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ORIGINAL ARTICLE

# Using orthogonal experimental method optimizing surface quality of $CO_2$ laser cutting process for PMMA microchannels

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**Abstract** $CO_2$ laser cutting is an advanced processing technology, which can, according to the computer-aided design graphics, cut a variety of shapes in the surfaces of many polymer sheets. This work aims to analyze the effect of laser power, scanning speed, and processing times on the surface roughness of polymethyl-methacrylate microchannels with $CO_2$ laser LCJG-1290 cutting process. There are several experiments designed by us, and the results were analyzed by orthogonal experimental method. Finally, optimal power, scanning speed, and processing times were obtained, and in the optimal case, the arithmetical mean roughness (Ra) can reach as small as 110 nm.

**Keywords** $CO_2$ laser · Polymer sheet · PMMA sheet · Orthogonal test method · Arithmetical mean roughness

## 1 Introduction

Emergence of advanced intricate shape and unusual size of parts and strict design requirements restrict the conventional machining methods. Among the advanced machining methods, laser beam machining (LBM) is one of the most widely used thermal energy-based non-contact-type advance machining process which can be applied for almost a whole range of materials [1]. The laser technology not only was applied to cut high polymer materials, such as Kevlar-49 [2] and nylon 6 [3], but also was used to sinter 3D hard metal functional parts [4], weld the Al–Mg alloy [5], and drill [6]. Among various types of lasers, CO2 lasers are one of the most established for machining in industries.

In terms of channel fabrication of the Microfluidic Chip, it is a convenient and simple processing method that the $CO_2$ lasers control the appropriate power laser to process a variety of complex channel shapes on the polymethyl-methacrylate (PMMA), an organic polymer material. $CO_2$ lasers dominate this application due to their good-quality beam combined to high-output power [7]. Li et al. described a simple and rapid method for fabrication of droplet microfluidic devices on polystyrene substrate using a $CO_2$ laser system [8]. Romoli et al. presented an innovative technique concerning $CO_2$ laser machining in order to create 3D cavities to be used as molds for the casting of polymer resins, by vaporizing PMMA layer by layer [9]. Davim et al. demonstrated a study to evaluate the effect of the processing parameters (laser power and cutting velocity) under the quality of the cut of PMMA [10]. In the same year, Irawan et al. reported on the rapid fabrication of microstructures in an optical fiber using a $CO_2$ laser system which helps exposing the optical fiber core to the measurand [11]. Madic et al. presented comparative modeling of $CO_2$ laser cutting using multiple regression analysis and artificial neural network [12]. Kurt et al. made use of analysis of variance (ANOVA) and regression analyses to find the optimal levels and to analyze the effect of the process parameters on the dimensional accuracy of engineering plastic materials [13]. The width of kerfs and quality of the cut edges are affected not only by laser process parameters but also the workpiece material thickness. Eltawahni et al. took advantage of $CO_2$ laser for cutting of four thicknesses of PMMA by implementing Box-Behnken design to develop the experiment [14]. Yang et al. utilized the progressive Taguchi neural network model to propose a prediction model of a $CO_2$ laser

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cutting experiment using [15]. Prakash et al. researched the influence of laser cutting times on the channels of the PMMA chip and presented the numerical model [16]. It is important that identification of the dominant factors significantly affect the cut quality. The cutting of polymer composite using $CO_2$ laser could involve in producing penetration energy in the process [17].

Many documents about laser processing only briefly mentioned the roughness of the microchannels, but we systematically and effectively analyzed the effect of laser parameters on the surface roughness of PMMA microchannels with a $CO_2$ laser. Traditional experimental methods usually required long cycle and heavy workload, but the orthogonal experiment method precisely optimized related processing parameters with less experiments and the arithmetical mean roughness (Ra) can reach as small as 110 nm. In this paper, the main contribution to the microfluidic field is that we have analyzed the effect of laser power, scanning speed, and processing times on the surface roughness of PMMA microchannels with $CO_2$ laser LCJG-1290 cutting process and a convenient method has been proposed to fabricate better microchannels. The analysis procedure is as follows: First, the surface roughness which was expressed in several ways was selected, and among them, average roughness is commonly used and often quoted as Ra symbol. Second, according to the laser parameters, a $L_9(3^3)$ orthogonal test table was performed. Then, the instrument data were aggregated and the optimal conditions were obtained. Finally, the surface quality of the channel under optimal conditions was verified.

