Precision Engineering 45 (2016) 176–186

Contents lists available at ScienceDirect

Precision Engineering

journal homepage: www.elsevier.com/locate/precision

Experimental analysis of the machinability in the thermally assisted milling process of zirconia ceramics

Toru Kizaki*, Naohiko Sugita, Mamoru Mitsuishi

The University of Tokyo, 7-3-1 Hongo Bunkyo-ku, Tokyo, Japan

ARTICLE INFO

Article history:
Received 27 October 2015
Received in revised form 16 January 2016
Accepted 31 January 2016
Available online 2 March 2016

Keywords:
Y-TZP
Ceramics
Central composite design
Machinability
Thermally assisted machining

ABSTRACT

Yttria-stabilized tetragonal zirconia polycrystal (Y-TZP) is a promising material for dental restoratives. The fabrication method of such dental restoratives is usually as follows: (1) hot pressing of zirconia powder (2) machining of pre-sintered zirconia (3) sintering. However, the current method has disadvantages such as low geometrical accuracy and long process time. It was adopted since the fully sintered Y-TZP is extremely difficult to machine. If a suitable milling process for fully sintered Y-TZP can be established, it will enable an accurate, efficient, and cost-effective process. The milling process is important for three-dimensional free-form fabrication, which is required for manufacturing dental restoratives. In this study, we propose a thermally assisted milling process in which a fully sintered Y-TZP workpiece is directly heated to several hundred degrees by a heater to soften it and enhance its machinability. In a practical situation, the machinability must be predicted in advance to determine the proper machining conditions, including the workpiece temperature. In order to make such predictions, the machining phenomena occurring during thermally assisted machining must be understood. In addition, the quantitative relationships between the workpiece temperature, cutting conditions, and the resulting machinability must be characterized. In the present study, we conducted a series of straight-milling experiments to observe the machining phenomena and obtain the quantitative relationships between the machining conditions and the machinability of Y-TZP using the proposed thermally assisted milling process. A series of experiments were performed using the central composite design method. The results of the experiments revealed that raising the workpiece temperature significantly reduces cutting resistance and the tool wear. Although a greater amount of fracturing occurred when the workpiece was heated, the resulting roughness of the bottom surface of the grooves did not increase. Quantitative relationships between the machining conditions, including the workpiece temperature, and the machinability were established using a curve-fitting method.

1. Introduction

Yttria-stabilized tetragonal zirconia polycrystal (Y-TZP) is a promising material in the biomedical field. It is mainly used as a material for dental crowns and fixed partial dentures [1] owing to its high hardness, high fracture toughness, chemical inertness, and its white color, which is similar to that of human teeth. Y-TZP is known as a material that is difficult to machine because of its high mechanical strength at room temperature. The current manufacturing method comprises three steps: hot pressing, green-part machining, and final sintering. In this method, approximately 20% volumetric shrinkage occurs in the final sintering step. This shrinkage must be accounted for in the machining process prior to the sintering. In addition, the sintering procedure is lengthy, commonly taking more than 7 h. Thus, an accurate, efficient, and cost-effective machining method for fully sintered Y-TZP is desired.

The fully sintered Y-TZP is so difficult to machine that even a grinding tool with a diamond grit undergoes significant wear in the process. Thus, the machinability must be enhanced by utilizing a material property. A unique feature of Y-TZP is that its fracture toughness decreases at elevated temperatures, a phenomenon caused by its crystal structure. The decrease of the fracture toughness at elevated temperature is explained in the following part. The crystal structure of the pure zirconium oxide is monoclinic, while Y-TZP, which includes 3 mol% yttria (Y_2O_3) as an additive, maintains a tetragonal structure even at room temperature [2]. The tetragonal structure of Y-TZP contributes to its high-fracture toughness, which is attributed to a stress-induced transformation toughening mechanism that prevents crack propagation [3]. This was first discovered by Garvie et al. [4]. The details are as follows: The tetragonal

---

* Corresponding author. Tel.: +81 03 5841 6357; fax: +81 03 5841 6357.
E-mail address: kizaki@nml.t.u-tokyo.ac.jp (T. Kizaki).

http://dx.doi.org/10.1016/j.precisioneng.2016.02.010

structure of Y-TZP, which is metastable at room temperature, transforms into a monoclinic structure at a high-pressured condition, such as the high-pressure condition that occurs at a crack-tip, when the grain size exceeds approximately 0.4 μm [5]. The transformation from tetragonal to monoclinic induces a volumetric change; the resultant compressive dilatational stress prevents further crack propagation. However, the toughening mechanism disappears at a temperature above approximately 400 °C; at these temperatures, the fracture toughness decreases because the tetragonal structure becomes stable. Although the Y-TZP material used in our study has a grain size of nearly 0.4 μm, we demonstrated in our previous work [6] that its fracture toughness and its bending strength decreased at elevated temperatures.

