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Efficient and precise cutting of zirconia ceramics using heated cutting tool

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ABSTRACT

The thermally assisted machining of yttria-stabilized tetragonal zirconia polycrystal using a cutting tool heated with induction heating was proposed. Although the conventional thermally assisted machining cannot be applied to drilling, the proposed method can be. Heat transfer from the heated cutting tool to the workpiece was simulated analytically, and the result showed that heating of the tool up to 500 °C produced an increase of 150–400 °C in the workpiece temperature. Cutting experiments demonstrated an improvement in machinability.

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1. Introduction

Yttria-stabilized tetragonal zirconia polycrystal (Y-TZP) is an engineering ceramic used for biomedical applications including dental restoratives and femoral ball heads [1]. The primary mechanical properties of Y-TZP are listed in Table 1. Y-TZP adopts a tetragonal structure at a room temperature [2], and its structure transforms into monoclinic under large compressive stresses, for example, at a crack generation site. Crack propagation is prevented by a compressive dilatational stress associated with the structural transformation, and this so-called stress-induced transformation toughening mechanism leads to Y-TZP's high fracture toughness [3], which differentiates Y-TZP from other ceramics. However, the high mechanical strength makes the machining of Y-TZP difficult. Therefore, precise, efficient, inexpensive machining of Y-TZP is desired.

Table 1
Mechanical properties of Y-TZP.

Fracture toughness	Approximately 8.0
Thermal conductivity (W/mK)	2.0
Thermal diffusivity (m^2/s)	8.3

To machine the so-called difficult-to-cut materials such as Y-TZP, a number of cutting technologies have been developed, including ultrasonic vibration-assisted machining [4–7] and laser-assisted machining [8–11]. As for Y-TZP, the decrease in mechanical strength at high temperatures is notably large. Thus, in this study, a cutting method using a heated tool is proposed. The conventional thermally assisted machining methods such as laser-assisted machining cannot be applied for drilling. However, the proposed method has the potential for application to drilling.

2. Methods

2.1. Mechanical properties of Y-TZP at elevated temperature

The bending strength and fracture toughness were measured at elevated temperatures using a testing machine (Instron, "4507") [12], and the results are shown in Fig. 1(a). The experiment revealed a sharp decrease in mechanical strength at high temperatures. The decreased mechanical strength indicates a possible improvement in Y-TZP's machinability at high temperatures.

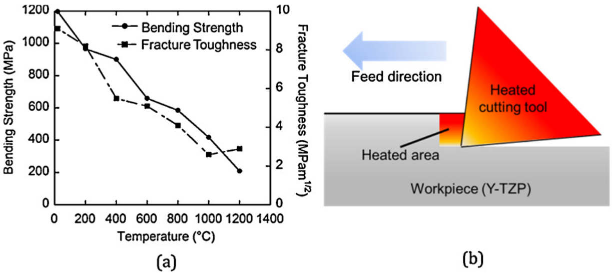

Fig. 1. Thermally assisted machining of Y-TZP. (a) Mechanical strength of Y-TZP at elevated temperature [12]. (b) Schematic diagram of proposed machining scheme in semi-orthogonal cutting setup.

2.2. Thermally assisted machining using heated tool

Thermally assisted machining is a cutting process assisted by softening of the workpiece using heat. For example, laser-assisted machining is a thermally assisted machining method, and the workpiece is heated locally using a laser beam prior to cutting [13]. The present authors proposed the laser-assisted machining (LAM) of Y-TZP [12]. In the proposed LAM of Y-TZP, the workpiece is heated and partially ablated with a UV laser before material removal using a cutting tool. Although the proposed method proved to be efficient for turning and milling, it could not be

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applied to drilling because the laser beam cannot reach the cutting edge area of drilling. To develop a thermally assisted machining method that is also applicable to the drilling of completely sintered Y-TZP, we propose a machining method using a heated tool. In this study, we investigate the proposed machining method in simple grooving instead of drilling for conducting basic analysis. A schematic diagram of the proposed process is shown in Fig. 1(b).

In previous works related to thermally assisted machining using a heated tool, cutting tools were heated with a gas torch [14,15]. In the present study, the workpiece is softened owing to by the heat transferred from the induction-heated rake face of the cutting tool. Induction heating increases the cutting tool temperature to up to 500 °C within several seconds and keeps the temperature constant during the cutting process. In terms of the controllability of cutting tool temperature, induction heating is superior to heating with a gas torch.

In the following section, a simulation conducted for estimating a rise in workpiece temperature is described. In addition, cutting experiments were performed for investigating the machinability improvement achieved using the proposed thermally assisted machining method.

3. Temperature distribution simulation

3.1. Modelling of heat transfer process

For estimating workpiece temperature rise owing to the heat transferred from the heated cutting tool, an analytical simulation was conducted. A schematic diagram of the analytical model is shown in Fig. 2. Fig. 2(a) shows a cross-sectional view of the cutting process. In the proposed method, heat is transferred through the contact area between the workpiece and the heated cutting tool. The heat transfer is modelled as that from a moving rectangular-shaped heat source to the workpiece surface, and the heat liberation rate of the workpiece is assumed to be uniform. The model is shown in Fig. 2(b). The temperature distribution in the workpiece material is calculated using the method described in [16] as below.