## 2 Materials and methods

### 2.1 Material details

The modeling material is one of the most widely used organic polymer materials named PMMA, whose chemical formula is (C5H8O2)n. The grade and the method of manufacture determine the properties of PMMA. The PMMA sheets were processed by Xintao PMMA company in Shenzhen whose raw materials are imported from Japan's MITSUBISHI chemical company. According to related experiments, the continuous use temperature of the PMMA sheet is 80 °C and remains in the solid glassy state until it reaches the transition temperature of about 100 °C and then it becomes moldable. When the temperature reaches 140 °C above, the plate can be shaped into any shape. The PMMA sheet has a good transmittance, about 91.8 %, which makes it very convenient to be processed by $CO_2$ laser.

### 2.2 $CO_2$ laser system and channel production process

In this study, a $CO_2$ laser (LCJG-1290, Nanjing Latron laser Technology Co., Ltd. Jiangsu Province) was used. The precision control of laser processing needs to be realized by the control system and all the processing is carried out under the control of numerical control instruction. General laser processing system is equipped with a programming system (NC system) which is an important part of laser processing and directly affects the processing quality and production efficiency. Automatic programming combining computer and CAD technology to complete NC programming was conveniently used in the laser. Firstly, software CAXA 2011 was used to draw the graphics that you want to process and then the graphics file was input into the computer and displayed on the screen. Finally, by the CAM system of the laser, the process of the trajectory data extraction, trajectory planning, simulation, and interference check were completed automatically until the processing program is generated.

Figure 1 shows the schematic of the laser microchanneling process on PMMA. According to the sheet thickness (about 1.35 mm), the operating power should be 0.6 to 20 W, the scanning speed should be 1 to 50 mm/s, and the operating voltage should be 220 V with the error being 10 V. Control panel of the laser includes the power control device, scanning speed button, total power indicator, emergency stop button, and servo power button. The operation panel is clearly understood to be easy to operate.

### 2.3 Evaluation parameters

In order to study the effect of cutting parameters (laser power, scanning speed, and processing times) on surface roughness, a contact-type precision surface roughness meter (JB-4C, Shanghai Taiming Optical Instrument Co., Ltd. Shanghai) is used to detect the surface roughness in this work. The surface roughness is expressed in several ways. Among them, average roughness is commonly used and often quoted as Ra symbol. Ra is defined as the arithmetic average value of the absolute value ($Z(x)$) on the vertical axis of all profiles in the range of

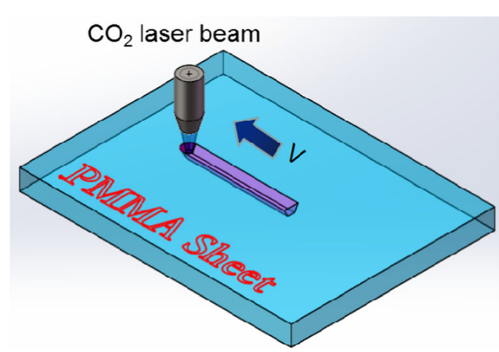


**Fig. 1** Schematic of laser microchanneling process on PMMA

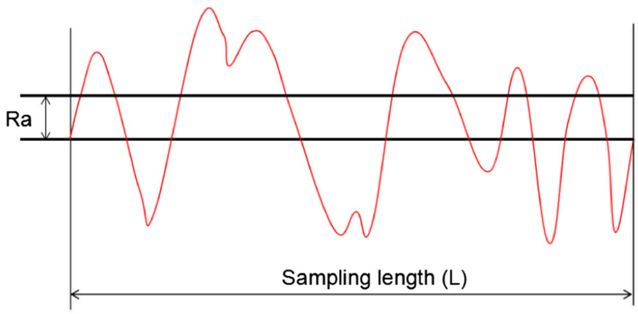


**Fig. 2** Schematic of laser microchanneling process on PMMA

the sampling length after the filter removes the shape error and the larger ripple content as shown in Fig. 2. It can be expressed as Eq. (1).

$$\mathrm{Ra} = \frac{1}{L}\int_{0}^{L} |Z(x)| d(x) \tag{1}$$

where Ra is the arithmetic average presenting surface roughness, $Z(x)$ is the ordinate of the profile curve, and $L$ is the sampling length.

