Feasibility study of ultrasonic vibration assisted grooving for Zirconia ceramics

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Zirconia (ZrO_2) ceramics are widely utilized in aerospace, biotechnology, and other industrial fields due to their exceptional material properties. However, it is challenging for conventional grinding (CG) to meet industrial requirements due to its inherent hardness and brittleness. To address this issue, we proposed tilted grooving (TG), which has been experimentally proven to effectively reduce grinding forces, and thus can reduce wheel wear. However, due to the inclination of the grinding wheel axis, the value of the machined surface roughness of TG is greater than that of CG. Ultrasonic-assisted machining is a well-recognized method for enhancing surface quality and is extensively applied in the precision machining of hard and brittle materials. Therefore, we combine these two approaches and introduce a novel method, called ultrasonic vibration-assisted tilted grooving (UVTG), for ceramic part fabrication. First, the motion trajectory of a single abrasive grain is derived based on its kinematics. Then, the apparatus of UVTG is developed according to its processing principle for experimental evaluations. The experimental results validate that UVTG can effectively improve the machining performance and reduce surface roughness without increasing grinding force and temperature, thereby affirming the feasibility of UVTG for ZrO_2 ceramics.

1. Introduction

ZrO_2 ceramics have outstanding mechanical properties such as high hardness, flexural strength, resistance to bending and scratches, etc. [1]. They can also withstand complex environments that metals cannot [2]. As a result, ZrO_2 ceramics are highly sought after for their exceptional physical and chemical properties, making them a versatile material with diverse engineering applications in fields ranging from aviation [2], 3 C products [1], and biomedical applications [3]. However, these excellent properties also lead to challenges in the manufacturing processes to achieve required efficiency and part quality.

Grinding is the most commonly applied method for rough and finish machining of ceramics, but there are many problems during the process. Due to its inherent hardness and brittleness, ZrO_2 ceramics are prone to crack propagation, generating surface and subsurface damages during grinding, which affects the dimensional accuracy and mechanical properties of the parts. As a result, the machining processes require a small material removal rate and a longer processing time, which restrict the process efficiency. In addition, the wear of the grinding wheel is severe, leading to high production costs.

To address these problems, various technologies have been developed, including conventional helical milling (CHM). In CHM, the tool follows a circular trajectory with a forward feed speed, which offers several advantages, such as lower average force and temperature due to the periodic intermittent cutter-workpiece contact. This can result in a prolonged lifespan of the cutter and significantly improve productivity. However, dimensional inaccuracies, such as distortion, may still occur due to insufficient stiffness. Inclined grinding (IG), initially proposed by Suzuki in 1998 [4], tilts the grinding wheel with respect to the axis of the workpiece spindle. This increases the contact stiffness between the wheel and workpiece, thus reducing distortion during grinding and consequently achieving better surface quality. As a result, we proposed tilted grooving (TG) by combining CHM and IG. Based on our previous experimental results [5], TG can significantly reduce the average grinding force compared to conventional grinding (CG) (up to a maximum reduction of about 40%), thus can reduce wheel wear and can also effectively reduce the average grinding temperature compared to CG (by approximately 25%), while the surface roughness (Ra) of TG is larger than that of CG due to the inclined wheel configuration. Ultrasonic vibration-assisted machining is considered as one of the most common methods for brittle materials, with the advantages of achieving smaller surface and higher surface integrity [6]. Therefore, TG integrates with ultrasonic vibration, and a novel approach, namely ultrasonic vibration assisted titled grooving (UVTG), is proposed to improve the surface integrity of TG.

In this paper, the kinematics of UVTG will be modeled, and an experimental apparatus of UVTG has been developed accordingly. Based on this, a set of experiments were carried out to investigate the grinding force, temperature, and surface quality, which support the feasibility of UVTG for ZrO_2 ceramics.

