Influence of electrochemical discharge machining parameters on machining quality of microstructure

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Abstract
As a nontraditional processing technology, electrochemical discharge machining (ECDM) can process glass and engineering ceramics precisely. This technology has proven to be a potential process for glass 3D microstructure. However, the key to expanding the application of ECDM is how to improve machining accuracy. This research conducted micro-hole and microgroove machining. Power voltage and frequency influence on hole processing efficiency, hole entrance diameter, and hole limit depth was explored. We considered four factors affecting ECDM—the voltage and frequency of the pulse power supply, the tool electrode feed rate, and the rotation speed. We studied their influence on the roughness of the microgrooves. The results show that machining efficiency, entrance diameter, and limit depth of micro-holes increased with the increase in voltage but decreased with the increase in power frequency. The results show that the roughness of microgrooves has an apparent positive correlation with the power voltage. In contrast, it had an evident negative correlation with the power frequency and electrode speed. The bottom surface roughness of microgrooves can be as minor as 0.605 μm. Various complex 3D microstructures on the glass surface by layer-by-layer method proved the great potential of ECDM.

Keywords Electrochemical discharge machining · Glass · Micro-hole · Microgroove · 3D microstructure

1 Introduction
Insulating and hard-brittle materials such as glass are widely used in micro-electro-mechanical systems (MEMS) because of their excellent chemical and physical properties. However, the hardness and brittleness of glass dampen its micro-fabrication. To achieve better processing quality and efficiency, scholars from various countries have developed many processing methods in recent years, including laser processing [1], chemical etching [2], ultrasonic processing [3], and so on. Laser processing can micro-process hard and brittle materials with high efficiency. However, the equipment is expensive, and the high-energy density easily forms micro-cracks on the workpiece surface. Chemical etching techniques (such as HF etching) can provide excellent processing accuracy and fine clarity. However, complex processing, low etching rate, and high environmental requirements limit its popularity. Ultrasonic processing is also suitable for processing hard and brittle materials, with a high material removal rate (MRR) and good surface integrity. However, due to the high-frequency action of mechanical force, it is easy to cause micro-cracks, and the processing tools wear quickly. ECDM needs more straightforward equipment and lower costs compared with the nontraditional processes, and the machining process is more flexible [4–7]. These advantages make ECDM have great potential in processing nonconductive and hard-brittle materials.

ECDM has been studied for decades [8–12]. In ECDM, a tool electrode and an auxiliary electrode are both immersed in the electrolyte, and the surface of the auxiliary electrode is much larger than that of the tool electrode. Connect the power source between the tool electrode (cathode) and the auxiliary electrode (anode), and bubbles will produce on the surface of the tool electrode. As the reaction continues, the density of the bubbles increases and coalesces into a gas layer that separates the electrode from the electrolyte. The formation of gas film takes place by coalescence of hydrogen bubbles formed due to electrochemical reaction and vapor bubbles formed due to evaporation of electrolyte. The electrochemical reaction on the cathode leads to hydrogen gas generation and the electrochemical reaction on anode electrode leads to oxygen gas generation. When the gas
layer electric field is high enough, it occurs electrical breakdown and produces much energy. The energy produces high temperature and high pressure, which melts and throws out the material [13, 14]. At the same time, the heat also promotes the chemical corrosion of the alkaline solution on the glass workpiece, and the two works together to achieve the material removal [15, 16].

Kurafuji and Suda first proposed ECDM and used it to drill holes in glass [8], and scholars have gradually begun to study the machining of microgrooves. Later, researchers applied ECDM in other materials and micro-manufacturing. Paul and Korah [17] proved the material removal model and temperature model of ECDM. They found that the MRR and temperature range of pulse direct current (DC) power supply are better than DC power supply. Jui et al. [18] studied the effect of tool electrode rotation. They found that proper rotation speed significantly improved the roundness of holes but had no significant effect on the critical voltage and critical current. At the same time, the influence of NaOH concentration on the diameter of entrance and exit of holes was explored and found that both are proportional to the concentration. Abou Ziki et al. [19] studied the influence of electrolyte concentration, tool-surface gaps, and power supply voltage on the surface texture of microgrooves. They obtained different surface textures of microgrooves by controlling the above parameters.