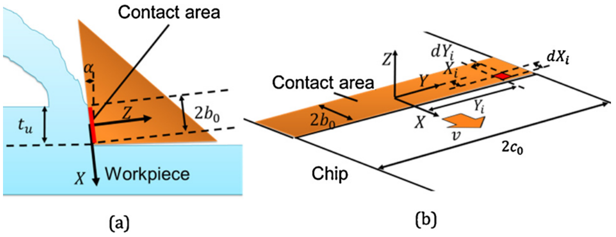

Fig. 2. Modelling in simulation. (a) Schematic diagram of orthogonal cutting. (b) Simplified model of workpiece-tool contact area.

$$\theta_m = \frac{q_{\text{rec}} v}{16\lambda a \pi^{3/2} \cdot 4 b_0 c_0} \int_{Y_i=-c_0}^{+c_0} dY_i \int_{X_i=-b_0}^{+b_0} dX_i \exp\left[-\frac{(X-X_i)v}{2a}\right] K_m(u_i) \tag{1}$$

$$K_m(u_i) = \int_0^{v^2 t/4a} \frac{dw}{w^{3/2}} \exp\left(-w - \frac{u_i^2}{aw}\right) \tag{2}$$

$$u_i = \frac{v \cdot \sqrt{(X - Xi)^2 + (Y - Y_i)^2 + Z^2}}{2a} \tag{3}$$

The variables are as follows: θ_m: the temperature rise (K) of the point represented by the moving coordinates X, Y, Z: q_{rec}: heat liberation rate of the heat source (J/s): v: feed speed of the heat source (m/s): λ: the thermal conductivity of Y-TZP (W/mK): a: the thermal diffusivity of Y-TZP (m^2/s): b_0: half of the contact area length (m): c_0: half of the width of chip (m); x_i and y_i: coordinates of a differential segmental element of rectangular heat source: t: process time (s). For determining q_{rec}, steady state heat flow is assumed. The temperature of the cutting tool and the contacting chip surface is T_{tool} (°C). The other side of the chip facing the air has a room temperature (T_{room} (°C)). For simple calculation, chip thickness is assumed to be equal to the depth of cut (t_u (m)). Under these assumptions, the heat liberation rate can be obtained as below:

$$q_{\text{rec}} = 4 b_0 c_0 \lambda \cdot \frac{(T_{\text{tool}} - T_{\text{room}})}{t_u} \tag{4}$$

By using Eqs. (1)–(4), the temperature rise in a quasi steady state is obtained.

3.2. Temperature distribution simulation

A simulation of heat transfer from the cutting tool to the workpiece was conducted using the aforementioned equations. The simulation parameters are listed in Table 2. The results for the depth of cut of 5 μm and 15 μm are shown in Fig. 3. The figure shows the cross sectional plane (i.e., the x–z plane) of the workpiece. The heat transfer in the negative z direction was calculated for a length equal to the depth of cut, assuming that chip thickness was nearly equal to the depth of cut. As the results show, the proposed method can generate temperature rise of approximately 150–400 °C in the workpiece for improving the machinability.

Table 2
Simulation parameters.

Depth of cut (μm)	5.0
Feed speed (mm/min)	300
Tool temperature (°C)	500
Room temperature (°C)	20
Contact length (μm)	5.0
Time after the process (s)	10

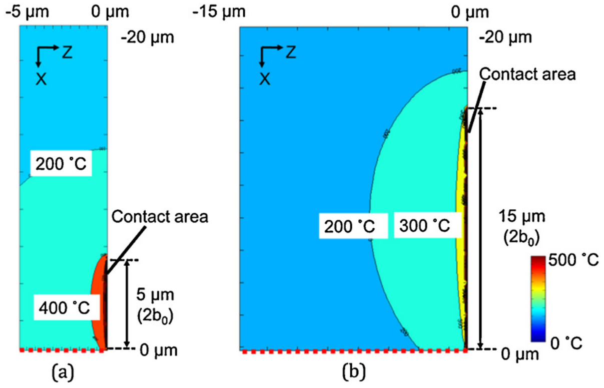

Fig. 3. Simulation results for the depth of cut of (a) 5 μm and (b) 15 μm.

4. Experiments

4.1. Setup and condition

Cutting experiments which machine grooves using a round nose tool were conducted for demonstrating the machinability improvement. The designed experimental setup is shown in Fig. 4(a) and (b). A cutting tool with a cubic boron nitride insert having a nose radius of 0.2 mm (Kyocera corporation, VBGW110302T00815ME) was placed in an induction heating coil (Nippon Future Co., Ltd.). The coil was cooled using compressed cooling air (0.3 MPa) flowing through it. The power output of the device was 800 W, and its oscillating frequency was 50–75 kHz.

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