## 3 Results and discussion

### 3.1 Effect of laser power, laser scanning speed, and processing times on processing stability

Several groups of experiments have been done to study the effect of various factors on the parameter Ra clearly. Figure 3 shows the orthogonal experiment schematic in 3D drawn by Solidworks 2012. In order to ensure the accuracy of measurements, all tests were repeated at least three times. The next section described orthogonal experiment in detail.

According to a three-factor and three-level orthogonal table, nine groups of experiments were designed. Three cases of 3, 4, and 5 referring to Table 2 were selected from the nine experiments, and then three channels were detected by the probe of the surface roughness meter to output to the computer's screen. Results of the software

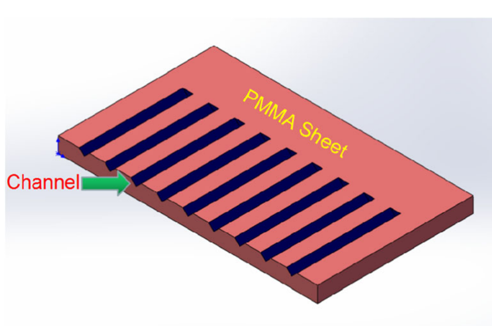


**Fig. 3** Schematic of orthogonal experiment

**Table 1** Levels and factors in the orthogonal experiments

| Level | *A* (laser power) (w) | *B* (laser scanning speed) (mm/s) | *C* (processing times) |
|---|---|---|---|
| 1 | 6 | 5 | 1 |
| 2 | 9 | 10 | 2 |
| 3 | 12 | 15 | 3 |

analysis were showed in Fig. 4. Random testing sites are necessary, so that it can more accurately explain the whole change trend of the surface roughness.

Figure 4 shows analysis diagrams of three cases which were drawn by the software of the surface roughness meter. In each case, three testing sites were detected randomly and their median was chosen to present in Fig. 4. The median is typical and reasonable according to numerical theory.

### 3.2 Orthogonal experiment

From only a few experiments, a Taguchi method [18] with high precision can be designed to study the laser power, laser scanning speed, and processing times on the property of the processing surface. The laser power, laser scanning speed, and processing times were selected as the main factors. Orthogonal levels and factors are listed in Table 1.

In order to show the results more clearly, a diagram (Table 2) is drawn based on the results listed in Table 1. As shown in Table 2, the laser power 9 w, laser scanning speed 10 mm/s, and processing three

**Table 2** The results of orthogonal experiment

| Experiment no. | *A* | *B* | *C* | Roughness Ra |
|---|---|---|---|---|
| 1 | 1 | 1 | 1 | 0.343 |
| 2 | 1 | 2 | 2 | 0.353 |
| 3 | 1 | 3 | 3 | 0.445 |
| 4 | 2 | 1 | 2 | 0.298 |
| 5 | 2 | 2 | 3 | 0.164 |
| 6 | 2 | 3 | 1 | 0.307 |
| 7 | 3 | 1 | 3 | 0.418 |
| 8 | 3 | 2 | 1 | 0.436 |
| 9 | 3 | 3 | 2 | 0.235 |
| T1 | 0.38 | 0.353 | 0.247 | |
| T2 | 0.256 | 0.318 | 0.359 | |
| T3 | 0.363 | 0.329 | 0.393 | |
| *R* | 0.124 | 0.035 | 0.146 | |

