Characteristic analysis of rotating ultrasonic machining applied in zirconia grinding

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Abstract. This research uses rotary ultrasonic grinding technology to grind zirconia (ZrO₂) ceramic. The purpose is the optimization of processing parameters for rough and fine grinding. According to Taguchi method, optimized processing parameters will be available to find and successfully verified. The objective function of rough grinding is the material removal rate (MRR), and a maximum is expected. The processing parameters can be spindle speed, ultrasonic power, feedrate, and cutting depth. The best MRR is 1.92mm³/s in Taguchi’s experiment, and the optimized MRR is 2.14mm³/s, which can be increased by 1.11 times. Moreover, the objective function of fine grinding is surface roughness (Ra), which needs to find a minimum value. The control factors are spindle speed, ultrasonic power, feedrate, and the number of times of grinding. In the Taguchi experiment, the minimum roughness predicted by the fine grinding is Ra0.16, but the roughness is obtained Ra0.2 by the verification experiment. It may be that the effects of the factors are not completely independent, and there are interactions between them. The predicted value will not be completely correct via the superposition of each factor effect. It can also be found that the independence of the fine grinding speed, ultrasonic power and feed factor is not strong enough for the variation analysis. It affects the results of the prediction and confirmation experiment.

1. Introduction
Zirconia is a ceramic material with high strength, high hardness, high corrosion resistance, high wear resistance, and high temperature resistance. It is widely utilized in semiconductor, aerospace, and biomedical industries. Zirconia ceramics machining shows its advantage and importance when it comes to geometric complexity, precision, and microminiaturization. In the past, cutting caused massive tool abrasion. The precision of zirconia machining was unsatisfying, and the surface fracture increased the production cost. Therefore, diamond grinding wheel used to be the main device to overcome the difficulty in processing brittle materials, such as ceramics [1-2]. Recently, ultrasonic has been integrated into machine tools [3-4]. It has become a new option and a new trend to grind brittle materials. However, in zirconia ceramics grinding, ultrasonic technology is only used in the final step of fine machining because it can only carry out small amounts of grinding volume and performs low processing efficiency. This research conducts rough grinding on zirconia using diamond mounted points and rotary ultrasonic machining (RUM) technology. The research inspects the best processing parameters for the maximum material removal rate. It is also set to acquire the best surface roughness by fine grinding zirconia.

2. Motive and purpose
In biomedical field, zirconia has recently been used as the materials for artificial joints and porcelain teeth due to its composite crystals and high fracture resistance. Under the circumstance of X-ray
examinations, zirconia, which is non-metal, shows no interfering effects compared to metals. However, zirconia is known as difficult materials in cutting process. Therefore, besides using high strength and high hardness tools, the trend turns to use grinding techniques to deal with zirconia. In 2005, Hsu [5] used diamond wheel grinder to process micro grooves. His research inspected the choices of various wheel grinders and examined the parameters that affected the precision of dimensions and shapes. He concluded that high rotation speed performed better rigidity and slightly narrowed down the breach width of the grooves, which made the wheel grinder more durable. In 2009, Lee [6] accomplished both rough-grinded and fine-grinded aluminum ceramic with high speed by using minor diameter diamond mounted points. He analyzed how different grinding conditions would affect the wear of diamond mounted points, the grinding force, and the surface roughness. In 2013, Wu [7] carried out a research on soda-lime glass and sapphire. He utilized RUM and inspected the parameters that affected the quality of brittle fracture and the stability of micro-hole spacing. The surface roughness and tool durability were also observed in this research. In 2015, Wang [8] utilized diamond mounted points to mill and drill zirconia. He respectively used straight line milling, cycloid milling, and peck drilling as his methods in order to inspect brittle length, surface roughness, maximum material removal rate, and tool durability. This research is designed to use RUM grinding technology and achieve parameter optimization. Under the Taguchi methods setting, rough grinding is conducted by using #80 diamond mounted points. The quality characteristic of rough grinding is larger the better for material removal rate (MRR). The best processing parameters for the maximum MRR are acquired. Fine grinding is conducted by using #800 diamond mounted points. The quality characteristic of fine grinding is smaller the better for surface roughness. The best processing parameters are also inspected and acquired.

