

## Study on Micromilling Processes for Polymethyl Methacrylate

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**Abstract.** Polymethyl methacrylate (PMMA) has been commonly used to manufacture polymer microfluidic devices owing to its advantages such as low cost, biocompatibility and optical properties. The forecast regression model of surface roughness is constructed for micromilling of PMMA by the least square method. Surface roughness is selected as the judging criterion to study micromilling processes. Experiments have been processed on a three-axis desktop micromilling machine tool by conducting six different micromilling ways composed of the downfeed from outside and inside of the workpiece, climb milling, and conventional milling. Experimental results show that the forecast model is realistic to reflect the results of the experiments. The surface roughness achieved by the downfeed from outside of the workpiece is better than that from the inside of the workpiece when other micromilling settings are fixed. The smallest surface roughness value is achieved with the blend of climb milling and conventional milling, and the maximum surface roughness value is achieved with the conventional milling.

### Introduction

With the progress of science and technology, the miniaturized product has a broad application prospect in various fields such as the aerospace, automotive, biological medicine, environmental monitoring, military, etc. Micromilling is a kind of important machining process, which occupies a pivotal position in the fabrication of miniaturized products. Furthermore, micromilling process is a kind of very potential microfabrication technique with high efficiency, high flexible, and low environmental pollution [1].

PMMA has a lot of advantages, such as low cost, biocompatibility, optical properties and so on. Its good characteristics are used to replace silicon and glass in microfluidic chips [2][3]. Micromilling is accurate and efficient to machine geometrical features of miniaturized products. Micromilling process has a key role on the fabrication quality. However, it is mainly decided through trial and error method. In addition, the experience of micromilling is less and still in the exploring stage [4-6]. At present, surface roughness works as the main evaluation index to measure the processing quality, which is the basis to conduct process studies [7]. There are always multiple variables in the actual experiments, among which there usually exist complex relationships. Regression analysis is the most commonly used statistical method to deal with the correlativity among variables [8-10]. Therefore, to study the micromilling processes for PMMA material, this article uses the least squares fitting method combined with the software MATLAB to create the regression model.

## Experimental Preparation

The machine tool used for the experiment is a desktop three-axis micromilling machine tool 3A-S100, as shown in Fig.1. The spindle is driven by pneumatic turbine with aerostatic bearings and the rotating speed is  $80,000 \text{ min}^{-1}$ . Both axial runout and radial runout are within  $1\mu\text{m}$ . The transmission system adopts high performance linear motors for the three linear axes. Open-architecture controlling system is used by applying the PMAC motion controller and a PC.

The full-closed loop control system of 3A-S100 is formed by installing the grating ruler with the resolution of  $5\text{nm}$  for all three axes. The final positional accuracy of each axis is within  $0.6\mu\text{m}$ . The milling cutter is made of tungsten carbide with the diameter of  $1\text{mm}$ . The size of the PMMA sample is  $30 \text{ mm} \times 30 \text{ mm} \times 20\text{mm}$ .

## Regression Mode

In the micromilling experiment, surface roughness is regarded as the evaluation index. However there are many variables affecting on the surface roughness value. Based on the literature and the authors' experiences, axial direction, feed engagement, and radial direction are selected as major factors to build polybasic mathematical model. Consequently, the orthogonal experiments are conducted and the related data are obtained as shown in Table.1.



Fig.1 Miniaturized micromilling 3A-S100

Table.1 Experimental results

Experiment number	Axial direction ( $\mu\text{m}$ )	Feed engagement ( $\mu\text{m/z}$ )	Radial direction (mm)	Surface roughness ( $\mu\text{m}$ )
1	11	3	0.22	0.677
2	11	4	0.26	0.665
3	11	5	0.30	0.630
4	11	6	0.34	0.664
5	13	3	0.26	0.596
6	13	4	0.22	0.603
7	13	5	0.34	0.440
8	13	6	0.30	0.508
9	15	3	0.30	0.452
10	15	4	0.34	0.332
11	15	5	0.22	0.312
12	15	6	0.26	0.347
13	17	3	0.34	0.557
14	17	4	0.30	0.469
15	17	5	0.26	0.393
16	17	6	0.22	0.527

