Ultrasonic-assisted grinding experiments on quartz glass and investigation of factors influencing surface roughness

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Abstract. In order to study the grinding mechanism of quartz glass, a three-factor four-level orthogonal test under ultrasonic grinding and non-sonic grinding conditions was designed to investigate the laws of spindle speed, feed rate and depth of cut on the surface roughness of quartz glass. The extreme difference analysis and the analysis of influencing factors were carried out for ultrasonic grinding and non-ultrasonic grinding experiments. The experimental results show that the surface roughness of ultrasonic grinding quartz glass decreases with the increase of spindle speed, increases with the increase of feed speed and increases with the increase of depth of cut. The surface roughness of non-sonic grinding quartz glass increases with increasing spindle speed, increases with increasing feed rate, and decreases with increasing depth of cut. This study provides important implications for the study of the grinding mechanism of quartz glass.

1. Introduction
Quartz glass materials with high hardness and good thermal stability are widely used in important fields such as mold, automobile manufacturing, aerospace, national defense science and technology.

Three brittle optical materials (quartz glass, sapphire glass and RS-SiC) were selected by Xinhong Yang and Jecai Han [1] for grinding tests under ultrasonic and non-sonic conditions to investigate the effect of changes in cutting parameters on surface roughness and to compare the similarities and differences of the three materials. Zhongwei Hu and Mingjian Shao [2] conducted axial ultrasonic vibration-assisted grinding tests on four different crystal faces of sapphire glass, respectively. Tawakoli [3] et al. developed and studied the application of axial ultrasonic vibration technology and applied it to 42CrMo4 dry grinding. Ali Zahedi [4] et al. carried out an experimental study on ultrasonic-assisted internal grinding of Al₂O₃-ZrO₂ ceramic materials and carried out a study to analyze the effect of machining energy and surface quality.

In this paper, ordinary grinding and ultrasonic-assisted grinding were performed on quartz glass using an ultrasonic-assisted grinding processing device and an orthogonal test method, and the effects of the two grinding methods on the surface roughness of quartz glass were compared to investigate the test parameters for obtaining the optimal surface roughness.

2. Materials and methods
The material of this experiment is quartz glass, and the basic performance parameters of its material are shown in Table 1 below. The force gauge model number is 9527B and the machine model number is MLA150691. Ultrasonic generator model UBT40-33B, ultrasonic device consists of ultrasonic
The ultrasonic frequency is 31620 Hz.

The experimental processing method is shown in Figure 1.

**Table 1** The main properties of quartz glass

| Property                | Value  |
|-------------------------|--------|
| Density \( \text{g/cm}^3 \) | 2.2    |
| Tensile strength \( \text{MPa} \) | 1100   |
| Poisson's ratio         | 0.14-0.17 |
| Fracture toughness \( \text{MPa} \cdot \text{m}^{0.5} \) | 0.81 |
| Elastic Modulus \( \text{GPa} \) | 77     |

**Figure 1** Schematic diagram of processing

The orthogonal test is a multi-factor optimization experimental design method that selects a representative portion of sample data points from an experiment. This time, a three-factor, four-level orthogonal test was used, and the three experimental factors involved were: spindle speed, feed rate, and depth of cut \[^5\]. The specific parameters are designed as shown in Table 2 (where \( A \) is the spindle speed, \( B \) is the feed rate and \( C \) is the depth of cut).

**Table 2** Orthogonal test parameter table

| Level | Factor A(r/min) | Factor B(mm/min) | Factor C(mm) |
|-------|-----------------|------------------|--------------|
| 1     | 2500            | 10               | 0.1          |
| 2     | 3000            | 20               | 0.15         |
| 3     | 3500            | 30               | 0.2          |
| 4     | 4000            | 40               | 0.25         |

3. Results and discussion

3.1. Experimental result

A three-factor, four-level orthogonal test was conducted on quartz glass according to the cutting parameters shown in Table 2, and the surface roughness of ultrasonically and non-sonically ground quartz glass was examined with a contact roughness tester, respectively, with a sampling frequency of 20,000 Hz in this paper, and the more stable surface roughness in processing was selected as the experimental analysis data after several measurements \[^6\]. Specific experimental data are shown in Tables 3 and 4 below.
3.2. Results and discussion.