2. Kinematics of UVTG

To demonstrate the trajectory of a single grain on the grinding wheel during TG, the Cartesian coordinate system $\{O_w, x_w\ y_w\ z_w\}$ is introduced as shown in Fig. 1, which shows the schematic diagram of a grinding wheel trajectory during TG. The length and the radius of a grinding wheel are l (the distance from point O_w to O_T) and r_t, respectively. The grinding wheel rotates with respect to its axis own at a speed of n_T and exhibits conical pendulum motion around the revolution axis at a rotary speed of n_r in a clockwise direction. Simultaneously, the grinding wheel feeds along the x_w-axis direction at a speed of v_f.

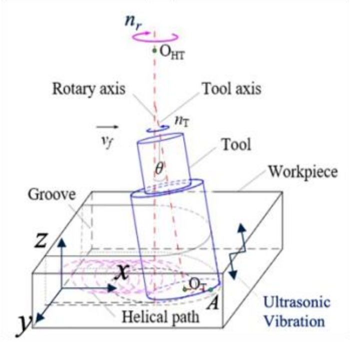

Fig. 1 Schematic diagram of UVTG

Point A represents a random point along the circumferential edge on the end face of the grinding wheel, and for simplicity, supposed that the initial position (when the wheel is not tilted) of point A, P_A, is expressed as:

$$P_A = [r_t \quad 0 \quad l \quad 1]^T \tag{1.}$$

The grinding wheel rotates at the speed n_T in the counterclockwise direction. According to the rotation representations in homogeneous coordinates, the rotation matrix that defines the wheel rotation at the time instance t with a rotation angle of $2\pi n_T t$ can be given as:

$$Rotz = \begin{bmatrix} \cos(2\pi n_T t) & -\sin(2\pi n_T t) & 0 & 0 \\ \sin(2\pi n_T t) & \cos(2\pi n_T t) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2.}$$

Considering the inclination of the grinding wheel, let the dashed wheel rotate a certain angle θ in the counterclockwise direction with respect to the y_w axis, thereby the corresponding rotation matrix can be defined by:

$$Roty = \begin{bmatrix} \cos\theta & 0 & \sin\theta & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\theta & 0 & \cos\theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.}$$

Afterwards, the revolution of the tilted grinding wheel revolves clockwise at a rotary speed of n_r around the z_w axis. Hence, the rotation matrix of the revolution with a rotation angle of $2\pi n_r t$ is derived by:

$$Rotr = \begin{bmatrix} \cos(2\pi n_r t) & \sin(2\pi n_r t) & 0 & 0 \\ -\sin(2\pi n_r t) & \cos(2\pi n_r t) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4.}$$

Furthermore, the transfer matrix of the infeed in the x_w direction is given by:

$$Tx = \begin{bmatrix} 1 & 0 & 0 & v_f t \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5.}$$

Therefore, the trajectory of a single grain during TG, P_{TG}, is obtained accordingly.

$$P_{TG} = Tx \cdot Rotr \cdot Roty \cdot Rotz \cdot A \tag{6.}$$

Meanwhile, with the introduction of axial ultrasonic vibration on the grinding wheel, the trajectory of a single grain during UVTG can be considered as the TG trajectory simultaneously superimposing axial ultrasonic action with an amplitude of A and a frequency of f. Therefore, the transfer matrix caused by feed speed and ultrasonic vibration, T_{uv}, is expressed as:

$$T_{uv} = \begin{bmatrix} 1 & 0 & 0 & (A\sin(2\pi f t) + e)\sin\theta\sin(2\pi n_r t) + v_f t \\ 0 & 1 & 0 & (A\sin(2\pi f t) + e)\sin\theta\cos(2\pi n_r t) \\ 0 & 0 & 1 & A\sin(2\pi f t)\cos\theta \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{7}$$

Therefore, the trajectory of UVTG, P_{UVTG}, is shown in Fig. 2.

$$P_{UVTG} = T_{uv} \cdot Rotr \cdot Roty \cdot Rotz \cdot P_A \tag{8}$$

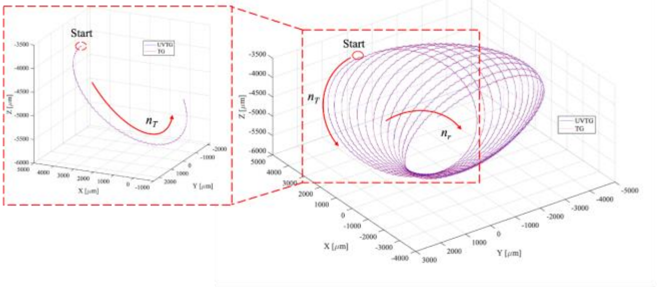

Fig. 2 Trajectory comparison between TG and UVTG (A=20μm, f=1KHz)