The machinability is expected to be enhanced by utilizing the decrease of the fracture toughness and the bending strength at elevated temperatures. Thermally assisted machining is a process that benefits from the reduction of workpiece strength when its temperature is raised. Various heat sources have been applied to elevate the workpiece temperature in a process. For instance, laser-assisted machining (LAM) processes have been applied to various materials, such as silicon nitride ceramics [7], Magnesia-partially-stabilized zirconia [8], and Inconel 718 [9]. In addition, a plasma-enhanced machining process [10] has been reported, and processes in which the cutting tools are heated in the machining of metals [11] and elastomers [12]. In this work, we propose a thermally assisted milling process for Y-TZP that can be applied to manufacturing dental restoratives. The milling process is crucial for the fabrication, since the dental restoratives require three-dimensional free-form shaping to ensure the fit to each patient. In the proposed method, the workpiece is directly heated by a heater to the desired temperature, and then subsequently cut by a milling tool. This method is simpler than other thermally assisted machining processes, but still efficient because of the small size of the workpieces in the field of dentistry, where the whole workpiece must be heated. In a practical situation, the machinability must be predicted in advance to determine the proper machining conditions, including the workpiece temperature. In order to make such predictions, the machining phenomena occurring during the thermally assisted machining must be understood. In addition, the quantitative relationships between the workpiece temperature, the cutting conditions, and the resulting machinability must be characterized. In the present study, we conducted a series of straight-milling experiments to observe the machining phenomena and to obtain the quantitative relationships between the machining conditions and the machinability of Y-TZP using the proposed thermally assisted milling process.

2. Methods

We propose a thermally assisted process for machining Y-TZP that takes advantage of the decrease in fracture toughness at elevated temperature. In this process, the workpiece is heated by an external heat source and the heated area is subsequently removed by a cutting tool. The machinability of Y-TZP at elevated temperatures must be characterized to develop the thermally assisted machining process. In addition, the relationships between the cutting conditions and the machinability must be quantitatively determined.

2.1. Experimental setup

We conducted a series of straight milling experiments of Y-TZP in which the workpiece was heated to different temperatures using a heater. The experimental setup is shown in Fig. 1(a) and (b). The cutting conditions are shown in Table 1, where each of the four conditions have three levels. The cutting distance of each process was 20 mm. Square endmills were used that were made of tungsten carbide with a diameter of 2 mm and with two cutting edges (MS2MSD0200, Mitsubishi materials corporation, Tokyo, Japan) [Fig. 1(c)]. Y-TZP blocks with dimensions of 20 mm × 20 mm × 4 mm (NPZ-10, Nippon tungsten Co., Ltd., Fukuoka, Japan) were used [Fig. 1(d)]. A cylindrical heater with a diameter of 8 mm (Rayrod® super, Sakaguchi E.H Voc Corp., Tokyo, Japan) was placed under the workpiece. A force sensor (type 9272, Kistler Japan Co., Ltd., Tokyo, Japan) was used in combination with a charge amplifier (5070, Kistler Japan Co., Ltd., Tokyo, Japan) to measure the thrust force, the force in the feed direction and the torque. The sampling frequency of the force data collection was 1 kHz. Each process was monitored by a high-speed video camera (VW-6000, Keyence Corporation, Osaka, Japan) and a thermography device (InfRec R300SR, Nippon Avionics Co., Ltd., Tokyo, Japan). The surface temperature of the workpiece was measured and monitored using the thermography. The temperature variation along the thickness direction of the workpiece was considered to be so small that the distribution was assumed to be uniform along the sub-millimeter range of the depth of cut that was adopted in the experiments. A three-axis machining center (VM4, OKK Corporation, Hyogo, Japan) was used for the experiments.

Table 1
Machining conditions.

Workpiece temperature (°C)	26, 238, 450
Feed speed (mm/min)	5, 12.5, 20
Rotational speed (min^{-1})	1000, 1750, 2500
Cutting speed (mm/min)	6280, 10,990, 15,700
Depth of cut (μm)	0.1, 0.3, 0.5

2.2. Design of experiments

In order to understand how the machinability depends on machining conditions, the machinability was described as a second-order polynomial function of all four machining conditions: the workpiece temperature, the feed speed, the spindle rotational speed, and the depth of cut. This function is expressed in the following equation:

$$y = \sum_{i=1}^{4} \beta_i x_i + \sum_{i=1}^{4} \beta_{ii} {x_i}^2 + \sum \sum_{i<j=2}^{3} \beta_{ij} x_i x_j + \varepsilon \tag{1}$$

where y is the response such as the cutting force, tool wear, or surface roughness. x represents the machining conditions or factors. The coefficients β must be obtained through the experiments. The number of coefficients to be determined is $4 + 4 + \left((4 \times 3)/2\right) + 1 = 15$. Although at least 15 experiments must be conducted to determine all the coefficients, the minimum number of experiments does not guarantee the validity of the obtained coefficients. In order to obtain reliable values for each coefficient, the following things must be considered. The standard error $\text{Var}\left[\hat{y}(\boldsymbol{x})\right]/\sigma^2$ must be low even near the limits of the ranges of each machining condition, it must be possible to predict the pure error, and the lack of fit must be testable. In addition, the model needs to fit the measured values well, and must be robust against outliers. In order to obtain accurate models to predict machinability, we adopted a central composite design (CCD), which is a novel experimental design method [13]. The CCD method possesses the following characteristics. The CCD allows prediction of the interactions of two different factors. The repetition at the center of the range of the factors allows the pure errors and the lack of fit to be evaluated. The parameter sets possess rotatability, which means that the predicted variance is symmetrically distributed around the center of the parameter field. In this work, the experiment was designed to have 26 different sets of conditions, as shown in Table 2. The maximum