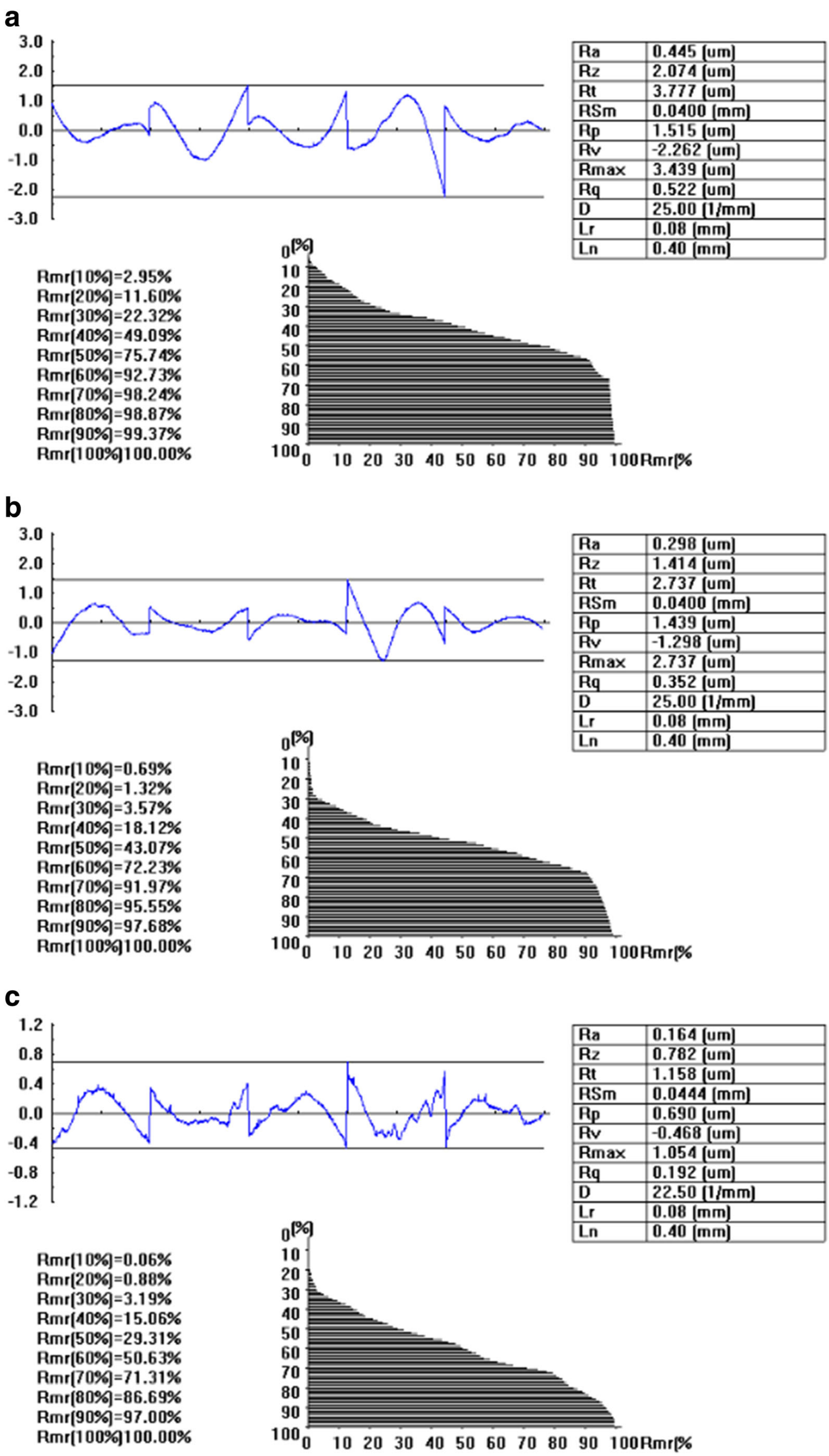


**Fig. 4** Analysis diagrams of three cases of 3, 4, and 5: **a** case 3, **b** case 4, **c** case 5

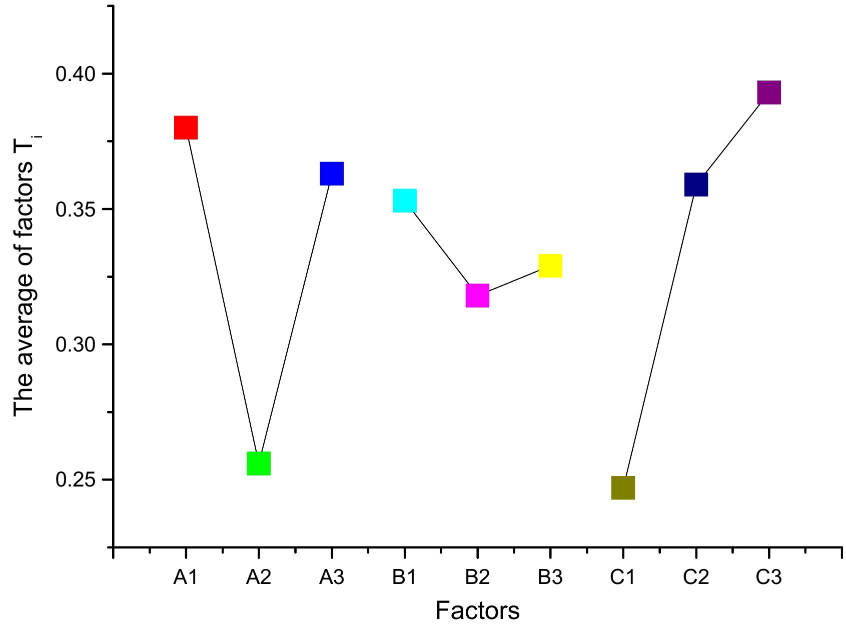


**Fig. 5** The plot of the surface roughness of microchannels in nine cases

times can be set to obtain the best surface roughness in nine cases.

T1, T2, and T3, respectively, indicate the average of factors in each level. For example, T1 with 6 w laser power is computed as follows:

$$T1(6\text{w laser power}) = (0.343 + 0.353 + 0.445)\big/3 = 0.38 \qquad (2)$$

$R$ represents range, which can estimate the sensitivity of the various factors. The range ($R$) was calculated by Eq. (3).

$$R = |\text{Tmax-Tmin}| \qquad (3)$$

According to the information listed in Table 2, the results were drawn on a diagram. As shown in Fig. 5, the degree of sensitivity can be ranked as processing times > laser power > laser scanning speed.

Figure 5 shows the Ra under in various cases after analysis of orthogonal experiments. The steeper the line is, the greater the influence of the factor on surface property of microchannels is. The processing time is the most sensitive factor for processing improvement. The adaptive operation mode from Fig. 5 is A2B2C1. That is, the laser with power 9 w, scanning speed 10 mm/s, and processing one time can cut a smoother microchannel.

### 3.3 Channels display under optimum operating conditions

Through the above analysis, the optimal channel was manufactured with the laser power 9 w, scanning speed 10 mm/s, and cutting one time. Figure 6a, b, which was shot by Zeiss Axiovert 200 metallographic microscope with a magnification of ×100, shows the different surface properties of the microchannels in the optimal case and case 5 of the orthogonal experiments. It is very apparent that the surfaces of three random positions of the optimal channel were smoother and more inerratic, whose median of surface roughness Ra even reaches 0.11 μm. As seen from Fig. 6b, ruleless pores and pits generated and Ra reached 0.164 μm. Through the above analysis, orthogonal test method proved to be an effective and convenient way to deal with optimization problems.

## 4 Conclusions

A simple method for optimizing manufacturing parameters of $CO_2$ laser cutting PMMA microchannels has been presented. By estimating the arithmetic average value Ra, a numerical parameter representing the surface roughness, effect of three main parameters containing laser power, laser scanning speed, and processing times on the surface property of PMMA microchannels with CO2 laser cutting is researched. In order to optimize the parameters clearly, the orthogonal experiment is implemented. The optimal outputs with the laser power 9 w, laser scanning speed 10 mm/s, and cutting one time has been obtained. When $CO_2$ laser was used to cut PMMA sheets, the degree of sensitivity of three parameters should be considered, which can be ranked as processing times > laser power > laser scanning speed. At last, through the orthogonal test method, a good surface of the PMMA microchannel is processed by the $CO_2$ laser cutting with the optimal parameters, whose surface roughness (Ra) even reaches 0.11 μm. The presented method facilitates flexible use of $CO_2$ laser for fabricating quickly and efficiently PMMA microchannels.

