{4}$$

where $i$ is the number of level and $l$ is the number factors [25].

$R$ represents the sensitivity of the various factors and is calculated by Eq. (5).

$$R = |T_{\max} - T_{\min}| \tag{5}$$

where $T_{\max}$ and $T_{\min}$ respectively show maximum and minimum in whole array.

In Table 3, the range $R$ represents the influencing results of all factors. The maximum influence is laser power among all parameters. The laser moving velocity is the minimum.

In order to clearly express the effect of factors in Table 3, a factor response figure is presented. Figure 6 shows a factor response figure. In the figure, the line is steeper and the influence of factor is greater. The line represents laser power is close to the vertical, so it is the most sensitive factor for processing improvement. A level combination of better parameters for the $CO_2$ laser machining in the experiment is A2B3C2. It says laser power of 8 W, laser moving velocity of 15 mm/s, and length of microchannel of 70 mm.

### 3.4 Verify the optimal result

According to the above result, a verified experiment was completed using $CO_2$ laser machining with laser power of 8 W, laser moving velocity of 15 mm/s, and length of microchannel of 70 mm. Figure 7 shows the SEM photo of optimal microchannel on PC sheet using $CO_2$ laser machining. The picture has clearly shown the profile of microchannel. Compared with initial microchannel, the microchannel was smoother. According to the numerical computation, it proves that the optimal parameter was better. The width error was smaller. The result of experiment verified the method was feasible.

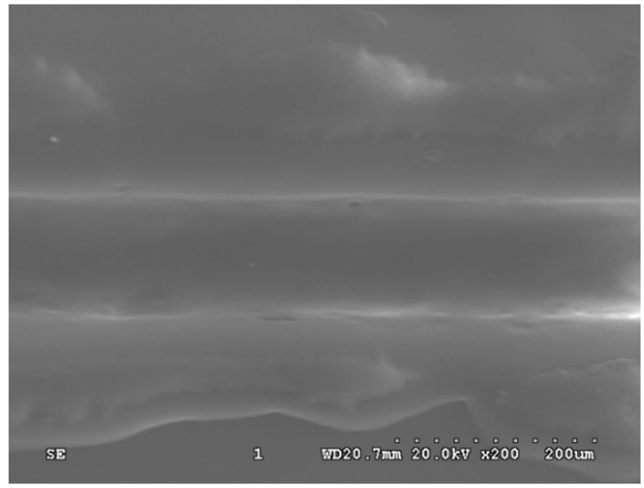


**Fig. 7** The SEM photo of optimal microchannel

## 4 Conclusions

Microchannels on the PC sheet are processed using $CO_2$ laser LCJG-1290. The width error of microchannel is effected by $CO_2$ laser parameters which include laser power, machining speed, and length of microchannel. In order to optimize the width of microchannel, the orthogonal experiment method is successfully applied in this experiment with $L_9(3^3)$ orthogonal test table. The result shows the degree of sensitivity of three different $CO_2$ laser parameters is ranked as laser power > length of microchannel > laser moving velocity. The optimal parameters are laser power of 8 W, laser moving velocity of 15 mm/s, and length of microchannel of 70 mm. Finally, a verified experiment confirms the authenticity of optimal datum. In the experiment, the metallographic microscope and SEM are applied for ensuring the accuracy of experiment. In addition, a combination of photochemical and photothermal processes of $CO_2$ laser plays an important role during the process of $CO_2$ laser machining. With the increase of temperature of PC, the phenomena including melting, decomposition, and vaporization are generated. This paper presents a fast and efficient experiment for the fabrication of the microfluidic chip on PC using $CO_2$ laser machining technology.

**Acknowledgements** This work was supported by the National Natural Science Foundation of China (51405214), Liaoning Province Doctor Startup Fund (20141131), Fund of Liaoning Province Education Administration (L2014241), and the Fund in Liaoning University of Technology (X201301).

