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Full Length Article

An atomic-scale and high efficiency finishing method of zirconia ceramics by using magnetorheological finishing

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ABSTRACT

Zirconia ceramics is a valuable crucial material for fabricating functional components applied in aerospace, biology, precision machinery, military industry and other fields. However, the properties of its high brittleness and high hardness could seriously reduce its finishing efficiency and surface quality by conventional processing technology. In this work, we present a high efficiency and high-quality finishing process by using magnetorheological finishing (MRF), which employs the permanent magnetic yoke with straight air gap as excitation unit. The sub-nanoscale surface roughness and damage free surface can be obtained after magnetorheological finishing. The XRD results and SEM morphologies confirmed that the mechanical shear removal with ductile modes are the dominant material removal mechanism for the magnetorheological finishing of zirconia ceramic. With the developed experimental apparatus, the effects of workpiece speed, trough speed and work gap on material removal rate and surface roughness were systematically investigated. Zirconia ceramics finished to ultra-smooth surface with surface roughness less than Ra 1 nm was repeatedly achieved during the parametric experiments. Additionally, the highest material removal rate exceeded 1 mg/min when using diamond as an abrasive particle. Magnetorheological finishing promises to be an adaptable and efficient method for zirconia ceramics finishing.

1. Introduction

Zirconia ceramics, as a new functional material, are widely used in aerospace, biology, precision machinery, military industry and other fields [1–3]. Excellent physical properties of the zirconia such as high hardness, small density, good insulation performance and thermal conductivity make it a valuable crucial material [4,5]. Not only such physical advantages but also mechanical advantages of wear resistance, anti-corrosion, anti-crush and heating resistant are bring a bright application future of zirconia in modern industry [6]. Owing to these excellent properties, zirconia ceramics has been widely used in fabricating component of the aero engine, inertial guidance missile, precision bearings and seals, and so on. This puts forward higher requirements for the surface processing of zirconia ceramic, which demands a high-quality surface with nanoscale roughness and without surface/subsurface damage simultaneously. However, due to the high brittleness and high hardness of zirconia ceramic materials, the finishing of such components has been faced a great challenge.

Developing finishing methods of zirconia ceramics have been raised numerous interests in recent years. Fiocchi et al. [7] reported that the ultra-precision U_d-lap grinding was capable of processing flat 3Y-TZP surfaces with nanometric finishing. The best surface roughness of R_a 60.63 nm can be obtained by using #300 grinding wheel dressed with U_d=5. Zheng et al. [8] established the cutting force model in ultrasonic vibration assisted grinding of zirconia ceramics. Through theoretical analysis and experiments, they found that cutting force was the main factor that affects the processed surface/subsurface quality. Although the machining efficiency of ultra-precision grinding was satisfactory, however, the nanoscale surface roughness could not be achieved and critical cracks were easy to generate [9]. The ultrasonic vibration assisted grinding can improve the surface quality, however, the grinding related defects such as scratches are still cannot be avoided [4]. Furthermore, the free abrasive assisted lapping is easy to cause surface/subsurface damages due to the application of a certain normal load during machining, and the processing efficiency is unstable [10,11].

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As a typical flexible finishing technology, magnetorheological finishing (MRF) takes advantages of extremely low normal force and very small cut induced by abrasives during machining, which can process out a high quality and damage-free surface [12]. In addition, constrained by the magnetic field, the slurry in the magnetorheological fluid is well-distributed on the interface of workpiece and MR ribbon stably, contributing to the continued and efficient material removal [13]. Hong et al. [14] introduced a wheel based MRF polishing process of alumina-reinforced zirconia ceramics, by using the electromagnet with arc air gap as the excitation unit. The fine roughness of Ra 1.96 nm can be obtained after 60 min finishing. The conventional wheel-based MR process made a significant impact on the fabricating of the nanometric precision surface. Nevertheless, the efficiency would become an issue towards the large surfaces machining due to the tiny material removal rate of the generated "MR polishing spot" in the process [14,15]. And the cost would be greatly increased for the use of raster tool path strategy to machining the large dimension workpiece.

The aim of this study is to develop a high efficient and high quality MRF process for flat zirconia ceramics surfaces. A permanent magnetic (PM) yoke with a straight air gap was employed as the magnetic excitation unit. This new type of the PM yoke can make the instantaneous finishing contact area considerably enlarged. The effects of different abrasives (diamond, ceria oxide, aluminum oxide) on the surface roughness were systematically investigated. The scanning electron microscopy (SEM) and X-ray diffraction (XRD) have been used to characterize the finished ground surface of zirconia ceramics. The results indicate that the diamond abrasive exhibited an excellent material removal ability without inducing surface damages in MRF process.

