BIOMATERIALS AND POLYMERS HORIZON (2022) 1(1), 15-21
https://doi.org/10.37819/bph.001.01.0123

RESEARCH ARTICLE

Check for updates

An experimental study of PMMA precision cryogenic micro-milling

Ying Yan[1], Yujia Sun[1], Bo Li[1], Ping Zhou[*]

[1]Key Laboratory for Precision and Non-traditional Machining Technology of Ministry of Education, Dalian University of Technology, Dalian 116024, China.
**Corresponding author: pzhou@dlut.edu.cn*

ABSTRACT

Polymethyl methacrylate (PMMA) has been used more and more widely in the fields of microfluidic devices and high-precision optical components due to its excellent mechanical and optical properties. Micro-milling is one of the methods that has been used in the machining of polymer materials. The machinability of PMMA is highly dependent on temperature, and the cryogenic method is also applied to control the processing temperature. In this work, the PMMA was milled with different processing parameters at the temperature of -55℃ and 25℃. The influence of each milling parameter on the surface quality under different temperature conditions were investigated. According to the results, the cutting depth is the dominant factor that influenced the surface roughness. The shape accuracy of the rectangular microgroove processed under low-temperature conditions is better. The material removal mechanism under different temperatures was also discussed, and the material is cut in a brittle way under low temperatures.

ARTICLE HISTORY

Received: 07-06-2021
Revised: 19-08-2021
Accepted: 09-10-2021

KEYWORDS

Cryogenic machining
Micromilling
Surface roughness
Material removal
Polymer materials

Introduction

Polymers have been widely applied in modern industries due to their distinctive properties, biocompatibility, low thermal conductivity, optical characteristics, low cost and so on (Cowie et al.,2007, Korkmaz et al.,2017). Particularly, polymer devices with microstructures are broadly used in many applications such as precision energy and optical system, microfluidic chips and drug delivery applications (Lin et al.,2003, Sun et al.,2015, Wu et al.,2007). There are many kinds of polymers, and the main applications are polyamide (PA), polybutylene terephthalate (PBT), polymethyl methacrylate (PMMA), polydimethylsiloxane (PDMS), polyetheretherketone (PEEK), and polytetrafluoroethylene (PTFE) (Spierings et al.,1991, Zheng et al.,2011). PMMA has good comprehensive mechanical properties, and it is at the forefront of general-purpose plastics. But it obtains poor heat resistance with the heat distortion temperature of 96 °C (Atkins et al.,1975). When the temperature is lower than 127 °C, the thermal conductivity of PMMA increases with the increase of temperature, which helps to transfer the heat in machining to the environment in time (Han et al.,2016).

At present, the leading manufacturing methods for PMMA microfluidic chips are hot pressing, injection molding, carbon dioxide (CO2) laser etching, photolithography, and precision machining (Yu et al.,2014, Albert et al.,2004). Although these methods advanced the PMMA manufacturing field, most of these methods require high temperature, complex procedures involving multiple steps, expensive equipment or chemical processing, which may lead to low productivity (Yang et al., 2013, Luo et al., 2004).

High-speed micro-milling is a time-efficient method with low cost and has the capability to fabricate complicated and multi-level microstructures. It is one of the precision machining techniques with a diameter of less than 1 mm and a length range of 10 mm-100 mm. Due to the sharp reduction of tool diameter and feed rate compared to conventional milling, micro-milling shows different machining mechanisms than traditional millings, such as size effect, minimum cutting thickness, and effective rake angle, etc. (Li et al.,2016), which make the material removal mechanism more complicated and difficult to determine. Micromilling is actually a combination of multiple turning tools, and it is less studied than traditional milling. The complete theoretical system and uniform evaluation standard of micro milling are in urgent need.