3. Experimental principles and methods

3.1. Rotary ultrasonic machining

Ultrasonic machining is a combination of high speed milling and high frequency vibration to remove material. This processing forms a technology that can be combined with grinding and impact fracture. It can include ultrasonic machining (USM) and rotary ultrasonic machining (RUM). Compared with traditional cutting, ultrasonic machining processes less cutting force. This advantage produces less wear on a tool because less chips are stuck on the tool, which extends the tool life and enhances the cutting performance. The accuracy and quality of the workpiece will be also improved when the cutting resistance decreases. Therefore, the ultrasonic machining is suitable for cutting hard and brittle materials [9].

For rotary ultrasonic processing, the ultrasonic power and frequency are controlled and diamond abrasives can be mounted in the tool to process the workpiece. Two types of tool are available. One is the shrink fit tool, the other is PCBN tool. The ultrasonic power is related to the Z-axis amplitude of the tool. Piezoelectric elements inside the tool are driven to generate vibration in the Z direction. The greater the power, the greater the amplitude of the tool on the Z-axis during processing. The travel range is about 2-100 microns, and each manufacturing company has different settings. In RUM, the abrasives on the tool hammer the materials with ultrasonic vibration. The rotation tool also grinds and rips the materials in a high speed manner. Microparticle is therefore produced and is immediately taken away by the coolant. Ultrasonic processing is able to prevent the temperature escalation. This machining method prolongs tool durability and increases surface roughness. Through this approach, brittle materials can be handled well because cracks are able to be diminished.

3.2. Taguchi method

The orthogonal array of Taguchi methods can acquire useful statistical information with fewer experiments. It can be represented in a symbolic format as \( L_a(b^c) \), where \( a \) represents the number of experiments, \( b \) the number of levels, and \( c \) the number of factors. In order to examine the effectiveness of an experiment, a function is usually designed and assigned as a standard to measure the effectiveness. This assigned standard is called signal-to-noise ratio (S/N ratio). The higher S/N ratio is, the less the quality loses. In a set of experiments, if a group has higher S/N ratio, it means that the level of the factors
is more ideal to the set value of the quality expectation. Three categories of S/N ratios depending on the desired performance response are as follows [10]:

1. Nominal the best: quality characteristic is a fixed target value \( m \).
\[
S/N = -10 \log \left( \frac{1}{n} \sum_{i=1}^{n} (y_i - m)^2 \right) \tag{1}
\]

2. Larger the better; LTB: the target value of quality characteristic is the larger the better. The value can be infinite.
\[
S/N = -10 \log \left( \frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i} \right) \tag{2}
\]

3. Smaller the better; STB: the target value of quality characteristic is the smaller the better. The value can be zero.
\[
S/N = -10 \log \left( \frac{1}{n} \sum_{i=1}^{n} y_i^2 \right) \tag{3}
\]

where \( y_i \) represents the \( i \)-th result of a set of \( n \) repetitions.

3.3. Volume material removal rate
Material removal rate represents how many materials are removed in a certain time unit. In order to speed up the process, MRR is used to enhance efficiency and reduce time cost. Generally, an increase of cutting depth, cutting width and feedrate are three ways to improve MRR. However, tool durability is therefore compromised. It is crucial to research for optimized parameters. This research is to process brittle materials by grinding, which is different from the cutting process by regular tools.

![Figure 1. Ultrasonic assisted machining center (Tongtai UV-5).](image)

4. Experimental design
This research is designed to grind zirconia ceramics by ultrasonic assisted machining center made by Tongtai Machine & Tool Co., Ltd shown as Figure 1. This machining center is able to perform automatic frequency scan and power setup, by which the ultrasonic tool holder can produce periodic vibration. Using Taguchi methods, this research investigates the optimized parameters for material removal rate of rough grinding, and the optimized parameters for the surface roughness of fine grinding. Figure 2 shows that the tool for rough grinding (grit size: 80) and fine grinding (grit size: 800) are diamond
mounted points with 6mm diameter shank. In order to have better results on chip removal and heat dissipation, this research requires diamond mounted points that have 2mm cross recess on the bottom. Figure 3 shows the end surface of the diamond mounted points under the Keyence 3D digital microscope.