As shown in Tab.1, the total number of experiment  $n=16$ . There exists a kind of polybasic non-linear relationship between the surface roughness value  $y$  and the specific factor  $x_i$ . The function relationship between the surface roughness value  $y$  and the three factors (axial direction  $x_1$ , feed engagement  $x_2$  and radial direction  $x_3$ ) approximately conforms to the ternary quadratic polynomial model:

$$y=b_0+b_1x_1+b_2x_2+b_3x_3+b_4x_1x_1+b_5x_1x_3+b_6x_2x_3+b_7x_1^2+b_8x_2^2+b_9x_3^2 \quad (1)$$

where,  $b_0 b_1 b_2 b_3 b_4 b_5 b_6 b_7 b_8 b_9$  are regression coefficients.

The fitting of the least square multinomial curve does not require that the date point  $p_i(x_i, y_i)$  accurately passes the curve. However, the sum of the square error of the data points require to reach the minimum. Namely, the approximate curve  $y=y(x)$  of curve  $y=f(x)$  needs to be solved. Given the

error  $L_i = y^*(x) - y_i$ , the fitting method is selected based on the principle of  $L_i^2 = \min \sum_{i=1}^n [y^*(x_i) - y_i]^2$ .

The software Matlab has powerful numerical computation and system analysis functions. It is a kind of problem solving tool with high programming efficiency and convenience. Non-linear least squares data fitting can be realized by the function `nlinfit` of Matlab.

The m file as program carrier is created according to the multivariate function model. The function is defined in the m file and each coefficient and variable are edited, which is ready for subsequent procedures. After solving the `nlinfit` function, the `nlparc` function and the `nlpredc` function is used to solve confidence interval of regression coefficient, the predicted values, and the confidence interval radius. Then, the regression coefficient is examined.

$$[\text{beta}, \text{r}, \text{j}] = \text{nlinfit}(\text{x}, \text{y}, @\text{myfun}, \text{beta0}) \quad (2)$$

where,  $x$  acts as the matrix of the independent variable,  $y$  acts as the column vector of the dependent variable, `myfun` is the name of m file, `beta0` is estimation value of the undetermined coefficient in the function model, `beta` is regression coefficient that be estimated, `r` is residual, `j` is Jacobi matrix.

Regression coefficient is:

$$\text{beta} = [3.7783, -0.3879, -0.1280, 0.3071, -0.0108, -0.1213, -0.0960, 0.0155, 0.0303, 2.0312]$$

Confident interval of regression coefficient is:

`betac = nlparci(beta, r, j)`, where `nlparci` function is solved and the result is shown as follows.

$$\text{betac} = [-1.3453, 8.9019; -0.8277, 0.0519; -0.9179, 0.6619; -21.6827, 22.2969; -0.0437, 0.0221; -0.9447, 0.7021; -1.7428, 1.5508; 0.0033, 0.0277; -0.0186, 0.0791; -28.5016, 32.5641]$$

Confident interval of predicted value is:

`[betay, betayr] = nlpredci(@myfun, x, beta, r, j)`, the result is solved by `nlpredci` function, `betay` is the predicted value, `betayr` is the confident interval radius, as shown below.

$$\text{betay} = [0.7282, 0.6546, 0.6404, 0.6854, 0.5550, 0.5006, 0.4099, 0.4635, 0.4930, 0.3621, 0.4144, 0.3915, 0.5420, 0.4431, 0.4189, 0.4694]$$

$$\text{betayr} = [0.1816, 0.1443, 0.1443, 0.1816, 0.1443, 0.1443, 0.1443, 0.1443, 0.1443, 0.1443, 0.1443, 0.144, 3, 0.1816, 0.1443, 0.1443, 0.1816]$$