Kobayashi (Kobayashi et al.,1984) focused on the ultra-precision machining of PMMA. Based on their results, the surface roughness decreased with the feeding rate reduction. They proposed the feasibility of plastic machining with high dimensional accuracy and good surface quality. Albert J. Shih (Albert et al.,2004)manufactured elastomer with end mills in different diameters (3.18/6.35/12.7 mm), materials (cemented carbide, carbon steel) and tool shapes (single-tooth, two-tooth). The structural stiffness of the elastomer workpiece under different geometric configurations was analysed by finite element analysis. Also, it was found that the machined surface quality was improved by using solid carbon dioxide. Okuda (Okuda et al., 2009) described the cutting characteristics and the shape error of the groove when the end mill finished PMMA with a small diameter. It was found that the surface roughness of 1 μm R_z or less could be obtained, and the width of the channel became less than the tool diameter. Additionally, the deflection of the end mill caused by the cutting force would also affect the shape error of the groove. To study the optimum manufacturing parameters of micro-milling polymer materials, Jirapattaraslip (Jirapattaraslip et al., 2009) used four-tooth steel end mill cutters to mill PMMA with high speed. The results revealed that feed rate was the main factor that affected tool wear. The low feed rate and high cutting speed were recommended to mill PMMA to keep the long tool life. Korkmaz (Korkmaz et al., 2017) machined the PMMA with a single-crystal diamond end mill cutter diameter 450 μm. In their work, the chip formation, groove integrity, surface roughness, and cutting force were analysed. The obtained surface roughness was less than 70 nm, and the milling force is less than 1N. The full factor test method and the three-way analysis of variance (3-way ANOVA) test were applied to make the conclusion that the feed rate and spindle speed are the main factors affecting the surface roughness, and the effects of cutting depth were found to be negligible. Chen (Chen et al., 2014) studied the effects of spindle speed, feed rate, cutting depth and compressed air/lubricant on the surface roughness of PMMA after processing with a two-tooth end mill (diameter: 200 μm). The experimental results were analysed with the all-factor experimental method and the signal-to-noise ratio analysis method. The minimum surface roughness was 130 nm and obtained at the spindle speed of 20000 r/min, the feed rate of 300 mm/min and cutting depth of 10 μm. They also concluded that the use of compressed lubricants in the process did not improve the surface quality.

At present, the manufacturing of polymer materials is focused on finding the optimal parameters under different processing conditions. More research should be done to better understand polymer surface quality influence factor and material removal mechanism. It is known that the surface quality characteristics are being influenced by processing parameters such as cutting speed, cutting depth and feed rate during machining. In this work, PMMA is utilised as the experimental sample, and the high-speed micro-milling orthogonal experiments were conducted with it under the temperature of -55℃ and 25℃. The machined surface roughness were measured to analyse the influence of spindle speed, cutting depth and feed rate on surface quality. The relationship between milling force and surface quality was discussed and the optimal processing parameters were proposed according to the results.

Research Methodology

A precision small lathe used in this experiment, as was shown in Fig.1. The ultra-fine particle cemented carbide micro milling cutter (Mitsubishi Japan, purchased from Misumi China, model MS2SS) was applied as the machine tool with a diameter of 1 mm. In order to maintain the consistency of the tool runout during the machining process, the position of the tool holder was marked. Therefore, the position of each clamping was kept the same. For the sake of eliminating the influence of tool superposition wear on the machined surface, each group of the experiments was conducted with a new micro milling cutter. The PMMA workpiece was sprayed with liquid nitrogen continuously during the processing. In this work, nine orthogonal high-speed micro-milling experiments and three sets of single-factor experiments. The samples are cut into 50 mm×50 mm×5 mm thin plates. The three-factor and three-level orthogonal parameters are shown in Table 1. The single factor experiment parameters are shown in Table 2. and Table 3. The surface roughness value (Sq) is selected as a characterising parameter of surface quality, and it is measured by a laser confocal microscope (Keyence VK-X250).