### Table 3  Surface roughness table of ultrasonic-assisted grinding quartz glass

| Level | Spindle speed (r/min) | Feed speed (mm/min) | Cutting depth (mm) | \( R_a \) |
|-------|-----------------------|---------------------|--------------------|---------|
| 1     | 2500                  | 10                  | 0.10               | 0.57    |
| 2     | 2500                  | 20                  | 0.15               | 0.85    |
| 3     | 2500                  | 30                  | 0.20               | 1.87    |
| 4     | 2500                  | 40                  | 0.25               | 1.19    |
| 5     | 3000                  | 10                  | 0.15               | 0.42    |
| 6     | 3000                  | 20                  | 0.10               | 0.84    |
| 7     | 3000                  | 30                  | 0.25               | 1.68    |
| 8     | 3000                  | 40                  | 0.20               | 1.60    |
| 9     | 3500                  | 10                  | 0.20               | 3.44    |
| 10    | 3500                  | 20                  | 0.25               | 1.07    |
| 11    | 3500                  | 30                  | 0.10               | 0.87    |
| 12    | 3500                  | 40                  | 0.15               | 0.50    |
| 13    | 4000                  | 10                  | 0.25               | 0.83    |
| 14    | 4000                  | 20                  | 0.20               | 3.21    |
| 15    | 4000                  | 30                  | 0.15               | 1.04    |
| 16    | 4000                  | 40                  | 0.10               | 1.40    |

### Table 4  Surface roughness of non-ultrasonic assisted processing quartz glass

| Level | Spindle speed (r/min) | Feed speed (mm/min) | Cutting depth (mm) | \( R_a \) |
|-------|-----------------------|---------------------|--------------------|---------|
| 1     | 2500                  | 10                  | 0.10               | 0.75    |
| 2     | 2500                  | 20                  | 0.15               | 0.67    |
| 3     | 2500                  | 30                  | 0.20               | 2.23    |
| 4     | 2500                  | 40                  | 0.25               | 1.28    |
| 5     | 3000                  | 10                  | 0.15               | 1.81    |
| 6     | 3000                  | 20                  | 0.10               | 2.84    |
| 7     | 3000                  | 30                  | 0.25               | 2.20    |
| 8     | 3000                  | 40                  | 0.20               | 1.86    |
| 9     | 3500                  | 10                  | 0.20               | 0.69    |
| 10    | 3500                  | 20                  | 0.25               | 0.86    |
| 11    | 3500                  | 30                  | 0.10               | 1.97    |
| 12    | 3500                  | 40                  | 0.15               | 0.95    |
| 13    | 4000                  | 10                  | 0.25               | 3.62    |
| 14    | 4000                  | 20                  | 0.20               | 0.86    |
| 15    | 4000                  | 30                  | 0.15               | 0.65    |
| 16    | 4000                  | 40                  | 0.10               | 3.43    |

The optimal combination of parameters for the experiments on quartz glass under ultrasonic and non-sonic grinding was calculated from the data in Tables 3 and 4, and the data shown in Tables 5 and 6 were obtained from the extreme difference values. The larger the polar difference proves that the factor has a greater degree of influence on the corresponding quartz glass surface roughness, and according to the size of the polar difference, the order of the influencing factors of ultrasonic-assisted grinding of quartz glass surface roughness is determined, and the processing parameters are optimized to improve processing efficiency and reduce processing costs [7].
Table 5  Ultrasonic-assisted grinding of quartz glass surface roughness analysis table

| A (spindle speed(r/min)) | B (feed speed(mm/min)) | C (cutting depth (mm)) |
|-------------------------|------------------------|------------------------|
| \( \bar{k} \)          | \( k \)                | \( \kappa \)           |
| 1.12                    | 1.32                   | 0.92                   |
| 1.14                    | 1.49                   | 1.02                   |
| 1.47                    | 1.37                   | 2.53                   |
| 1.62                    | 1.17                   | 1.19                   |
| Max                     | 1.62                   | 1.49                   |
| Min                     | 1.12                   | 1.17                   |
| Very bad                | 0.5                    | 0.32                   |
| Excellent level         | A1                     | C1                     |
| order                   | C>A>B                  |                        |