However, with the development of modern technology, it is necessary to process two-dimensional or even complex 3D structures on the glass to meet application needs, which have high requirements for processing accuracy and surface roughness—for example, microfluidic systems and microreactors made of glass. However, there are few studies on selecting proper parameters to machine complex 3D microstructures by exploring the effects of different experimental parameters of ECDM on the processing effects of micro-holes and microgrooves. Compared with the existing research, this article took into account the changes of the gas layer in different processing processes and used other processing methods to explore different focuses. When processing micro-holes, using gravity feed processing, the gas layer is restricted by the hole wall, and the side of the gas layer is subjected to the pressure of the hole wall. The MRR and limit depth are studied, and the influence of the overcut at the entrance is also explored. Uniform feed is used when machining microgrooves because the side cutting is used, the force of the gas layer is different from that of hole machining. At this time, the side of the gas layer is mainly subjected to pressure in the forward direction, and the bottom of the gas layer receives the pressure from the bottom of the microgroove. The bottom surface roughness of the microgrooves was studied. Layer-by-layer processing is used when processing three-dimensional structures. When performing three-dimensional machining, at the first entry point of each layer, the air layer's force is the same as that of the hole. The force of the subsequent air layer is as same as that of the groove—finally, combining the test results of micro-holes and microgrooves, selecting appropriate processing parameters to conduct a 3D processing experiment, and obtaining high-speed and high-quality processing results.

Compared with the existing research [20, 21], this article has better economic benefits for effective processing at a lower voltage (17-25 V). In this paper, the tool electrode used the electrode with thread on the surface, which is more conducive to the electrolyte circulation in the processing area.

1.1 Experimental design

1.1.1 Experimental setup

We designed and made an ECDM experiment device, as shown in Fig. 1. The experiment equipment mainly included (a) the electrochemical discharge system, (b) the detection system, and (c) the electrode movement system. The electrochemical discharge system mainly included a pulse DC power supply (GKPT series, Shenzhen Shicheng Electronic Technology Co., Ltd.), an auxiliary electrode (made of graphite block, size 80×20×15 mm³), a tool electrode (made of tungsten carbide, R=0.1 mm)

![Fig. 1 Schematic diagram of the experimental apparatus](Image)
and a solution tank (made of acrylic plate, size 160×120×80 mm³). The detection system mainly included an oscilloscope (1 GHz bandwidth, 5GS/s sampling rate) and a current probe (CP8030B, Shenzhen Zhiyong Electronics Co., Ltd.). The current probe collected the current signal in the circuit and displayed and recorded the waveform of the current signal on the oscilloscope. The electrode movement system mainly included an X–Y–Z three-axis motion processing platform, a rotating spindle, a computer, and a motion controller. The processing platform realized X–Y–Z three-axis movement and rotation through a computer-controlled motion controller. The motion platform driver used 128 subdivisions. The step angle of the stepping motor was 1.8°, and the lead of the X–Y–Z three-axis ball screw was 5 mm. So, the motion resolution of the three-axis CNC platform was 0.195 μm. That is, under a single pulse, the distance moved by any axis is only 0.195 μm, which can fully meet the needs of low-speed feed in the experiment.

The solution tank was fixed on the processing platform, and the workpiece was a square piece of soda-lime glass with a size of 30×30×2 mm³, which was fixed at the bottom of the solution tank by a bracket. The processing parameters are shown in Table 1.

| Parameters     | Values                                    |
|----------------|-------------------------------------------|
| Solution       | 20 wt.% NaOH                              |
| Workpiece      | Soda-lime glass (size 30×30×2 mm³)        |
| Tool electrode | Tungsten carbide (WC, R = 0.1 mm)         |
| Auxiliary electrode | Graphite block (size 80×20×15 mm³)   |
| Pulse duty cycle | 50%                                      |
| Tool immersion | 2 mm                                      |