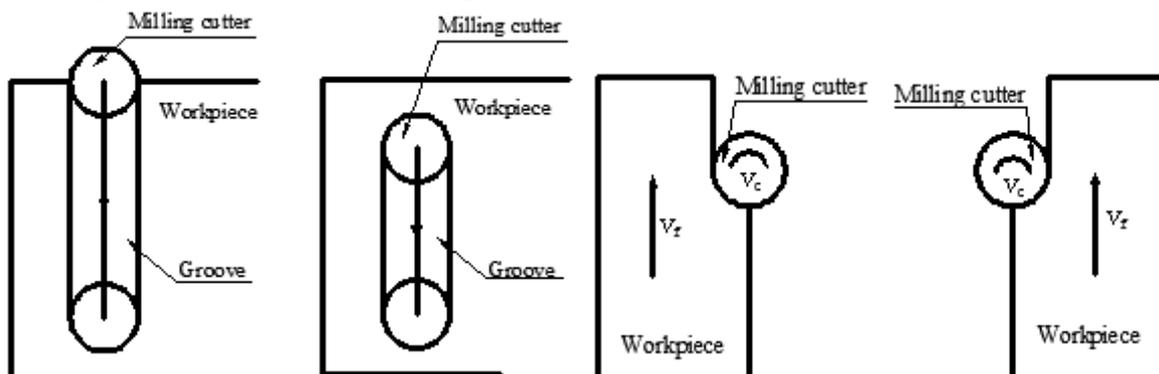
Regression function can be solved as follows.

$$y = 3.7786 - 0.3879x_1 - 0.1280x_2 + 0.3071x_3 - 0.0108x_1x_2 - 0.1213x_1x_3 - 0.0960x_2x_3 + 0.0155x_1^2 + 0.0303x_2^2 + 2.0312x_3^2 \quad (3)$$

As we can see from the above equations, the regression coefficient is within the confident interval of regression coefficient. The predicted model is fitted and built by combined actions of the axial cutting depth, each feeding and the radial cutting depth. It can be regarded as the prediction reference for micromilling results of PMMA material. Then, the predicted model obtained via experiments will be evaluated and analyzed.

## Experimental evaluation

In this experiment, the purpose is to determine how the influence of different processes on milling surface roughness values. Consequently, the suitable micromilling process can be identified. Surface roughness value is the evaluating index in these experiments.



(a) (b) (c) (d)  
Fig.2 Milling modes

The process selected can be divided into two kinds. One is the plunge cutting path, which includes plunge cut outside workpiece as shown in Fig.2(a) and inside workpiece as shown in Fig.2(b). Another one is the micromilling style, which includes down milling and up milling as shown in Fig. 2(c) and Fig. 2(d), respectively.

Because different plunge cut ways and milling method are considered for the experiments, the milling process is planned at first and the specific plan is shown in Tab.2. The second and fifth experiments adopt the combined down and up milling, where every groove are micromachined by the milling cutter with a single admission. Consequently, the width of the groove is 1mm in diameter as that of the milling cutter. The first and the fourth experiments adopt up milling, where the cutting path is a reciprocating one, as shown in Fig.3(a). The third and the sixth experiments adopt down milling, where the groove cutting path is the same as the above one, as shown in Fig.3(b).

In the experiment, the axial cutting depth  $a_p=15\mu\text{m}$ , the feed engagement  $f_z=5\mu\text{m/z}$ , and the radial cutting depth  $a_e=0.34\text{mm}$ . The data are from the optimum milling parameters obtained from analyzing the orthogonal experiments shown in Tab.1. The axial cutting depth is very small, which leads to inconvenient tool settings. Furthermore, the workpiece surface has flatness errors. Therefore, the milling depth is difficult to be determined. In the experiments, multi plunge in cutting processes are adopted. Each groove has a plunge cut number of four in the axial direction. Namely, each groove is micromilled four times in sequence.