Table 6  Non-ultrasonic assisted grinding quartz glass surface roughness analysis table

| A (spindle speed(r/min)) | B (feed speed(mm/min)) | C (cutting depth (mm)) |
|-------------------------|------------------------|------------------------|
| \( \bar{k} \)          | \( k \)                | \( \kappa \)           |
| 1.23                    | 1.72                   | 2.45                   |
| 2.08                    | 1.31                   | 1.02                   |
| 1.12                    | 1.76                   | 1.02                   |
| 2.14                    | 1.88                   | 1.41                   |
| Max                     | 2.14                   | 1.88                   |
| Min                     | 1.12                   | 1.31                   |
| Very bad                | 1.02                   | 0.57                   |
| Excellent level         | A4                     | B4                     |
| order                   | C>A>B                  |                        |

3.3. Analysis of factors affecting surface roughness.
The surface roughness of quartz glass after the experiment was measured by single-factor ultrasonic and non-ultrasonic assisted grinding of quartz glass, and the following line graphs can be obtained as shown in Figures 2, 3 and 4, and the following analysis can be obtained by collating the experimental data.

3.3.1. The influence of spindle speed on surface roughness
As shown in Figure 2, the line graph of the effect of single-factor variable spindle speed on the surface roughness of quartz glass was found that the surface roughness of quartz glass decreased with the increase of spindle speed by analyzing the experimental data. Due to the systematic error in the experiment, there is a significant fluctuation in the surface roughness when the spindle speed reaches 3500r/min under ultrasonic conditions, and the error is large relative to the initial surface roughness, and the overall roughness decreases significantly relative to the initial roughness when the error factor is removed.

3.3.2. The influence of feed speed on surface roughness
Figure 3 shows the line graph of the effect of feed rate on surface roughness. From Figure 3, it can be found that under ultrasonic conditions, the roughness of the ground surface is increasing as the feed rate increases, and there is a significant fluctuation in surface roughness when the feed rate increases to 40 mm/min, but the final roughness value increases relative to the original roughness value. Under non-sonic conditions, the roughness value of the ground surface decreases relatively as the feed rate increases. There is a fluctuation in the roughness value when the feed rate reaches 60 mm/min, but the overall trend is decreasing with respect to the initial roughness value.
3.3.3. Influence of grinding depth on roughness

The graph of the effect of grinding depth on roughness is shown in Fig. 4. Through the experimental data, it is found that in non-sonic grinding, the surface roughness decreases gradually as the cutting depth increases, and the surface roughness fluctuates when the cutting depth reaches 0.25 mm. As the depth of cut increases, the contact area between the tool and the workpiece increases, the cutting force increases, accelerating tool wear and leading to fluctuations in surface roughness. In ultrasonic machining, the surface roughness value is gradually increasing with the increase of cutting depth, and there is a large fluctuation of surface roughness when the cutting depth reaches 0.15 mm. In ultrasonic grinding, the presence of vibration during the grinding process due to the addition of ultrasonic waves causes a tendency for the roughness of the grinding surface to increase, but overall it decreases compared to the initial surface roughness of the material.
4. Conclusion

This article starts with the characteristics of quartz glass materials and studies the removal mechanism of ultrasonic grinding and non-ultrasonic grinding of quartz glass. Experimental research shows that the removal mechanism of quartz glass grinding is mainly divided into plastic removal, brittleness removal, and powder removal. Comparing the experimental data and analyzing the influencing factors of the surface roughness of the quartz glass grinding process according to the range, the research conclusions are as follows:

1. Ultrasonic grinding and non-ultrasonic grinding of quartz glass, the surface roughness of the quartz glass decreases with the increase of the spindle speed, and the surface roughness of the quartz glass increases with the increase of the feed speed.

2. The surface roughness of ultrasonic ground quartz glass increases with the increase of cutting depth, and the surface roughness of non-ultrasonic ground quartz glass decreases with the increase of cutting depth.

3. The processing parameters for ultrasonic grinding of quartz glass to obtain the best surface quality are: spindle speed 2500r/min, feed speed 80mm/min, and cutting depth 0.1mm.

4. The processing parameters for non-ultrasonic grinding of quartz glass to obtain the best surface quality are: spindle speed 4000r/min, feed speed 80mm/min, and cutting depth 0.1mm.

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