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Study on Critical Ductile Grinding Depth of Nano ZrO_2 Ceramics by the Aid of Ultrasonic Vibration

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Abstract. The crack extension course and ductile removal mechanism of nano ZrO_2 ceramics were analyzed in this paper. On the basis of contrast tests with or without ultrasonic vibration, the influences of critical ductile grinding depth on grinding forces and surface quality were studied by dynamometer, SEM and AFM in different grinding condition. The reason for the increase of the critical grinding depth was discussed based on the analysis of grinding force and ultrasonic vibration course. At last, the formation mechanism of surface topography observed by AFM in ductile domain was analyzed. The research indicated that ultrasonic machining could obtain nano finished surface with high efficient.

Introduction

Nano ceramics possesses excellent mechanical property and physical characteristics in contrast to conventional engineering ceramics, so it has tremendous application prospect. Ductile domain grinding technique is one of primary machining method for nano ceramics in ultra-precision machining. All hard brittle material will be removed with plastic flow instead of brittle fracture in a situation that the grinding depth is small enough [1]. Its critical ductile grinding depth could be described by a simple energy principle equation as the following [2].

$$d_c = \xi\left(\frac{E}{H}\right)\left(\frac{K_C}{H}\right)^2 \qquad (1)$$

Where ξ is Coefficient of different materials, E is Young's modulus, Kc is fracture toughness, and H is Vickers hardness. *Bifano* defined that the fracture rate of the grinding surface less than 10% is ductile grinding. When grinding depth a_p is less than or equal to d_c, ductile grinding can be available for hard brittle material. Eq.1 shows that critical ductile grinding depth is only involved with material characteristic. But, in fact, it also involved with processing method and parameter.

Only by the discovery of grinding mechanism, can the grinding technology optimization be obtained [3]. In ultrasonic vibration grinding, microstructure analysis of the damaged surface due to the high frequency dynamic impact of an abrasive particle indicates the presence of two phenomena that contribute to material removal: the deformation at the point of impact and the brittle structure below the impact zone [4]. From the dynamic impact tests, material removal in the ultrasonic machining process is due to the effect of the impact velocity. At higher impact velocity, material is removed by a network of intergranular microcracks and form the propagation of lateral and median cracks. These cracks merge at the surface dislodging sections of the material and then form grinding surface. In ultrasonic grinding, workpiece is impacted by the high frequency and high-energy which will produce many microcracks. Owing to the randomness of abrasive grains, when the crackle has not been expanded to the deep level, the impact of high frequency makes the crackle change

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expanding direction and makes it no time for the brittle material to fracture, and thus induces the material continue to be removed in ductile mode. So it will increase critical ductile grinding depth.

The Experimental Conditions and Method

The experimental device of ultrasonic vibration grinding is shown in Fig.1. The grinding machine was precision instrument grinder. The material of the workpiece is nano ZrO_2 ceramics. The Vickers-hardness is 12Gpa, the Young's modulus is 360Gpa, the bending strength is 600-700Mpa, the fracture malleability is 9.0-9.3Mpa.m$^{1/2}$, the density is 3.96 - 3.99g/cm^3 and grain size is 50-60 nm. The values of surface roughness were averaged from six points normal to groove mark of the surface with JJ1-B contact stylus roughometer. The microstructure of surface was observed by SEM and AFM (the type is CSPM2000, X-Y direction resolution is 0.13nm, and Z direction resolution is 0.01nm), and the grinding force was measured by a strain-gauge dynamometer (SDC-CJ4A) mounted under the support plate. The ultrasonic vibration was automatically controlled around a frequency of 20 KHz and the amplitude of vibration was hold at 12μm. The diamond wheel was dressed (profiled by #200SiC block, sharpened by #400Al_2O_3 block). Turning the support board of the ultrasonic vibration device could test the effect of different vibration direction on grinding character.