### 1.1.2 Machining procedures

In this study, we systematically carried out experiments on machining micro-holes, microgrooves, and 3D microstructures. In the micro-hole experiment, we used a workpiece gravity feed system (Fig. 2) for processing micro-holes, which was composed of a digital dial indicator (Ace Instrument Co., Ltd.) and a pulley slider. The digital dial indicator was for the detection of the processing depth of micro-holes during the experiment. The workpiece was clamped on the slide carriage, and the balancing weight pulled the slide carriage to move upward along the sliding rail. So, the workpiece and the tool electrode always keep in contact. The balancing weight was adjusted to keep a contact force of about 10 g between the tool electrode and the workpiece. The head of the digital display dial indicator kept in contact with the balancing weight. During the micro-hole machining, the height of the balancing weight drops (that is, the machining depth of the workpiece) can display by the digital display dial indicator. Record the processing depth every 10 s (S) during the processing, and set the total processing time to 60 S. The difference of the processing depth recorded in two adjacent times divided by the period (10 s) is the MRR of this period. The tool electrode rotation speed was 1000 rpm.

During the electrochemical discharge micro-hole machining process, the average power consumed by the machining area $P_0$ is [22]:

![Fig. 2 Schematic diagram of gravity feed system of ECDM micro-hole drilling](image)

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\[ P_0 = (U - U_d)\bar{I} - R\bar{I}^2 \]  

(1)

In the formula, \( U \) is the output voltage of the power supply, \( U_d \) is the electrolyte decomposition voltage, \( \bar{I} \) is the average current, and \( R \) equals the resistance between the two electrodes in the electrolyte.

Spark discharge occurred both at the bottom of the electrode and the sidewall of the electrode. Nevertheless, only the spark discharge produced at the bottom of the electrode increases the depth of the micro-hole, while the spark discharge produced on the sidewall does not help the depth of the micro-hole. It increased the diameter of the micro-hole. During the processing, the power acting on the bottom of the micro-hole is:

\[ P_b = \frac{\xi - ft_1}{f} \left( (U - U_d)\bar{I} - R\bar{I}^2 \right) \frac{A_b}{A_i} \]  

(2)

where \( \xi \) is the duty cycle of the output power supply, \( f \) is the power output frequency, \( t_1 \) is the formation time of the gas layer, \( A_b \) is the area of the bottom of the electrode, and \( A_i \) is the total area of the electrode immersed in the solution.

It can conclude from Eq. 2 that when the power frequency \( f \) is lower or the pulse voltage \( U \) is higher, the processing power at the bottom of the electrode will become more prominent, and the heat released each unit time will be more, so the processing speed and processing depth will increase.

When the depth of the processed micro-hole is small, the electrochemical discharge micro-hole processing speed is [23]:

\[ v_k = \frac{2a}{b\sqrt{\pi}} \frac{1 - e^{-1/\bar{t}_0(k)}}{\sqrt{\bar{u}_0(k)}} \]  

(3)

where \( \bar{t}_0 = t_0 / \tau \), \( \tau = \beta/2a \) is the thermal conductivity of the workpiece material, \( b \) is the radius of the heat source, \( t_0 \) is the initial temperature at the beginning of processing, \( k \) is the ratio between the heat source power \( P_0 \) and the minimum power required to remove material \( P_{\text{min}} \).

Therefore, in the electrochemical discharge micro-hole machining process, the processing depth is:

\[ z_k = \int_0^{t_0} \frac{2a}{t_1 b\sqrt{\pi}} \frac{1 - e^{-1/\bar{t}_0(k)}}{\sqrt{\bar{u}_0(k)}} \]  

(4)

The above processing speed \( v_k \) and processing depth \( z_k \) are only applicable when the hole processing depth is shallow.

As micro-holes become deeper and deeper, circulating electrolytes in the hole becomes difficult [24–26]. Also, the bubbles produced by the electrolysis reaction will accumulate at the hole entrance, further hindering circulating electrolytes in the hole. It is difficult to form an effective spark discharge at the bottom of the electrode, resulting in a gradual decrease in MRR. Finally, when the electrolyte at the bottom of the hole is consumed, the processing cannot continue, and the depth of the micro-hole reaches a limit value. At the same time, the numerous store of bubbles at the entrance also makes the spark discharge in this area more intensive, which increase the diameter of the entrance and produce cracks on the surface.