4.1. Rough grinding
The tool for rough grinding is #80 diamond mounted points. Figure 4 shows the tool path simulation from NX CAM. Zirconia is processed along a straight line with a length of 100mm. The cutting width is 4mm and the total cutting depth is 1mm. Volume can be calculated by the actual depth of the grinding, and then MRR is calculated. This experiment will find and verify the parameter combination of control factors for the best material removal rate.

The control factors of rough grinding are A. spindle speed (rpm), B. ultrasonic power (%), C. feedrate (mm/min), and D. cutting depth (mm). Each factor is experimented on three levels which values are shown in Table 1. Table 2 indicates the orthogonal array L₉(3⁴), which contains 9 tests. The quality characteristic of rough grinding is larger the better for MRR. Actual volume and precise grinding time of each parameter are recorded.
Table 1. Control factors and level design for rough grinding.

|   | A. spindle speed | B. ultrasonic power | C. feedrate | D. cutting depth |
|---|-----------------|---------------------|-------------|----------------|
| 1 | 10,000          | 50                  | 600         | 0.04           |
| 2 | 11,000          | 75                  | 700         | 0.05           |
| 3 | 12,000          | 100                 | 800         | 0.06           |

Table 2. Orthogonal array $L_9(3^4)$ for rough grinding.

|   | A. spindle speed | B. ultrasonic power | C. feedrate | D. cutting depth |
|---|-----------------|---------------------|-------------|----------------|
| 1 | 10,000          | 50                  | 600         | 0.04           |
| 2 | 10,000          | 75                  | 700         | 0.05           |
| 3 | 10,000          | 100                 | 800         | 0.06           |
| 4 | 11,000          | 50                  | 700         | 0.06           |
| 5 | 11,000          | 75                  | 800         | 0.04           |
| 6 | 11,000          | 100                 | 600         | 0.05           |
| 7 | 12,000          | 50                  | 800         | 0.05           |
| 8 | 12,000          | 75                  | 600         | 0.06           |
| 9 | 12,000          | 100                 | 700         | 0.04           |

4.2. Fine grinding
The tool for fine grinding is #800 diamond mounted points. Zirconia is to be processed for 20mm grooves. Tool path simulation is shown in Figure 5. After fine grinding, each surface roughness under each factor is examined. Table 3 indicates four control factors and three levels. The control factors of fine grinding are spindle speed (rpm), ultrasonic power (%), feedrate (mm/min), and the number of times of grinding. The grinding depth is 5μm for each time. Each factor is experimented on three levels. Table 4 shows the orthogonal array $L_9(3^4)$, which contains 9 tests. The quality characteristic is smaller the better for surface roughness.

Table 3. Control factors and level design for fine grinding.

|   | A. spindle speed | B. ultrasonic power | C. feedrate |
|---|-----------------|---------------------|-------------|
| 1 | 10,000          | 50                  | 600         |
| 2 | 11,000          | 75                  | 700         |
| 3 | 12,000          | 100                 | 800         |
Table 4. Orthogonal array L₉(3⁴) for fine grinding.

|   | A. spindle speed | B. ultrasonic power | C. feedrate | D. number of times of grinding |
|---|------------------|---------------------|-------------|-------------------------------|
| 1 | 10,000           | 50                  | 600         | 2                             |
| 2 | 10,000           | 75                  | 700         | 4                             |
| 3 | 10,000           | 100                 | 800         | 6                             |
| 4 | 11,000           | 50                  | 700         | 6                             |
| 5 | 11,000           | 75                  | 800         | 2                             |
| 6 | 11,000           | 100                 | 600         | 4                             |
| 7 | 12,000           | 50                  | 800         | 4                             |
| 8 | 12,000           | 75                  | 600         | 6                             |
| 9 | 12,000           | 100                 | 700         | 2                             |