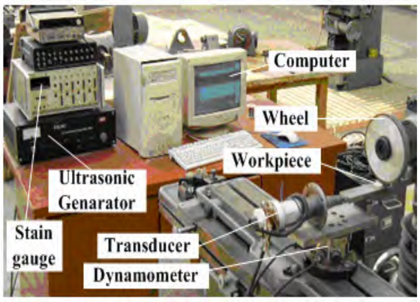


Fig.1 Test field

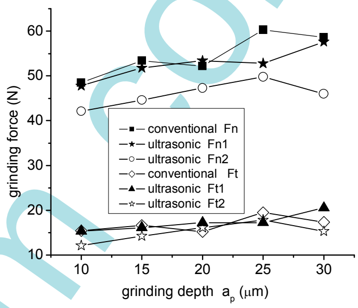


Fig.2 The effect of the grinding depth on the grinding force

Experiments and Discussions

Effect of Grinding Force on Critical Ductile Grinding Depth. Fig.2 shows the relation of grinding depth and grinding force generated at a wheel speed of 51m/s and the grit size of 350#, where Fn_1, Ft_1 is the grinding force when the vibration direction parallel to the speed of wheel and Fn_2, Ft_2 is the grinding force when vibration direction normal to the speed of wheel. The grinding force increases with the grinding depth. In the conventional grinding, grinding force reaches the maximum then has a trend of decreasing when the grinding depth up to 15μm. Fluctuation of grinding force is observed when the grinding depth reaches to 20μm, at the same time, brittle grinding is observed at the surface of workpiece, and the grinding temperature increases significantly. So we can say that critical grinding depth is 15μm at this moment. And the same result will be obtained in the ultrasonic vibration grinding, the critical grinding depth is about 25μm when vibration direction normal to the speed of wheel and the critical grinding depth is about 20μm when vibration direction parallel to the speed of wheel. Whether in ultrasonic or conventional grinding, grinding force decreases significantly when grinding model turns from ductile grinding to brittle grinding. Grinding force remarkable decrease is the first reason why the ultrasonic machining increases ductile grinding depth [5].

The Relation of Surface Quality and Critical Ductile Grinding Depth. Fig.3 shows the effect of the grinding depth on surface quality, where Ra_1 is the surface roughness when the vibration direction parallel to the speed of wheel and Ra_2 is the roughness when vibration direction normal to the speed of wheel. From Fig.3, the surface roughness has a trend of increasing with the grinding depth rising, and the surface roughness rises very slowly in the scope of critical ductile grinding depth, but the surface roughness increases sharply when the grinding depth is above the critical value. Fig.4 is the surface of conventional grinding at a grinding depth of 10μm in ductile grinding model. Fig.5 is an ultrasonic ductile grinding surface which vibration direction is normal to the speed of wheel at a grinding depth of 15μm. It can be seen that the surface roughness is still better than the one in conventional grinding and the groove is wider and deeper than the one in conventional grinding. From above, the critical ductile grinding depth in ultrasonic vibration is deeper than that in conventional grinding, so we can obtain precision surface by using ultrasonic vibration grinding with high efficiency.

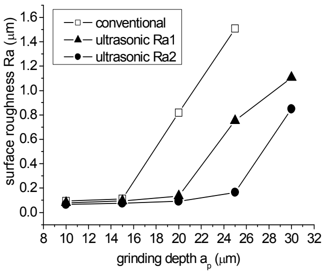


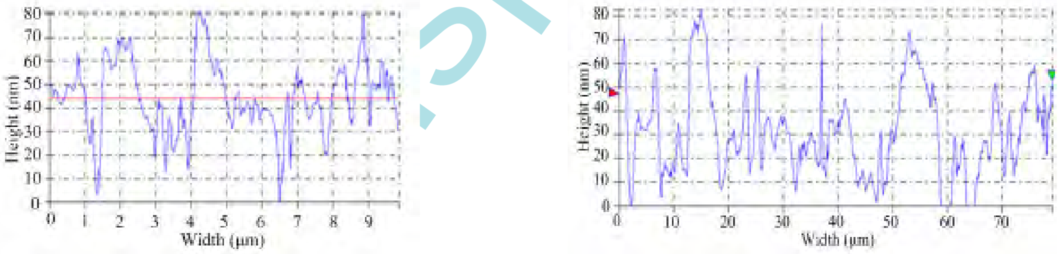
Fig.3 The effect of the grinding depth on the surface quality