## References


1. El-Taweel TA, Abdel-Maaboud AM, Azzam BS, Mohammad AE (2009) Parametric studies on the CO2 laser cutting of kevlar-49 composite. Int J Adv Manuf Technol 40(9–10):907–917
2. Ghosal S, Chaki S (2010) Estimation and optimization of depth of penetration in hybrid CO2 LASER-MIG welding using ANN-optimization hybrid model. Int J Adv Manuf Technol 47(9–12): 1149–1157
3. Antończak AJ, Nowak M, Szustakiewicz K, Pigłowski J, Abramski KM (2013) The influence of organobentonite clay on CO2 laser grooving of nylon 6 composites. Int J Adv Manuf Technol 69(5–8): 1389–1401
4. Wang XC, Laoui T, Bonse J, Kruth JP, Lauwers B, Froyen L (2002) Direct selective laser sintering of hard metal powders: experimental study and simulation. Int J Adv Manuf Technol 19(5):351–357
5. Teixidor D, Orozco F, Thepsonthi T, Ciurana J, Rodríguez CA, Özel T (2013) Effect of process parameters in nanosecond pulsed laser micromachining of PMMA-based microchannels at near-infrared and ultraviolet wavelengths. Int J Adv Manuf Technol 67(5–8):1651–1664
6. Rahmani-Monfard, K., Fathi, A., & Rabiee, S. M. (2015). Three-dimensional laser drilling of polymethyl methacrylate (PMMA) scaffold used for bone regeneration. The International Journal of Advanced Manufacturing Technology, 1–9
7. Li HW, Fan YQ, Foulds IG (2012a) Rapid and low-cost fabrication of polystyrene-based molds for PDMS microfluidic devices using a CO2 laser. In advanced materials research. Trans Tech Publications 403:4344–4348
8. Davim JP, Oliveira C, Barricas N, Conceição M (2008) Evaluation of cutting quality of PMMA using CO2 lasers. Int J Adv Manuf Technol 35(9–10):875–879
9. Eltawahni, H. A., Olabi, A. G., & Benyounis, K. Y. (2011, January). Assessment and optimization of CO2 laser cutting process of PMMA. In International Conference on Advances in Materials and Processing Technologies (AMPT2010). AIP Publishing 1315(1)1553–1558
10. Sun Y, Satyanarayan MVD, Nguyen NT, Kwok YC (2008) Continuous flow polymerase chain reaction using a hybrid PMMA-PC microchip with improved heat tolerance. Sensors Actuators B Chem 130(2):836–841
11. Riahi M (2012) Fabrication of a passive 3D mixer using CO2 laser ablation of PMMA and PDMS moldings. Microchem J 100:14–20
12. Toossi A, Daneshmand M, Sameoto D (2013) A low-cost rapid prototyping method for metal electrode fabrication using a CO2 laser cutter. J Micromech Microeng 23(4):047001
13. Chen X, Li T, Shen J, Hu Z (2016a) Fractal design of microfluidics and nanofluidics—a review. Chemom Intell Lab Syst 155:19–25
14. Chung CK, Syu YJ, Wang HY, Cheng CC, Lin SL, Tu KZ (2013) Fabrication of flexible light guide plate using CO2 laser LIGA-like technology. Microsyst Technol 19(3):439–443
15. Li H, Fan Y, Kodzius R, Foulds IG (2012b) Fabrication of polystyrene microfluidic devices using a pulsed CO2 laser system. Microsyst Technol 18(3):373–379
16. Prakash S, Kumar S (2015) Profile and depth prediction in single-pass and two-pass CO2 laser microchanneling processes. J Micromech Microeng 25(3):035010
17. Yang CB, Deng CS, Chiang HL (2012) Combining the Taguchi method with artificial neural network to construct a prediction model of a CO2 laser cutting experiment. Int J Adv Manuf Technol 59(9–12):1103–1111
18. Chen, X. Y., Gao, Q., Wang, X. L., & Li, X. D. (2016b). Experimental design and parameter optimization for laser three-dimensional (3-D) printing. Lasers in Engineering (Old City Publishing) 33
19. Chen X, Li T, Shen J (2016c) CO2 laser ablation of microchannel on PMMA substrate for effective fabrication of microfluidic chips. Int Polym Process 31(2):233–238
20. Chen X, Shen J, Zhou M (2016d) Rapid fabrication of a four-layer PMMA-based microfluidic chip using CO2-laser micromachining and thermal bonding. J Micromech Microeng 26(10):107001
21. Chen, X., Li, T., & Fu, B. (2016e). Surface roughness study on microchannels of CO2 laser fabricating PMMA-based microfluidic chip. Surface Review and Letters 1750017
22. Chen X, Li T, Shen J, Hu J (2016f) Optimization of processing micro-channels with CO2-laser on polyethylene terephthalate (PET) sheet. Opt Precis Eng 24(10):224–228
23. Qi H, Chen T, Yao L, Zuo T (2009) Micromachining of microchannel on the polycarbonate substrate with CO 2 laser direct-writing ablation. Opt Lasers Eng 47(5):594–598
24. Li H, Wang L, Cai Q (1991) Simplified calculation of temperature field in laser heating [J]. The Laser Technology 2:022
25. Chen, X., Li, T., Hu, Z., & Zhou, M. (2016g). Using orthogonal experimental method optimizing surface quality of CO2 laser cutting process for PMMA microchannels. Int J Adv Manuf Technol 1–7