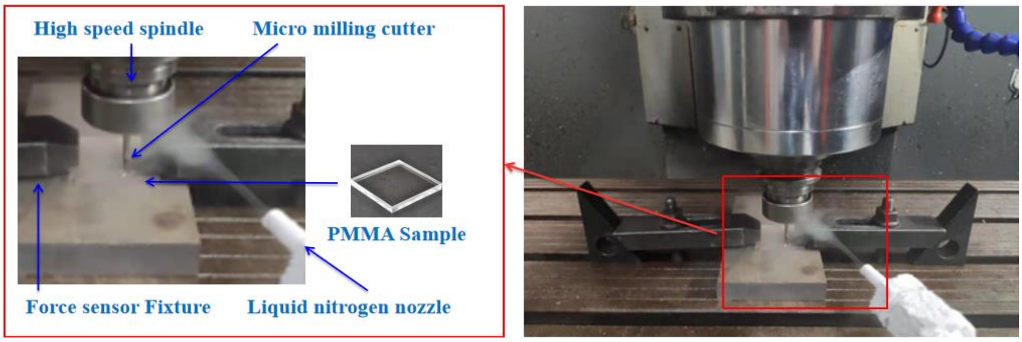

Figure 1. Photos of the experimental setup and sample

Factor	Level 1	Level 2	Level 3
A- Spindle speed（r/min）	2000	4000	6000
B- Feed rate（mm/min）	60	150	300
C- Cutting depth（mm）	0.2	0.4	0.6

Table 1. Various levels of three factors.

Factor	Level 1	Level 2	Level 3	Level 4
A- Spindle speed（r/min）	6000	6000	6000	6000
B- Feed rate（mm/min）	60	60	60	60
C- Cutting depth（mm）	0.05	0.1	...	0.6

Table 2. Single factor experiment on cutting depth.

Factor	Level 1	Level 2	Level 3	Level 4
A- Spindle speed（r/min）	6000	6000	6000	6000
B- Feed rate（mm/min）	40	80	...	320
C- Cutting depth（mm）	0.2/0.4	0.2/0.4	0.2/0.4	0.2/0.4

Table 3. Single factor experiment on feed rate.

Results and discussions

Roughness analysis by orthogonal experiments

In this paper, the surface roughness S_q value is selected as the sfinal surface quality characterising parameter. The processed PMMA was ultrasonically cleaned. Five points were taken along the groove under the laser confocal microscope to measure the roughness of the bottom surface (S_q). The average value was used as the final result of surface roughness. The experimental parameters based on various factors and levels are listed in Table.4.

Group No.	A	B	C
1	2000	60	0.2
2	2000	150	0.6
3	2000	300	0.4
4	4000	60	0.4
5	4000	150	0.2
6	4000	300	0.6
7	6000	60	0.6
8	6000	150	0.4
9	6000	300	0.2

Table.4 Experimental parameters based on various factors and levels.

Fig.2 shows the surface roughness S_q value corresponding to the milling parameters at the temperature of -55°C and 25°C. There is a significant difference in surface quality after milling at the temperature of -55°C and 25°C. The surface quality under the condition of -55℃ is relatively more stable with the change of the processing parameters, and the fluctuation of surface roughness S_q is relatively small. But the value of S_q fluctuates wildly at the temperature of 25°C. Based on the results of the orthogonal experiment at the temperature of -55℃, the surface roughness value is the smallest with the spindle speed of 6000 r/min, the feed speed of 60mm/min, and the cutting depth of 0.4 mm. Under the temperature of 25°C, the surface roughness value is the smallest when the spindle speed is 6000 r/min, the feed speed is 60 mm/min, and the cutting depth is 0.2 mm. According to the results, the higher spindle speed and smaller the feed rate would result in smaller surface roughness S_q. But the cutting depth has a different effect on the surface roughness value. In the case of a relatively small cutting depth of 0.2 mm, the surface roughness value of workpieces cut with liquid nitrogen cooling is larger than that of workpieces cut with a temperature of 25℃. With increasing the cutting depth (0.4 mm, 0.6 mm), the roughness value at the temperature of 25°C increases drastically. In general, the machining quality of -55°C is better than that of 25°C. The following is a specific analysis of the impact of cutting parameters on surface quality.