According to the formula, voltage and frequency are the main influencing factors. So, we experimented with these parameters. Table 2 shows the variation of processing parameters in the micro-hole experiment.

When processing microgrooves and 3D microstructures, it is not suitable for the processing method of gravity feed, so we used a constant feed. When the microgrooves become deeper, it is difficult for the electrolyte to enter the bottom of the processing area, making processing challenging to continue. Cutting from the side of the workpiece can effectively avoid this situation. This method can make the electrolyte quickly enter the processing area and ensure continuous spark discharge. Furthermore, this method is more conducive to the discharge of machining chips, thereby improving machining accuracy [27]. The machining parameters used in the machining microgroove experiment are shown in Table 3.

Before each experiment, preload the power supply for 2 min ECDM to raise the temperature of the electrolyte, so the following experiment can reach a stable and balanced state [28]. Use the current probe to collect the current signal, and display the waveform of the collected signal through the oscilloscope. Besides, every experiment was repeated 5 times under the same parameter conditions to reduce the experiment error. Then average the experiment results.

After the processing completed, the surface morphology of the micro-holes, the surface morphology of the

| Group | Voltage(V) | Frequency(×100 Hz) | Feed speed(μm/s) | Rotation speed(×100 rpm) |
|-------|------------|-------------------|-----------------|------------------------|
| 1     | 17, 19, 21, 23, 25 | 6                | 7               | 6                      |
| 2     | 21         | 1, 2, 4, 6, 8, 10 | 7               | 6                      |
| 3     | 21         | 3, 5, 7, 9, 11, 13| 3               | 6                      |
| 4     | 21         | 6                 | 7               | 1, 2, 4, 6, 8, 10      |
microgrooves, and the 3D morphology of the processed workpiece observed and photographed by a scanning electron microscope (SEM). Glass does not conduct electricity, it cannot observe directly through an SEM, so a layer of gold or carbon film must spray on the workpiece so that the workpiece material can observe under the SEM. The contour of the bottom surface of microgrooves was measured and calculated using a SURFCOM130A roughness meter.

2 Results and discussion

2.1 The influence of different experimental parameters on micro-holes processing

In the Group 1 micro-hole experiment, fix the power frequency at 600 Hz and set the voltage at 17 V, 19 V, 21 V, 23 V, and 25 V, respectively. Record the processing depth every 10 s (s) during the processing, and set the total processing time to 60 s. Figure 3 shows the relationship between micro-holes MRR and power supply voltage. The MRR is the difference of the processing depth recorded in two adjacent times divided by the period (10 s). That is, the slope $k$ in Fig. 3.

The results show that the MRR increased as the voltage increased. An increase in applied voltage increases the MRR due to the generation of more hydrogen gas bubbles resulting in a tremendous amount of discharge energy at the sparking zone. When the voltage increased, the gas layer formation time significantly shortened with the increase in the applied voltage. As the voltage increased, the number and speed of bubble generation increased, so the gas layer formation time significantly shortened, the power of spark discharge increased, and the MRR increased. Besides, the bubbles produced by the electrolysis reaction increased, the gas layer formed faster and more stable, the frequency of discharge increased, and the MRR also improved.

The results also show that the changing trends of MRR under different voltages were similar: they were all the largest in the initial time, and then the MRR remained basically unchanged after reducing to a particular value. (That is, the slope $k$ of the line in Fig. 3 was basically unchanged after 10 s). As the depth of the micro-hole increased, electrolytes became more difficult to circulate in the hole, which reduced the frequency of discharge at the electrode tip. So, the difference between different MRR under various voltage conditions decreased.

Figure 4 shows the relationship between the hole entrance diameter and the hole limiting depth with the power supply voltage. In ECDM, the specified work material can be machined only up to a certain depth, known as the limiting depth for a particular combination. The potential difference between the tool-electrode and the electrolyte decreases during the process as the tool keeps penetrating inside the work. This potential loss is mainly due to the accumulation of gas bubbles on the tool-electrode that restricts the electrolyte flow.