Fig.4 The conventional grinding surface (a_p=10μm)

Fig.5 The ultrasonic grinding surface (a_p=15μm)

(a) The surface of ultrasonic vibration grinding (b) The surface of conventional grinding

Fig.6 The 3D plot of the ultrasonic and conventional ductile grinding surface (a_p=10μm)



(a) The profile of ultrasonic ductile grinding (b) The profile of conventional grinding

Fig.7 The profile of the ultrasonic and conventional ductile grinding surface

Fig.6 shows the 3D plot of the ultrasonic and conventional ductile grinding surface with the same machining parameter which was examined with AFM. From the Fig. 6(a), the surface of workpiece is in a ductile grinding state and there are very few peaks and its grooves uniformly. By contrast, in conventional grinding (as shown in Fig. 6(b)), there are many peaks, non-uniform grooves and local ruptures in the workpiece surface. Fig.7 is 2D sub-region profiles of Fig. 6. We can clearly see the microscopic cross-section of the workpiece surface. The maximum distance between ridge and valley is about 75nm, and the average distance among ridges is about 2μm, the surface roughness Ra is about 65nm in Fig.7 (a). But in Fig.7 (b), the maximum distance between ridge and valley is about 85nm, and the average distance among ridges is about 300nm, the surface roughness is about 0.1μm. Therefore the surface quality and critical ductile grinding depth of hard brittle material could be improved by the aid of ultrasonic machining.

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Fig.8 is the 3D plot which is machined by ultrasonic ductile grinding in different vibration directions. There are no traces of rupture such as microcrack and breaking etc. The traces of grinding, the minute shear mark of cutting lip, the steps of grain boundary and the minute protuberant panorama can be seen clearly. The roughness of surface in Fig. 8(a) is larger than that of Fig.8 (b), the Zr particle (approved by energy spectrometer analyse) on the surface of workpiece appreciably extruded, and the grain boundary is very obvious in Fig.8 (a). The machined surface of the two kind of workpiece all have been formed by plastic shear mechanism of ductile grinding. The steps of these horniness particle boundaries are the main factor for controlling the roughness of ceramics crystal surface. The extrusive particle is smaller and the surface occurs tiny concaveconvex change when the vibration direction normal to the speed of wheel. The micro-protuberance has been overlaid by the nick of grinding lip when the vibration direction normal to the speed of wheel, so there are many micro shear marks on the surface. From above observation, It can be considered that the surface roughness of ultraprecise grinding is the superposition result by multi-waveform with different amplitude. These waveforms have regularity in the mar of abrasive particle and micro mar of cutting lip. However, there are nuances in microcosmic grain boundary step and micro protuberance with different direction. These waveforms are the major factors that control surface roughness of machined surface.

(a) Vibration parallel to the speed of wheel (b) Vibration normal to the speed of wheel

Fig.8 The 3D plot of the ultrasonic ductile grinding surface with different direction (a_p=5µm)

Conclusions

Ultrasonic machining could remarkable increase critical ductile depth of hard brittle material, and it could obtain ultra-precision surface with high efficiency. The reduction in the grinding forces is believed to be one of the main reasons for the increase in the critical depth of grinding.

From experiment it is found that the critical ductile depth of nano ZrO_2 ceramics in conventional grinding is about 15µm. The critical grinding depth in ultrasonic vibration grinding has related with vibration direction. When vibration direction is normal to the speed of wheel, the critical ductile depth of nano ZrO_2 ceramics is about 25µm, and when vibration direction is parallel to the speed of wheel, the critical ductile depth is about 20µm.

Over critical grinding depth of the workpiece, the grinding force will decrease, and then bouncing phenomenon appears, the value of surface roughness will dramatically increase. Ultra-precision grinding surface was the result superimposed by different amplitudes and multiple waveforms.

Acknowledgments

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