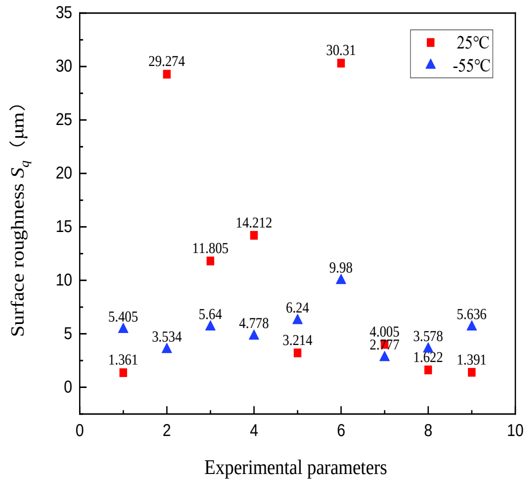

Figure 2. The bottom surface roughness Sq under different orthogonal experimental parameters (-55 ℃ and 25 ℃).

To determine the specific effect of each milling parameter on the surface roughness value. The characterisation of influence factors is used for specific evaluation. The calculation formula of the influence factors is shown as follows:

$$R = \frac{1}{n}\sum_{i=1}^{k} x_i^2 - \frac{\left(\sum_{i=1}^{k} x_i\right)^2}{nk} \qquad (1)$$

Where n=3, x_i represents the mean of surface roughness values measured at each level under a factor condition. The specific impact factor calculations is shown in Table 5.

Factor	-55°C	25°C
A- Spindle speed（r/min）	1.095	7.976
B- Feed rate（mm/min）	2.765	13.572
C- Cutting depth（mm）	3.002	19.208

Table 5. Factor analysis results to determine the key cutting parameter under different temperatures (-55 ℃ and 25 ℃).

The influence factor of the three cutting parameters on the surface roughness at the temperature of 25°C and -55°C is shown in Table 5. It can be concluded that the cutting depth has the most significant influence on the surface roughness value, while the spindle speed has a relatively small influence on the surface quality at the temperature of -55°C and 25°C. Under the temperature of 25°C, the surface roughness value after milling is affected by the parameters and changes more widely. The influencing factor is approximately 5 to 7 times that at the temperature of -55°C. When the cutting depth is greater than 0.4 mm, the processing at room temperature shows greater sensitivity to the cutting depth.

Effect of cutting depth on surface quality

As shown in Fig.3, it is the surface roughness S_q with different cutting depths 0.05 mm and 0.6 mm, with the spindle speed of 6000 r/min and the feed rate of 60 mm/min. In general, the surface roughness S_q increased with the cutting depth, and the surface quality was more sensitive to cutting depth under the temperature of 25°C. Whether it is at the temperature of -55°C or 25°C, the cutting depth directly affects the volume of the material removal area. When the cutting depth was between 0.4 mm and 0.6 mm, the surface roughness S_q changed from 4.339 μm to 14.892 μm. With a temperature of -55°C, the minimum surface roughness was achieved at the cutting depth of 0.4 mm~0.45 mm with a spindle speed of 6000 r/min and a feed rate of 60 mm/min. The surface quality is better with a small cutting depth (≤0.25mm) at the temperature of 25°C, and surface quality is better with a large cutting depth (≥0.3mm) at the temperature of -55°C.