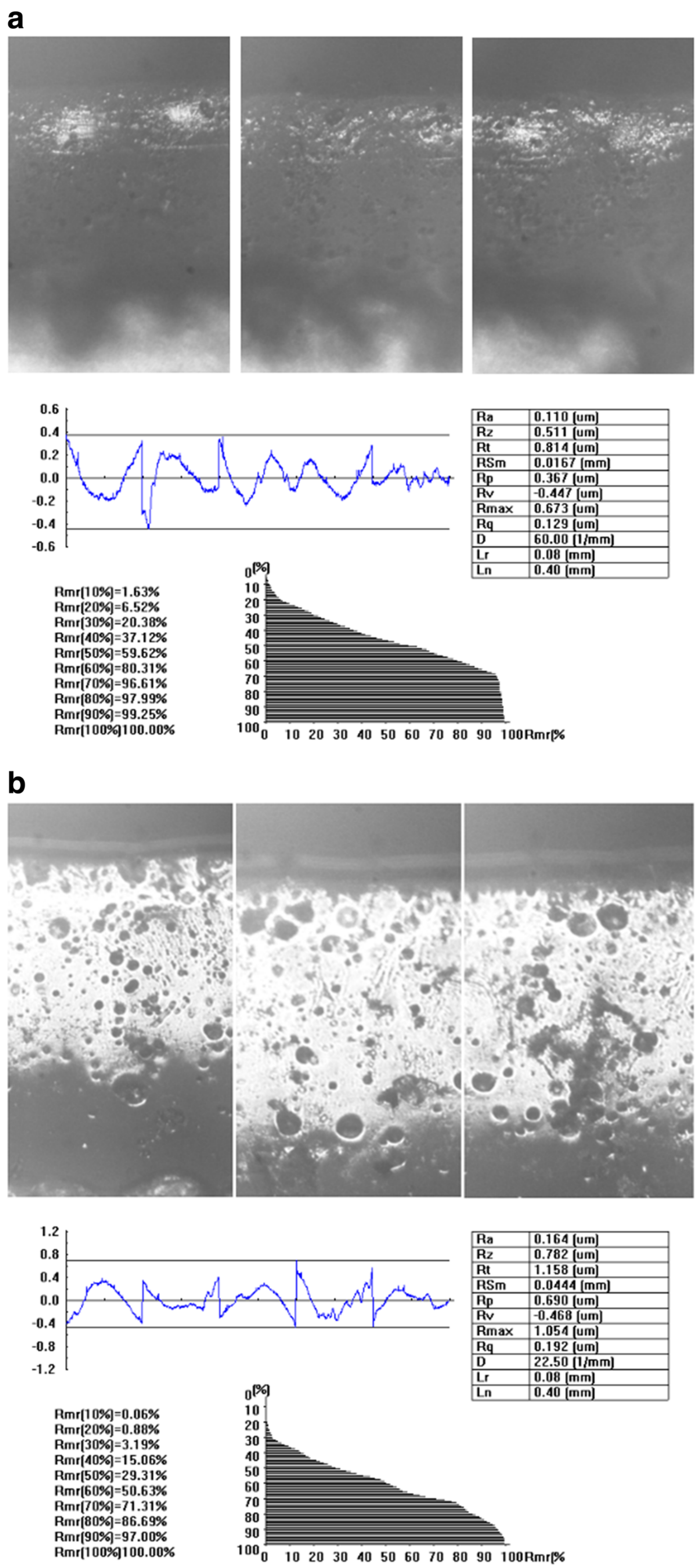


**Fig. 6** Comparison of the optimal case and case 5: **a** optimal case, **b** case 5 of the orthogonal experiments

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