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Fig. 3 Effect of power voltage on micro-hole MRR
to the tip of the tool-electrode, which results in a reduction of discharge activity and lowering chemical etching. The results show that as the voltage increased, the hole entrance diameter had a significant increase.

On the one hand, during the ECDM, discharge also occurred on the side of the electrode, which could increase the diameter of micro-holes. Moreover, we noted plenty of bubbles at the entrance of the hole, which also caused the discharge in this area to be denser and increased the diameter of the entrance. On the other hand, during the machining process, as the power supply voltage increased, the power of the discharge increased, which increased the heat removal of the material. During processing, discharge occurred at holes’ entrances.

Figure 5 shows the variation of machining current with voltage. The AB section is the gas layer formation time ($T_{AB}$). $T_{AB}$ gradually decreased, indicating that the gas layer generation time becomes shorter. The BC section is the pulse discharge time ($T_{BC}$). The AC section is the pulse duty cycle ($T_{AC}$), fixed in this experiment (50%). $T_{AC} = T_{AB} + T_{BC}$. $T_{AB}$ is shortened with the increase of voltage, while $T_{AC}$ remains unchanged, so the effective discharge time in a single pulse is prolonged with the rise of voltage, so the effective discharge time becomes longer. The higher the voltage, the longer the duration of discharge machining in a single pulse period, so more material is removed at the holes’ entrance. The increase in the diameter of holes facilitates the circulation of the electrolyte in holes, thereby promoting the growth in the limit depth of the processed holes, as shown in Fig. 4.

As shown in Fig. 5, $A_{max}$ is the maximum current monitored during the machining process. As the voltage increased, $A_{max}$ gradually increased, indicating that the discharge energy becomes larger. When the voltage is 21 V and 23 V, the BC segment pulse discharge process is more uniform, corresponding to a better quality machined surface. When the voltage is increased to 25 V, the BC segment pulse discharge process is not stable, which corresponds to the processing surface with poor quality. It shows that a stable gas layer is beneficial to improve the quality of surface processing.

Figure 6 shows the micro-holes entrance morphology when the power supply voltage was 21 V, 23 V, and 25 V, respectively. When the voltage is 21 V, the morphology and roundness of the hole are better. The higher the voltage, the more obvious defects such as micro-cracks and pits at holes entrance. The spark discharge process is generated in the form of pulses. During discharge, the material near the spark heated and expanded. When the pulse finished, this part of the material contacted the lower temperature electrolyte and cooled and shrank. At the entrance of the hole, the electrolyte is enough, and the frequency of spark discharge is high so that the material at the hole’s entrance continuously expands and shrinks. Under the effect of continuous thermal expansion and contraction, winkle-like defects would occur on the processed surface. When the voltage becomes higher, the energy produced by the spark discharge will increase. At the same time, for high voltage, some cracks will be produced in the machining zone due to excessive heat generation. With a further increase in applied voltage, these cracks may propagate and lead to the total rapture of the workpiece. Eventually, the entire piece of material will fall off, forming pits and other defects.

Fig. 4 The effect of power voltage on hole entrance diameter and limited depth
In the Group 2 micro-hole experiment, fix the power voltage at 21 V and set the frequency at 200 Hz, 400 Hz, 600 Hz, 800 Hz, 1000 Hz, and 2000 Hz, respectively. Record the processing depth every 10 S during the processing, and set the total processing time to 60 S. Figure 7 shows the relationship between micro-holes MRR and power frequency. Figure 7 shows similar features to Fig. 3. In the early processing stage, the change of power frequency had a more

Fig. 5 The variation of machining current with voltage. (a) 19 V, (b) 21 V, (c) 23 V, (d) 25 V

Fig. 6 Micro-hole entrance morphology processed at the power voltage of (a) 21 V, (b) 23 V, and (c) 25 V
significant impact on MRR, and low-frequency processing had high MRR. When the power frequency is reduced, the total time of gas layer formation becomes shorter, and the stable spark discharge time is longer. Therefore, the MRR was higher. As the processing time increased, the MRR at different frequencies was similar. The initial MRR was higher, and the machining depth was deeper in a short time. However, as the depth increases, circulating the electrolyte in the hole becomes difficult, which increases the difficulty of spark discharge at the electrode end, so the MRR also decreases.

