Effect of Spindle Speed on Performance Measures during Rotary Ultrasonic Machining of Fully Sintered Zirconia Ceramic

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ABSTRACT: In order to solve the problems of the complex secondary sintering process, such as the difficulty of controlling shrinkage rate and high fracture rate of pre-sintered zirconia ceramics, a method of complete sintered zirconia ceramics processing by rotary ultrasonic machining was proposed. The experiments of rotary ultrasonic machining and diamond grinding on fully sintered zirconia ceramics were carried out, and the effects of spindle speed on cutting force, maximum edge chipping size, and subsurface damage characteristics were studied. Through comparative analysis, rotary ultrasonic processing can not only reduce the cutting force, effectively inhibit the edge chipping of fully sintered zirconia ceramic material, but also significantly reduce the subsurface micro crack, which is a new way to achieve the low-damage processing of fully sintered zirconia ceramic dental prosthesis.

KEYWORDS: sintered zirconia, edge chipping, cutting force, RUM.

INTRODUCTION

Zirconia ceramic has a unique stress-induced phase transformation toughening effect. Its strength and toughness are more superior to conventional porcelain, and alumina ceramics, dental materials in recent years has become a big concern [1–3] At present, the production process of all-zirconia teeth is obtained by pre-sintering zirconia ceramic blocks after high-speed milling or grinding and then subjected to secondary sintering. However, pre-sintered zirconia ceramics in the secondary sintering process will change the volume shrinkage, which will be a direct impact on the Finishing process of the Crown [4,5]. While the process will produce a large number of micro-cracks that reduces its service life [6]. Thus, at this stage, in order to change the conventional processing of the zirconia ceramic crowns, it is the most ideal and convenient way ultrasonic vibration-assisted machining technology into the field of prosthodontics. Since the introduction of the ultrasonic machining technique may be implemented directly on the fully sintered zirconia ceramic, not only to avoid the secondary volume shrinkage during sintering, while reducing the waiting time for patients [7,8].

In recent years, rotary ultrasonic processing technology for its excellent machining results become the first choice for processing brittle materials. Alkawaz et al. [9] conduct a comparison study between RUM and conventional grinding to analyze the effect of spindle speed on the surface roughness. Abdo et al. [10] studied the machinability of biolox forte ceramic and the effect of machining parameters on tool wear, edge chipping, surface morphology, and surface roughness. Abdo et al.[11] analyzed the influence of µ-RUM parameters on performance measures of ZrO2 ceramic and concluded that at high spindle speed, low exit chipping could be obtained. Wang et al. [12] studied the influence of using compound step-taper tool on the edge chipping during RUM of quartz glass, and concluded that it could reduce the edge chipping by 60 – 80 %. This paper aims to study the machining of fully sintered zirconia ceramic using rotary ultrasonic machining. The effect of machining parameters on the Cutting force, edge chipping, and subsurface damage was studied, and the results were compared with conventional grinding.
EXPERIMENTAL SET-UP

Computer control machines are used in this experiment. HAAS VOP-C with a maximum of 7000 RPM. Although this machine is fully automated, for this experiment, it only uses manual data entry. This is because these experiments require simple movements. The experiment was conducted using a multilayer coating ball nose end mill insert with a 16 mm diameter, as shown in figure 1. The workpiece is a block of fully sintered zirconia ceramic. Its composition and mechanical properties are shown in table 1 and table 2, respectively.

Table 1. Workpiece composition

<table>
<thead>
<tr>
<th>Compound</th>
<th>Approximate %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zirconia ceramic</td>
<td>&lt; 96</td>
</tr>
<tr>
<td>Yttria</td>
<td>&gt; 4</td>
</tr>
<tr>
<td>Hafnia</td>
<td>&gt; 1</td>
</tr>
<tr>
<td>Alumina</td>
<td>&gt; 1</td>
</tr>
<tr>
<td>Silica</td>
<td>&lt; 0.02</td>
</tr>
</tbody>
</table>

Table 2. Workpiece properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending strength /MPa</td>
<td>800 - 1000</td>
</tr>
<tr>
<td>Fracture strength /MPa</td>
<td>1200</td>
</tr>
<tr>
<td>Vicker’s hardness /GPa</td>
<td>12</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>6.05</td>
</tr>
<tr>
<td>Young’s modulus (GPa)</td>
<td>210</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.31</td>
</tr>
</tbody>
</table>

Figure 1. Machine set-up
The workpiece size is 40 mm × 20 mm × 20 mm, and the experimental parameters are set, as shown in table 3.