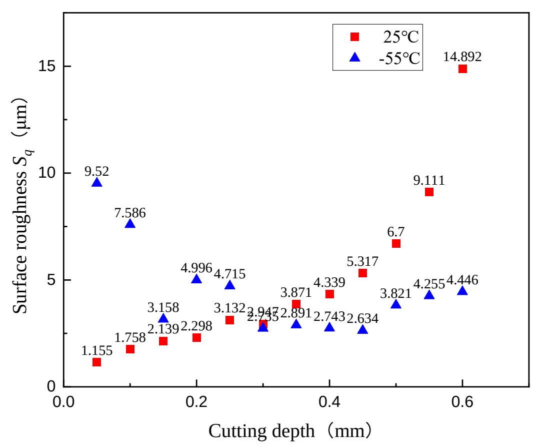

Figure 3. The bottom surface roughness *Sq* under different cutting depth (-55 ℃ and 25 ℃).

Effect of feed rate on surface quality

The change of surface roughness S_q with feed rate under different processing parameters is shown in Fig.4. In general, the increase of feed speed will lead to the increase of surface roughness, no matter the temperature is -55℃ or 25℃. Due to the effect of cryogenic shrinkage of the workpiece, the surface roughness value at 25°C is always better than the surface roughness value at -55°C with the cutting depth of 0.2 mm.As shown in Fig.4(a), when the cutting depth was 0.2mm, the surface roughness S_q changed slightly with the slow increase of feed rate at the temperature of 25°C. But the variation of the surface roughness S_q is larger at the temperature of -55°C. The maximum value of surface roughness S_q was found when the feed rate was between 80 mm/min~90 mm/min. In Fig.4(b), it can be seen that the surface roughness S_q at the temperature of 25°C is larger, and it changes significantly from 5.017 μm to 19.582 μm when the feed speed changed from 70 mm/min to 100 mm/min. However, the surface roughness S_q is stable, and it is much lower than that of the temperature of 25°C. The continuous increase of the feed rate will produce a relatively large impact and result in breaking the tool's cutting edge. Also, there will be more cracks generated at the surface of the PMMA workpiece. Therefore, in the PMMA milling process, a small feed rate is more conductive to surface quality.

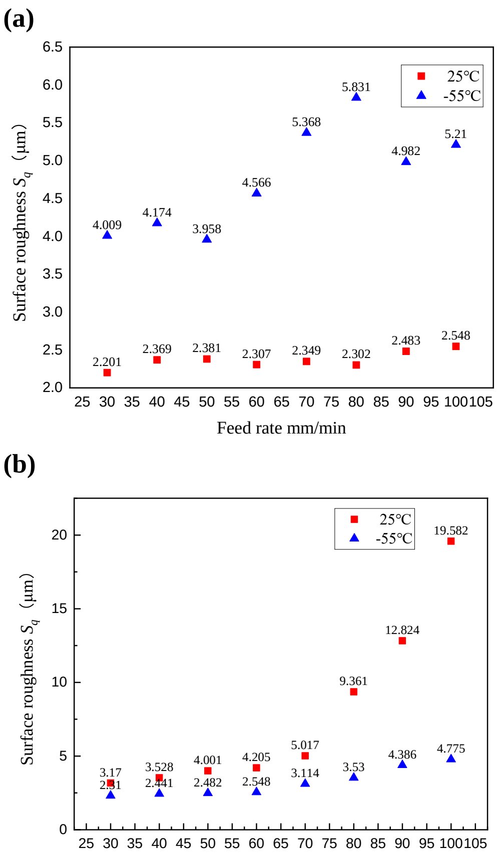

Figure 4. Surface roughness with different feed rate, (a) Cutting depth 0.2 mm, spindle speed 6000 r/min (b) Cutting depth 0.4 mm, spindle speed 6000 r/min.

Removal mechanism analysis

The removal mechanism is different at low temperature and room temperature. The large defects which were found on the workpiece after the milling process were displayed in Fig.5(a). It can be seen that at the temperature of -55°C, there were slag-like surface defects on both sides. They were the chips generated by the milling cutter blade acting on the part of the substrate with poor mechanical properties during the milling process. Therefore, it was inferred that the PMMA material tends to be removed brittlely at the temperature of -55°C. The surface morphology after milling at room temperature is shown in Fig.5(b). There was a large part of plastic deformation at the side of the grove. Therefore, it was concluded that the cutting heat would result in material softening, and the PMMA would be removed in a plastic way instead of in a brittle way.