Table.2 Experiments planning

Experiment number	Plunge cutting path	Micromilling style
1		Up milling
2	Outside	Combined milling
3		Down milling
4		Up milling
5	Inside	Combined milling
6		Down milling

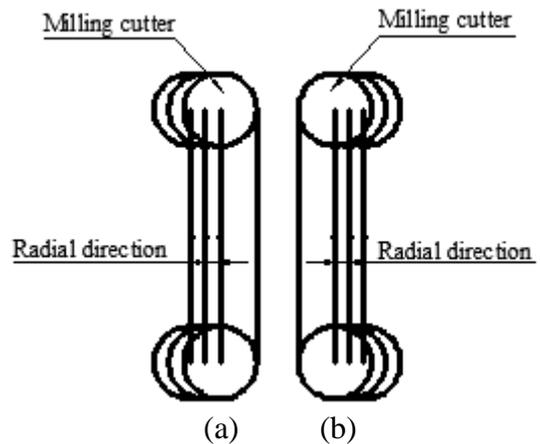


Fig.3 Tool path planning

From Table.2, the experiment needs milling 6 groove surfaces in total. Considering the positioning error due to several times installing between cutter and workpiece, and the effect of initial feed on up or down milling, the pre-milling grooves on the flank are prepared for grooves 1, 3, 4, and 6, as shown in Fig.4(a). After actual processing, the features of grooves are shown in Fig.4(b).

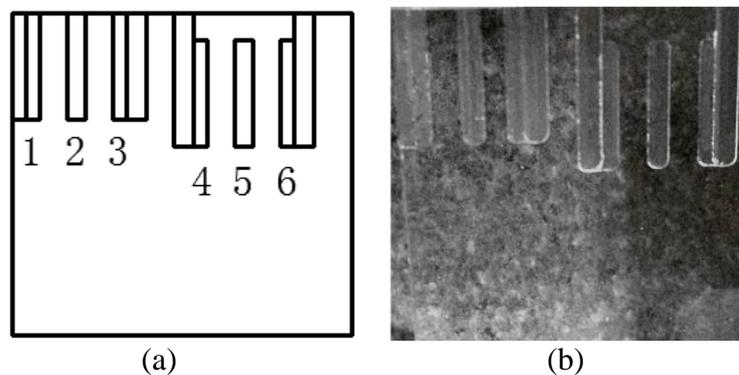


Fig.4 Experiments

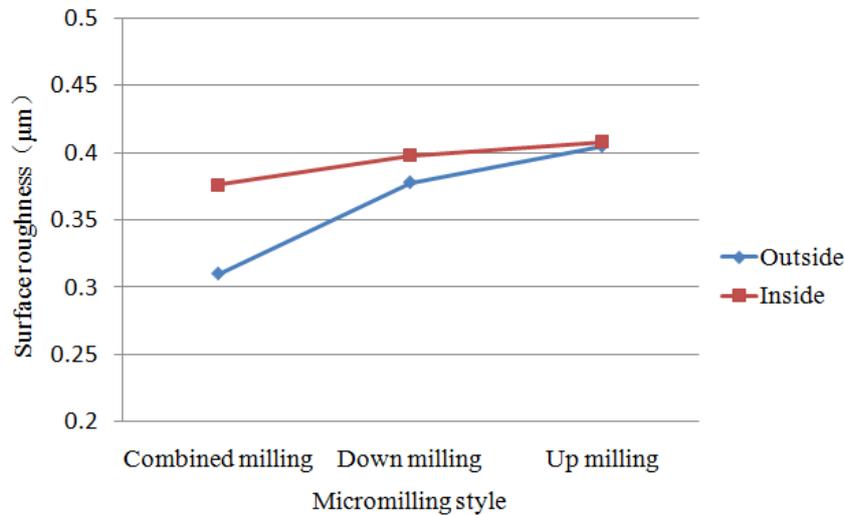


Fig.5 Comparison of surface roughness under different machining modes

In order to improve the measuring accuracy of the experimental results, each groove is measured four times and averaged. Final data are shown in Table.3.