Figure 8 shows the relationship between hole entrance diameter and hole limiting depth with power frequency. The
results show that the higher the power frequency, the smaller the entrance diameter. When the power frequency is high, the spark discharge position will be minor. A single pulse period includes gas layer formation time and discharge time. As the frequency of the power supply increases, the number of pulses per unit time increases; that is, the number of discharges increases, and more gas layer formation time is required. Therefore, the smaller the proportion of the system for spark discharge at the same time. Thus, the less material removed by heating, the smaller the hole size. The results also show that the limiting depth decreased with the increase of frequency. With the rise of power frequency, the diameter of micro-holes decreased. The smaller the diameter, the more unfavorable the electrolyte circulation in the hole, thus limiting the expansion of the limiting depth of the hole.

The change of the power frequency also has a significant influence on the morphology of micro-holes entrance. Figure 9 shows the micro-hole entrance morphology machined using 200 Hz, 400 Hz, 600 Hz, and 800 Hz power frequency. The figure shows that when the frequency is 600 Hz, the morphology and roundness of the hole are better. When the frequency is lower than 600 Hz, the action time of every single spark is longer. So, the heat accumulation effect is noticeable, which could cause the material around the hole to melt and remove in lumps, as shown in Fig. 9a–b. When the frequency is more significant than 600 Hz, the rapid thermal expansion and contraction result in a dense line (wrinkle-like defects) around the hole entrance, as shown in Fig. 9d.

According to the micro-hole experiment, the parameters selected as the power supply voltage 21 V and the frequency 600 Hz for processing. Figure 10 shows the micro-holes processed in this parameter optimization. The figure shows no obvious defects such as cracks at the entrance, the processing repeatability is good, and holes have good roundness, so the selected parameters are reasonable.

This section carried out the experiment of an electrochemical discharge micro-hole processing. This study analyzed the influence of voltage and frequency on micro-hole

![Figure 9](image-url)  
*Fig. 9  Micro-hole entrance morphology is processed at the power frequency of (a) 200 Hz, (b) 400 Hz, (c) 600 Hz, and (d) 800 Hz*
machining. We selected reasonable processing power parameters (voltage 21 V, frequency 600 Hz) through experimental comparison, which can achieve higher MRR and deeper holes. This experiment got smaller holes’ entrance diameter and better surface quality.

3 The influence of different experimental parameters on the roughness of microgrooves

This section mainly discussed the influence of four factors of power supply voltage, power supply frequency, tool electrode feed rate, and tool electrode rotation speed on the surface roughness of microgrooves by ECDM. Figure 11 shows the SEM images of microgrooves processed with different parameters. Below the microgrooves are the bottom surface roughness. The sampling length in the test is 500 μm. The sampling location for roughness measurement is the bottom of the microgroove, and the sampling length is 500 μm. The surface roughness values in the figure were 0.742 μm and 0.409 μm, respectively.

Figure 12 shows the relationship of microgroove roughness with power supply voltage, power supply frequency, electrode feed speed, and electrode rotation speed. The roughness value of the microgrooves had an obvious linear with the power supply voltage, power supply frequency, and electrode feed rate but had no clear linear relationship with the electrode rotation speed. The roughness value of

Fig. 10 Micro-holes with good roundness, good surrounding quality, and high repeatability—processed with optimized parameters

Fig. 11 SEM images and roughness measurement of microgrooves
the microgrooves increased with the increase of the voltage. When the power supply voltage increases, the average spark discharge current increases, increasing the spark discharge pulse. The rise in the voltage will also increase the frequency of the spark discharge, so the total heat produced becomes larger. The thermal influence of the machined surface was also more significant, causing the surface quality to decrease and the roughness value to increase.