5. Results

5.1. Optimized parameter analysis of rough grinding

Based on orthogonal array L₉(3⁴), zirconia is grinded by 100mm using #80 diamond mounted points. The actual cutting depth is measured. The bottom surface is divided into five points to measure the depth and the cutting time is also recorded. The average value of MRR can therefore be obtained. According to larger the better, equation (2) gives S/N ratio. The experimental results of quality characteristics of rough grinding are shown in Table 5. The MRR result of group 3 is relatively better and accompanied by the highest S/N value. Table 6 displays the mean S/N ratio for each factor, range and ranks calculated. The most influential parameter on MRR is cutting depth and secondly the feedrate. Following Table 6 shows that the best levels of factors are A₁(spindle speed 10,000 rpm), B₁(ultrasonic power 50%), C₃(feedrate 800 mm/min), and D₃(cutting depth 0.06 mm). These results are different from group 3 in MRR orthogonal array (Table 2 and Table 5). Therefore, verification test of optimization needs to be done and to be compared with group 3 in orthogonal array. The verification test is shown in Table 7. Compared to the parameters of group 3 in orthogonal array L₉(3⁴) of rough grinding, optimum factor combination has a better result. Hence, A₁B₁C₃D₃ is the best combination for MRR. Table 8 is ANOVA of control factors of rough grinding. The contribution of cutting depth is the most evident, which has the most influence on MRR. Therefore, alteration of this parameter should be done with extra care in order not to cause unnecessary effects.

Table 5. The experimental results of the quality characteristics of MRR for rough grinding.

|   | MRR (mm³/s) | S/N (dB) |
|---|-------------|----------|
| 1 | 1.088       | 0.732    |
| 2 | 1.467       | 3.331    |
| 3 | 1.918       | 5.655    |
| 4 | 1.906       | 5.602    |
| 5 | 1.224       | 1.758    |
| 6 | 1.288       | 2.199    |
| 7 | 1.540       | 3.753    |
| 8 | 1.603       | 4.098    |
| 9 | 1.117       | 0.961    |
Table 6. Factor response of rough grinding for S/N ratio.

| Level   | A     | B     | C     | D     |
|---------|-------|-------|-------|-------|
| 1       | 3.239 | 3.362 | 2.343 | 1.150 |
| 2       | 3.186 | 3.062 | 3.298 | 3.094 |
| 3       | 2.937 | 2.938 | 3.722 | 5.118 |
| E1→2   | -0.053| -0.300| 0.955 | 1.944 |
| E2→3   | -0.249| -0.124| 0.424 | 2.024 |
| Range   | 0.302 | 0.424 | 1.379 | 3.968 |
| Rank    | 4     | 3     | 2     | 1     |

Table 7. Verification test of optimization for MRR.

| Groups     | optimum factor combination |
|------------|----------------------------|
| group 3    | A1B3C3D3                   |
| group 4    | A1B1C3D3                   |
| MRR (mm³/s)| 1.918                      |
| S/N ratio  | 5.655                      |
|            | 2.145                      |
|            | 6.627                      |

Table 8. ANOVA of control factors of rough grinding.

| Factor | SS    | DOF | Contribution |
|--------|-------|-----|--------------|
| A      | 0.04057| 2   | 1.05%        |
| B      | 0.05716| 2   | 1.47%        |
| C      | 0.4405 | 2   | 11.35%       |
| D      | 3.343  | 2   | 86.10%       |
| Error  | 0.0012 | 36  | 0.03%        |
| Total  | 3.88243| 44  | 100%         |

5.2. Optimized parameter analysis of fine grinding

The experiment of fine grinding is set to investigate the surface roughness and find the optimization. Each experiment is conducted with different grinding number of times. After fine grinding, the surface roughness is measured with HOMMEL-ETAMIC roughness measurement shown in Figure 6. The experimental results of surface roughness are represented in Table 9. The surface roughness result $R_a = 0.18\mu m$ of group 4 is relatively better. In order to acquire the minimum surface roughness, S/N ratio is calculated by equation (3). Factor response of surface roughness for fine grinding is shown in Table 10. The most influential factor is the number of times of grinding, and then spindle speed, feedrate, ultrasonic power in descending order.