3. Experimental setup

To experimentally validate the feasibility of UVTG for ZrO_2 ceramics, a specially-designed experimental apparatus was established by installing an ultrasonic spindle onto a commercial CNC machine (B-500S, Guangdong Harvest Star Technology Co., Ltd, China) as shown in Fig. 3.

During the TG experiments, the electroplated diamond wheel with a mesh size of 80# and a diameter of 6mm (Shenzhen Changxing Diamond Abrasives Co., Ltd, China) was installed in an ultrasonic spindle (Multi-field Precision, K802430A.U), and the dimension of

ZrO_2 ceramic specimen is 50×30×3mm^3, whose relevant properties can be found in the previous paper [5]. The UVTG spindle feeds in the positive direction along the *x*-axis at a constant speed for processing. The process parameters to define the experimental condition are shown in Table 1. A dynamometer (HR-FP3103S, Shanghai Horizon Electronic Technology Co., Ltd, China) was employed to record the grinding forces. During the experiments, no grinding fluid was used, and the grinding temperature was measured by means of infrared camera (FLIR T660, Sweden), and the average of the measured data in one minute during steady-grinding state (after the grinding wheel entirely engaged into the workpiece) was taken as the final result. For the machined groove bottom, an instrument (ACCRETECH SURFCOMNEX, Japan) was used to measure the surface roughness. Each groove was measured three times along the feed direction, and the average of the three measurements was taken as the final result.

Fig. 3 The physical diagram of UVTG apparatus

Table 1 Experimental condition

Parameter/ unit	Value
Spindle speed/ rpm	16000
Revolution speed/ rpm	200
Inclination angle/ degree	5
Feed speed/ mm/min	1, 2, 3, 4, 5, 6
Vertical depth of cut/mm	1.5
Amplitude of ultrasonic vibration/ mm	0, 0.0022
Frequency of ultrasonic vibration/ KHz	31.5~ 32.4

4. Results and discussion

In this section, the experimental results obtained by TG and UVTG under different feed speeds are compared, including average grinding force, grinding temperature, and surface roughness of the groove bottom, followed by some discussions.

4.1 Grinding force and grinding force ratio

Fig. 4 displays the results of the average normal grinding force and the grinding force ratio (the ratio of the normal grinding force to the tangential grinding force F_n/F_t). From Fig. 4, the average normal grinding force is lower when the ultrasonic amplitude is added compared to no ultrasonic vibration case. However, the average tangential grinding force (force in the *x* direction) remains nearly unchanged with or without ultrasonic vibration.

The former can be attributed to the introduction of axial ultrasonic vibration that causes periodic separation between the tool-workpiece contact, reducing the contact time between individual diamond grains and the workpiece. The reduction in contact time leads to a decrease in frictional effects [7]. Additionally, the impact forces may promote the self-sharpening of abrasive grains, increasing the number of effective cutting edges, thereby reducing the average normal grinding force [8]. For the latter case, although ultrasonic vibration alters the contact length between a single abrasive grain and the workpiece's side surface, as well as the contact time with the bottom surface, the coupling effect of parameters, especially the inclination, revolution, and shape (such as a rounded corner) of the grinding wheel makes the average tangential force in UVTG highly complex.

The grinding force ratio is used to evaluate the performance of grinding wheels in the process. A smaller force ratio indicates higher grinding wheel performance [8]. From the chart, it can be observed that the force ratio of UVTG is always smaller than that of TG. This is because the introduction of ultrasonic vibration can enhance the self-sharpening of abrasive grains. However, as the feed rate increases, the material removal rate increases, leading to more severe chip adhesion and accumulation. At the same time, ultrasonic vibration can cause the generated debris to become smaller, making it easier for the grinding wheel to clog, thus affecting the sharpness of the grinding wheel during UVTG [9].