Table.3 Surface roughness measurement

Experiment number	Measurements				Averaged surface roughness (µm)
	(µm)				
1	0.403	0.402	0.409	0.404	0.405
2	0.325	0.318	0.296	0.301	0.310
3	0.385	0.380	0.368	0.379	0.378
4	0.403	0.417	0.400	0.412	0.408
5	0.368	0.380	0.374	0.380	0.376
6	0.392	0.406	0.391	0.401	0.398

According to Table.3, the broken line graph can be drawn to show the different influences of different milling processes on milling surface roughness values, as shown in Fig.5.

Fig.5 obviously shows that the surface roughness value of plunge cut from outside is smaller than that of plunge cut from inside. There are milling activities between the end cutting edge and workpiece when plunge cut from inside the workpiece, where the axial milling may have an effect on surface quality of flat surfaces. Among the milling process plans, down milling can get better surface roughness value and it is relatively stable comparing to others. While in the process of up milling, the cutting thickness increases gradually from zero. When the cutting thickness of cutter is less than the minimum thickness, the phenomenon that the cutter squeeze the workpiece appears and the material cannot be completely removed, which affects the cutting surface quality. While in the process of down milling, the cutting thickness starts with the maximum value and consequently better surface roughness value can be obtained comparing to up milling.

The up or down milling way of plunge cut outside the workpiece is adopted to build a multivariate non-linear regression model. To put the milling parameters which include axial cutting depth of 15 microns, feed engagement of 5µm/z and radial cutting depth of 0.34 mm into the forecasting model, the surface roughness value of 0.3122µm is solved. Comparing with the second experiment which adopts the same process, where the experimental surface roughness value is 0.310µm, the mathematics model is evaluated successfully. Meanwhile, other different processes can be arranged to continue to verify the analysis. Therefore, the established prediction regression model has good approximation of the relationship between the surface roughness value and micromilling parameters of axial cutting depth, feed engagement and radial cutting depth.

According to the optimum milling parameters obtained above, the experiment has been conducted to mill a sample with complex shapes. The milling parameters can be adjusted according to previous obtained ones when using small diameter cutters. When 0.5mm diameter cutter is used, groove features with good surface finish have been obtained, as shown in Fig.6.

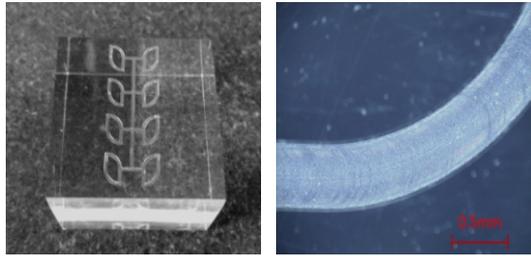


Fig.6 Micromilled groove features

After the ball add tape loading agencies, institutions force the ball the reverse spin, the ball close to pick the cue, pick the ball transfer fully energy to the ball, pick the ball effect is obvious stable. But it is found that the actual pick the ball after add tape loading agencies less than the theory calculated average distance.

## Conclusion

Aim at PMMA material, a study on micromilling processes has been carried out. The regression model between surface roughness and milling parameters has been built and verified. The surface roughness value is regarded as the evaluation criterion to conduct the micromilling process experiments and contrastive analyses. It shows that the processes have obvious effects on surface roughness. When the milling method is given, the obtained surface roughness value of plunge cut from outside is smaller than that of plunge cut from inside. Therefore, under the condition of the structure allows, the best design of the micro groove is the open structure in order to facilitate better micromilling surface quality. When the way of plunge cut is given, down milling can obtain a better surface roughness. Therefore, in order to get the better surface quality, when milling a micro groove, the best way is to adopt the micromilling cutter with a diameter the same as the width of the groove.

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