2. MRF apparatus and experimental details

2.1. The principle of MRF and experimental setup

As shown in Fig. 1, the workpiece is fixed on the fixture and can rotate with the B-axis, while the polishing trough is connected with the A-axis which rotates reversely with the B-axis. The magnetic excitation device is placed below the workpiece-axis (B-axis) whose distance from the workpiece can be adjusted, thus realizing the control of the strength of formed magnetic field. The whole device is fixed on the worktable of NC machining center, so that the polishing trough can move back and forth with the worktable along the X direction. A polishing pad is attached to the trough to increase the friction between the magnetorheological fluid and trough, making the MR fluid recyclable and updatable in the polishing disc. When the MR fluid flows over the gradient magnetic field, it will be stiffened to form a rectangular MR fluid ribbon within milliseconds. As a result, the CI particles will be arranged in a chain-like curve along with the magnetic line. Affecting by the magnetic field's gradient, the abrasives in MR fluid will float upward and assemble gather in the interface of workpiece surface and MR fluid ribbon. Then, the abrasive grains will be pressed into the workpiece surface by the pressure of MR ribbon. Material removal occurs when the abrasive grains move relative to the workpiece surface. The continuous renewed abrasives will continuously wipe workpiece surface, thus ensuring the sustainable and stable material removal during finishing process.

In order to increase the contact area between the MR ribbon and workpiece, the PM yoke with a long straight air gap was used in this study, as shown in Fig. 2(a). The novel developed magnetic excitation system mainly consists two permanent magnets made by N50 grade NdFeB and electrical pure iron (DT4). There is a long straight air gap between two N50 magnets, which the straight gradient magnetic field will form above the air gap because of magnetic leakage. The experimental apparatus mainly consists of lapping machining, speed governor, PM yoke and fixture, as shown in Fig. 2(b).

2.2. Materials and characterization

The flat zirconia ceramics sized in $40 \times 40 \times 1.1\ mm^3$, purchased from Shenzhen Hard Precision Ceramic Co., Ltd. (China), were used to carry out the parameter experiments. The CIPs with the average particles size of 3.2 μm and density of 7.87 g/cm^3 were purchased from BASF (Germany) with OP series. Abrasive powders of diamond, Al_2O_3 and CeO_2 (average particles size: 3.2 μm) were applied by ChangSha Xinhui Technology Co., Ltd. (China). The properties of zirconia ceramics are shown in Table 1.

The initial surface roughness of flat zirconia ceramic is about Ra 70–100 nm. All of the finished workpieces were ultrasonically cleaned up with acetone, absolute ethanol and deionized water, successively. Subsequently, the finished specimen was dried up. In order to obtain the material removal rate, the flat zirconia ceramics was weighted before and after finishing by using electronic balancer with a high resolution of 1 mg. Thus, the difference between two weights represents the mass removed during MRF process. Therefore, the material removal rate (*MRR*) can be calculated according to the following equation:

$$MRR = \frac{10^3 \times \Delta m}{t} \quad (1)$$

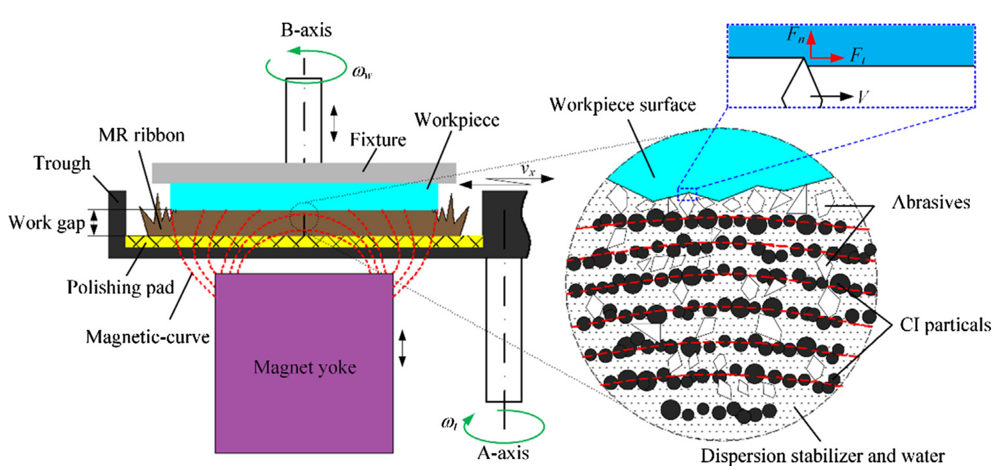

Fig. 1. The schematic diagram of planar magnetorheological finishing of zirconia ceramics.