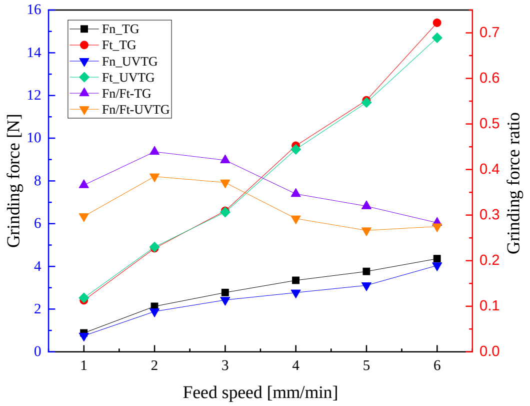

Fig. 4 Change of grinding force with feed speed

4.2 Grinding temperature

Fig. 5 displays the average grinding temperature during TG and UVTG. It was found that the introduction of ultrasonic vibration has

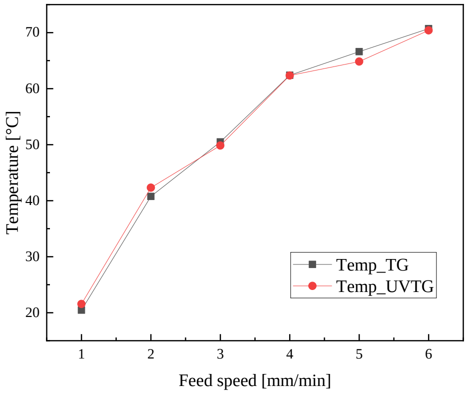

Fig. 5 Change of grinding temperature with feed speed

little effect on the average temperature, and this outcome could be attributed to the suboptimal parameters chosen for the amplitude and frequency of ultrasonic vibration. As mentioned before, the process of UVTG is highly complex, and further research should be conducted to develop a comprehensive analytical model that takes into account both grinding force and temperature. For another, without grinding fluid, the remained temperature from the previous progress might increases the latter results, resulting in the little change on the final results.

4.3 Surface roughness

According to Fig. 6, it can be observed that the addition of ultrasonic vibration reduces the value of surface roughness. This is attributed to the flattening effect of ultrasonically vibrating abrasive grains, which decreases the surface roughness [10]. Additionally, the enhanced self-sharpening of the grinding wheel due to ultrasonic vibration also contributes to the improvement of surface quality [9].

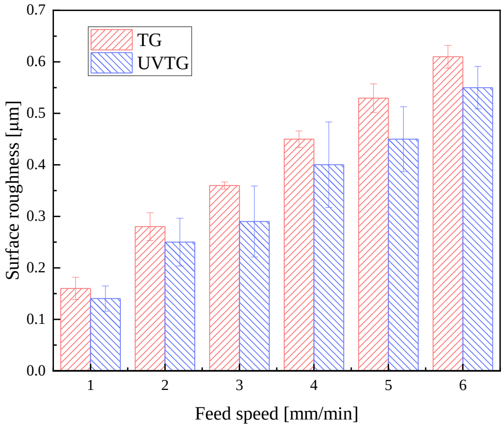

Fig. 6 Change of work-surface roughness with feed speed

4. Conclusions

This study is based on theoretical and experimental investigations to explore the influence of ultrasonic vibration on the slotting performance of zirconia ceramics. The conclusions are as follows:

(1) UVTG shows a lower grinding force ratio thus proving that can improve the machining performance due to the self-sharping effect caused by ultrasonic vibration. Besides, the motion of UVTG makes the contributions of a single grain to the tangential and normal forces more complex.

(2) The grinding temperature in UVTG is similar to that in TG, because of the accumulation of heat from prior processing and the selection of processing parameters.

(3) UVTG can further reduce the surface roughness value in TG due to the self-sharpening effect caused by ultrasonic vibration.

The kinematics and experimental findings provide that UVTG is a potential process for fabricating ZrO_2 ceramics, and a comprehensive model is necessary to be developed for optimizing the processing parameters.

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