Table 3. Process parameters

<table>
<thead>
<tr>
<th>Control parameters</th>
<th>3000 rpm</th>
<th>5000 rpm</th>
<th>7000 rpm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spindle speed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ultrasonic frequency, Us</td>
<td>23.5 kHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depth of cut</td>
<td>4 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feed, Fz</td>
<td>25 mm/min</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The cutting force in three directions under the two machining methods was measured by the KISTLER9257 dynamometer. The dynamometer was installed between the work surface and the workpiece, the dynamometer converts electrical signals into digital signals through the A/D converter, which are read and analyzed by DynoWare software. The chipping size was measured using the KEYENCE Ultra Depth of Field 3D microscope system (model: VHX-600E) to enlarge the edge of the exit position of the machining hole.

RESULTS AND DISCUSSION

Analysis of cutting force

In order to study the effect of spindle speed on the cutting force during the machining of sintered zirconia, Figure 2 shows the comparison results of cutting forces under RUM and conventional grinding.

![Figure 2. Effect of spindle speed on the cutting force.](image)

As can be seen from the above results, the rotational ultrasonic machining grinding force is generally less than conventional grinding. When the spindle speed is 3000 rpm – 5000 rpm, the difference of mean cutting force between the two processing methods is about 15 N, but when the speed reaches 7000 rpm, the mean cutting force of the rotary ultrasonic machining is the same as that of conventional grinding. Due to the periodic separation of the Rotary ultrasonic machining process between the tool and the workpiece, lead to the contact time between the two is shorter than conventional grinding. In the tool and workpiece contact time range, rotating ultrasonic cutting force may be higher or less than conventional grinding, but when the tool and the workpiece separation is not the role of cutting force. Therefore, when the spindle speed is low, the contact time of the tool and the workpiece in the Rotary ultrasonic machining process is short, there is no longer cutting force, and thus the mean cutting force is small. However, when the spindle speed is increased to a specific value, the contact time of the Rotary ultrasonic machining tool and the workpiece increases, when increased to substantially the same as the conventional grinding, the separation between the two does not exist, so the role of ultrasound-assisted significantly weakened, so that the cutting force of the two processing methods are closer. Also, the cutting force of the two processing methods is increased when the spindle speed decreases, and in the range of 3000 rpm to 5000 rpm decreased significantly more significantly than the magnitude of 5000 rpm to 7000 rpm. It can be seen that the spindle speed has a more significant impact on the cutting
force at low speeds. This is related to Lv et al. [13]. Using rotation Ultrasonic machining of glass-ceramic materials, research results are consistent.

Edge chipping analysis

Edge chipping not only affects the geometry of the part in ceramic processing, but it is also more critical that the edge chipping is reduced during the use of the part. Its strength leads to failure. Especially in the processing of oral restorations, the edge of the exit often has a more significant impact on its quality. This is because dental restorations are small in size and thin in thickness, especially at the neck edge, in order to meet the clinical precision requirements with the basal crown or remaining teeth, they are often thin-walled and have sharp edges. Therefore, corresponding measures must be taken to reduce the impact of chipping at the exit edge on the precision and quality of crown processing. Figure 3 and Figure 4 show the comparison of the edge chipping of the fully sintered zirconia ceramics obtained by conventional grinding and rotary ultrasonic machining at a magnification of 50 times at a spindle speed of 3000 rpm and 7000 rpm. Figure 5 shows the change of the maximum edge chipping width produced by the two processing methods at different speeds.

![Figure 3](image1.png)

**Figure 3.** Edge chipping of fully sintered zirconia at 3000 rpm (a) rotary ultrasonic machining (b) conventional grinding.

![Figure 4](image2.png)

**Figure 4.** Edge chipping of fully sintered zirconia at 7000 rpm (a) rotary ultrasonic machining (b) conventional grinding.

It can be known from the above detection and analysis results that under the same process parameters, the edge chipping of the rotary ultrasonic machining is significantly better than that of conventional grinding. When the spindle speed is 3000 rpm, in the case of conventional grinding, there are multiple cracks at the exit edge of the machined hole, and the maximum crack width is 735.61 μm, and when the speed reached 7000 rpm, the chipping situation improved to some level. Only 1 or 2 defects appeared at the top, but the maximum chipping width did not change significantly. This is mainly due to the large cutting force at low speeds, resulting in multiple cracks at the exit, but due to the impact of processing technology and the hardness of the fully sintered zirconia ceramic material, the edge chip size does not change much. A similar situation exists in rotary ultrasonic machining, but the degree of chipping changes in Figure 3 (b) and Figure 4 (b) are small, and there is no noticeable difference. It can be seen that, as far as the occurrence of edge
chipping is concerned, rotary ultrasonic machining is not affected by the spindle speed significantly compared with conventional grinding.