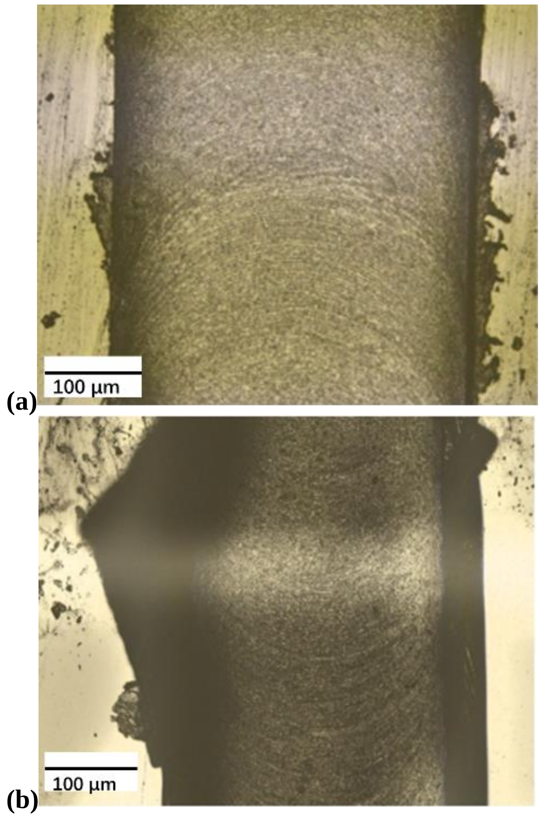

Figure 5. Larger defects on the workpiece surface after milling process, (a) -55°C (b) 25°C

The temperature may also influence the mobility of molecular chains. At low temperatures, the molecular chains are in a stable state, and movement ability is not good. The PMMA is more easily to be removed under this condition. Also, liquid nitrogen treatment can effectively reduce the local temperature of the cutting area and avoid the impact of plastic deformation induced by the temperature rising during the milling process.

Conclusions

1) Through orthogonal tests and analysis of the influence factor, the optimal machining parameters are determined to be spindle rotation speed of 6000 r/min, cutting depth of 0.4 mm, and the feed rate of 60 mm/min at the temperature of -55°C. The optimum surface roughness is 2.777 μm. The optimal processing parameters at 25°C are the spindle speed of 6000 r/min, cutting depth of 0.2

mm, the feed rate of 60 mm/min, and the optimum surface roughness of 1.361 μm.

2) Through the single factor experiment, it is determined that the feed rate has a consistent effect on the surface quality at the two different temperatures. The surface roughness increased with the increase of feed rate. However, the effect of cutting depth on roughness varies significantly at different temperatures. It shows that temperature is an important factor affecting the surface quality

3) At the temperature of -55°C, the PMMA is removed in a brittle way. But at the temperature of 25°C, the PMMA is easy to be softened with the increasing temperature, and most of the material is removed plastically. The results in this work indicate that the material removal mode is the core problem in the study of surface quality of polymer in cryogenic micro-milling.

Acknowledgements

The authors appreciate the financial support from the National Natural Science Foundation of China (No. 51975094), the Fundamental Research Funds for the Central Universities (DUT20LAB108).

References

Albert J.S., Mark A.L. & John S.S. (2004). End Milling of Elastomers—Fixture Design and Tool Effectiveness for Material Removal. *Journal of Manufacturing Science and Engineering*(1), https://doi:10.1115/1.1616951.

Atkins A.G., Lee C.S. & Caddell R.M. (1975). Time-temperature dependent fracture toughness of PMMA. *Journal of Materials Science*(8), https://doi:10.1007/BF00540829.