In Table 10, optimized parameters are A1(spindle speed 10,000 rpm), B1(ultrasonic power 50%), C2(feedrate 700 mm/min), and D3(6 times). These results are different from the best experiment (A2B1C2D3 in group 4) in orthogonal array of surface roughness for fine grinding. Verification test is therefore necessary.

Under the hypothesis of Taguchi methods, each control factor is independent without interactions. The predicted value of S/N ratio is 15.62 and surface roughness 0.16μm. However, compared to the average value of three confirmation tests, the discrepancy is up to 26.9%. It means that there are interactions.
between each factor. From the results of analysis of variance in Table 12, spindle speed, ultrasonic power, and feedrate seem to have similar contributions.

![Figure 6. HOMMEL-ETAMIC roughness measurement.](image)

**Table 9.** Experimental results of surface roughness.

| Surface Roughness Ra(μm) | S/N(dB) |
|--------------------------|---------|
| 1                        | 0.214   | 13.33  |
| 2                        | 0.196   | 14.13  |
| 3                        | 0.189   | 14.48  |
| 4                        | 0.18    | 14.87  |
| 5                        | 0.256   | 11.83  |
| 6                        | 0.224   | 12.98  |
| 7                        | 0.213   | 13.41  |
| 8                        | 0.205   | 13.75  |
| 9                        | 0.228   | 12.84  |

**Table 10.** Factor response of fine grinding.

|          | A  | B  | C  | D  |
|----------|----|----|----|----|
| LEV.1    | 13.98 | 13.87 | 13.36 | 12.67 |
| LEV.2    | 13.23 | 13.23 | 13.94 | 13.51 |
| LEV.3    | 13.33 | 13.43 | 13.24 | 14.37 |
| E¹→²     | -0.75 | -0.64 | 0.59  | 0.84  |
| E²→³     | 0.11  | 0.20  | -0.71 | 0.86  |
| Range    | 0.75  | 0.64  | 0.71  | 1.70  |
| Rank     | 2     | 4     | 3     | 1     |
Table 11. Verification test of optimization of surface roughness for fine grinding.

| Levels | group 4 | optimum factor combination | predicted value |
|--------|---------|----------------------------|-----------------|
|        | A2B1C2D3 | A1B1C2D3                  | A1B1C2D3        |
| Surface roughness Ra(μm) | 0.18 | 0.203 | 0.16 |
| S/N ratio | 14.87 | 13.87 | 15.62 |

Table 12. ANOVA of control factors of fine grinding.

| Factor | SS     | DOF | Contribution |
|--------|--------|-----|--------------|
| A      | 0.004123 | 2   | 11.99%       |
| B      | 0.002589 | 2   | 7.53%        |
| C      | 0.00313  | 2   | 9.10%        |
| D      | 0.015258 | 2   | 44.36%       |
| Error  | 0.0093  | 45  | 27.03%       |
| Total  | 0.0344  | 53  | 100%         |

6. Conclusions
Using Taguchi methods, this research is set to find the optimized parameters with minimum experimental parameter groups. By using diamond mounted points to grind the brittle zirconia, rough grinding and fine grinding are both inspected. In rough grinding, material removal rate is the larger the better, which means more materials are removed per time unit. According to S/N ratio factor response table of rough grinding, the best MRR(2.145mm³/s) is acquired by A1(spindle speed 10,000 rpm), B1(ultrasonic power 50%), C3(feedrate 800 mm/min), and D3(cutting depth 0.06 mm).
However, in terms of surface roughness of fine grinding, spindle speed, ultrasonic power, and feedrate have similar effects, which present a possibility for mutual influences and mixed interactions. The error of prediction is therefore evident.

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