![Figure 5](image.png)

**Figure 5.** Effect of spindle speed on the edge chipping.

When the spindle speed is 3000 rpm, during rotary ultrasonic machining, the maximum width of the ceramic workpiece edge chipping is 185.54 µm; when the spindle speed reaches 7000 rpm the minimum chipping size of 94.62 µm is achieved. This agreed with results obtained by Abdo et al. [11]. It can be seen that as compared with conventional grinding, the ultrasonic vibration helps to control the edge chipping of the fully sintered zirconia ceramics. Besides, as can be seen from Figure 6, in the case of rotary ultrasonic machining, the width of the maximum edge chipping decreases with the increase of spindle speed and decreases even more in the range of 3000 rpm to 5000 rpm than in the range of 5000 rpm to 7000 rpm. In the case of conventional grinding, the maximum edge chipping width decreases with the increases of the spindle speed in the range of 3000 rpm to 5000 rpm and increases with the speed range of 5000 rpm to 7000 rpm.

Analysis of subsurface damage characteristics

For ceramic dental prostheses, how to control subsurface microcracks is the key to determining their service life. The annual failure rate of ceramic crowns due to fracture is over 3%. This is mainly due to the brittle hardness of the ceramic material, and the crown. In thin-walled parts, in the process is easy to produce many micro-cracks caused by the impact of its oral environment, and occlusal forces during use lead to failure, as shown in Figure 6.

![Figure 6](image.png)

**Figure 6.** Effect of subsurface damage on the crown failure.

In this paper, the JSM-6300 scanning electron microscope was used to detect the subsurface microcracks of the two processing methods at different spindle speeds. Figure 7 shows the micro-cracks on the sub-surface of the sintered zirconia ceramic completely after ordinary diamond grinding. Figure 8 shows the test results after the rotary ultrasonic machining.
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Figure 7. Sub-surface crack during conventional grinding when spindle speed is: (a) 3000rpm  (b) 5000 rpm  (c) 7000 rpm

Figure 8. Sub-surface crack during rotary ultrasonic machining when spindle speed is: (a) 3000rpm  (b) 5000 rpm  (c) 7000 rpm.

The results of SEM show that the subsurface micro-cracks of the workpiece processed by ordinary diamond grinding are relatively obvious and are amplified. It can be seen by about 3000 times, as shown in FIG. 7(b) and 7(c). Especially when the spindle speed was 2000 rpm, many micro-cracks were found when SEM was amplified to 5500 times. Compared with ordinary diamond grinding, it is difficult to find micro-cracks on the subsurface of the work piece after rotary ultrasonic machining. When the spindle speed is 2000 rpm, no crack is found when the SEM is amplified to 7000 times, and the first microcrack can only be seen only when the other speeds are amplified to 5000 ~ 6500 times. This is mainly due to the impact frequency of ultrasonic vibration up to about 23.5 kHz, much higher than the grinding frequency of diamond grains. The zirconia dental material that is completely sintered is first subjected to the high-frequency impact of ultrasonic vibration during the processing, which damages its surface and subsurface, to facilitate the removal of diamond abrasive materials and realize the low-damage processing of the workpiece. Besides, the rotational speed of ordinary diamond grinding processing produced The influence of microcrack was obvious, and the microcrack gradually decreased with the increase of rotational speed, but there was no clear rule in rotational ultrasonic machining.

CONCLUSION

The following conclusions have been obtained through experiments of rotary ultrasonic machining and conventional grinding of fully sintered zirconia ceramics:

• The aid of ultrasonic vibration helps improve the surface and subsurface quality of completely sintered zirconia dental materials.
• In the processing of fully sintered zirconia dental materials, ultrasonic vibration is helpful to reduce the cutting force, especially when the spindle speed is low; the effect is noticeable. Meanwhile, the cutting force decreases with the increase of spindle speed.
• The assistance of ultrasonic vibration is conducive to suppressing the maximum edge chipping size of the workpiece. With the increase of the spindle speed, the maximum edge chipping size by further reduced.
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• In conventional grinding, micro-cracks on the subsurface of the workpiece are apparent. The assistance of ultrasonic vibration is helpful to reduce the workpiece surface micro-cracks, can achieve low damage during the processing of fully sintered zirconia dental materials.

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REFERENCES