Chen P.C., Pan C.W., Lee W.C. & Li K.M. (2014). An experimental study of micromilling parameters to manufacture microchannels on a PMMA substrate. *The International Journal of Advanced Manufacturing Technology*(9-12), https://doi:10.1007/s00170-013-5555-

Cowie J.M.G., & Arrighi V. (2007).*Polymers: Chemistry and Physics of Modern Materials, Third Edition*.CRC Press.

Han X.W. (2016). *Study on PMMA Polymer Thermal Engraving Technology for Microfluidic Analysis Chips*(Doctoral Dissertation,Harbin Institute of Technology, in Chinese).

Jirapattarasilp K. & Obma S. (2012). Tool Wear in Vertical Milling of Polymethyl-methacrylate Sheet. *AASRI Procedia*, https://doi:10.1016/j.aasri.2012.11.026.

Kobayashi A. & Hirakawa K. (1984). Ultraprecision Machining of Plastics. Part 1. Polymethyl Methacrylate. *Polymer-Plastics Technology and Engineering*(1), https://doi:10.1080/03602558408070029.

Korkmaz E., Onler R. & Ozdoganlar O.B. (2017). Micromilling of Poly(methyl methacrylate, PMMA) Using Crystal Diamond Tools. *Procedia Manufacturing(01)*, https://doi:10.1016/j.promfg.2017.07.017.

Korkmaz E., Onler R. & Ozdoganlar O.B. (2017).Micromilling of Poly(methyl methacrylate, PMMA) Using Single-Crystal Diamond Tools. *Procedia Manufacturing*, https://doi:10.1016/j.promfg.2017.07.017.

Li Y.G., Yan P., Huang Y. & Shan S.J. (2016). Preparation of PMMA microlens array based on X-ray mobile lithography.*Infrared and laser engineering*(06), 224-228. https://doi:CNKI:SUN:HWYJ.0.2016-06-034.

Lin B.C. (2003). Microfluidic chip lab and its functionalization. *Journal of China Pharmaceutical University(01)*, https://doi:CNKI:SUN:ZGYD.0.2003-01-000.

Luo Y., Lou Z.F., Chu D.N., Liu C., Wang L.D. (2004). Production of glass microfluidic chip. *Nanotechn-ology and precision engineering*(01),20-23. https://doi:CNKI:SUN:NMJM.0.2004-01-003.

Okuda K., Tsuneyoshi T., Li W. & Shibahara H. (2009). Study on Cutting of Micro Channel by End Mill with Small Diameter. *Key Engineering Materials*, https://doi:10.4028/www.scientific.net/KEM.407-408.351.

Spierings G.A.C.M. (1991). Compositional effects in the dissolution of multicomponent silicate glasses in aqueous HF solutions. *Journal of Materials Science*(12), https://doi:10.1007/BF01124681.

Sun J.H., Guan F.Y., Zhu X.F.... & Deng T. (2016). Micro-fabricated packed gas chromatography column based on laser etching technology. *Journal of Chromatography A*(01), https://doi:10.1016/j.chroma.2015.12.001.

Wu C.J., Jin Z.H. et al. (2007). Design and fabrication of a nanofluidic channel by selective thermal oxidation and etching back of silicon dioxide made on a silicon substrate. *Micromech. Microeng*. https://doi:17 (2007) 2393–2397.

Yang Q. & Li G.X. (2013). Research progress on micro-molding of polymers and their composites. *Polymer notification*(09),107-115. https://doi:10.14028/j.cnki.1003-3726.2013.09.007.

Yu M.F., Zeng H.M., Zhang H. & Que D.W. (2014). Research progress and application progress of microfluidic chip technology. *Plant protection*(04),1-8. https://doi:CNKI:SUN:ZWBH.0.2014-04-001.

Zheng X.L., Yan J.W. & Yang J. (2011). Research progress on materials and processing methods of microfluidic chips. *Sensors and Microsystems*(06),1-4+7. https://doi:10.13873/j.1000-97872011.06.016.