The roughness value decreased as the electrode feed rate increased. Meager feed rates will increase machining time and tend to increase the HAZ around the machined area. As the feed rate increases, the time required for the electrode to pass through the same point on the surface of the workpiece decreases, so the thermal effect of spark discharge at this point is also reduced, and the roughness was correspondingly reduced. However, too high a feed rate will also cause mechanical contact between the electrode and the workpiece surface. The feed rates faster than the mean material removal rate of the process may lead to failure of either the workpiece or the tool electrode. Therefore, the feed rate should not be too large during processing.

Figure 12d shows that the roughness value varied from 0.605 to 0.719 μm, but it did not change regularly with the electrode speed. Before the rotation speed reached 600 rpm, the rotation speed of the electrode surface of the threaded tool was too low to provide the centripetal force to form a dense air film, so the roughness was not significantly improved. After 600 rpm, the roughness tended to improve as the rotation speed increases. After the speed reached a particular value, sufficient centripetal force was provided, and the air film was relatively stable.
Machining 3D microstructure

For microgrooves with high aspect ratios, scholars usually adopt a layer-by-layer processing method. Because when the depth of the microgrooves processed in a single time is deep, it is easy to cause mechanical contact between the tool electrode and the workpiece, which causes obvious defects such as cracks on the processed surface of the workpiece. More serious will cause the tool electrode to break due to excessive contact force. In this experiment, considering the micro-hole machining and microgroove machining results, considering the machining quality and machining efficiency, we selected the machining parameters as power supply voltage 21 V, pulse frequency 600 Hz, electrode rotation speed 1000 rpm and electrode feed rate of 7 μm/s. Moreover, the 3D microstructure on the glass was processed by layer, with each layer feeding 100 μm. Figure 13 shows the 3D microstructures machined with the optimum parameters, a 3D image of one of them. The results show that the 3D microstructures processed by the optimized parameters were smooth without cracks and wrinkle-like defects.

5 Conclusions

This paper carried out ECDM experiments of micro-holes, microgrooves, and 3D microstructures on glass. Appropriate machining methods were selected to discuss the variation in machining efficiency and quality with different machining parameters. This paper systematically studies the power supply voltage, frequency, electrode rotation speed, and electrode feed rate compared with the existing research. The experiments of micro-hole (one-dimensional), micro-groove (two-dimensional), and three-dimensional machining were gradually carried out. The experimental results of micro-holes and micro-grooves are emphatically evaluated, focusing on the processing efficiency of micro-holes and the degree of over-cutting, and the roughness of micro-grooves is used as a measurement standard, and the optimal parameters are selected for the final three-dimensional processing. The conclusion is as follows:
1. In micro-hole machining, increasing the power supply voltage can increase spark discharge energy, thereby improving machining efficiency and increasing the limit depth of micro-holes. However, it will bring the increase of the entrance diameter and the deterioration of the entrance morphology. Choosing a lower power frequency will correspondingly shorten the time required for gas layer formation and prolong the duration of spark discharge, thereby improving processing efficiency and increasing the limit processing depth of micro-holes. However, the lower frequency also increased the entrance diameter, and the entrance morphology was poor. A power supply voltage of 21 V and a power supply frequency of 600 Hz are comprehensively selected as processing parameters.

2. In microgroove machining, the roughness of the micro-grooves was directly proportional to the power supply voltage, inversely proportional to the power supply frequency and the feed speed of the tool electrode, but had no apparent relationship with the electrode speed. A comprehensive comparison found that the selected voltage and frequency parameters are reasonable. The electrode rotation speed of 1000 rpm and the electrode feed speed of 7 μm/s was selected as the processing parameters.

3. Selecting reasonable processing parameters and adopting a layer-by-layer method can consider processing quality and efficiency in obtaining complex 3D micro-structures.

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Author contribution Zhao Douyan: conceptualization, methodology, writing-original draft preparation. Zhu Hao: data curation. Zhang Zhaoyang: writing-reviewing and editing. Xu Kun: visualization. Gao Jian: supervision. Dai Xueren: validation. Huang Lei: investigation.

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Declarations

Conflict of interest The authors declare no competing interests.

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