

## Study on Surface Quality of Nano ZrO<sub>2</sub> Ceramics in Grinding by the Aid of Ultrasonic Vibration

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**Abstract.** Nano ceramics possesses excellent mechanical property and physical characteristics in contrast to conventional engineering ceramics, so it has tremendous application prospect. Adopting ultrasonic composite processing we describe the influences of grinding speed, grinding depth, wheel granularity and no-spark grinding times on the surface roughness of nano ZrO<sub>2</sub> ceramics. By means of SEM and AFM the surface character and critical ductile grinding depth of nano ZrO<sub>2</sub> ceramics in the condition of conventional and ultrasonic grinding are also discussed. At last, the residual stress of surface and crystalline phase transformation under the condition of conventional grinding and ultrasonic vibration grinding were analyzed by X-ray diffraction. The research indicated that ultrasonic vibration grinding could obtain nano finished surface with high efficiency. The residual stress of nano ZrO<sub>2</sub> ceramics surface is determined much by different grinding styles.

### Introduction

Engineering ceramics, also called structure ceramics, has been applied widely for their merits of high hardness, light quality, resistant to high temperature and abrasion. But engineering ceramics has some shortages such as large brittle, bad uniform, low reliability, less malleable and intensity etc, so their application is limited. English scholar *Cahn* pointed out that nano ceramics were the strategic path to overcome the brittleness of ceramics [1]. Ductile domain grinding technique is one of primary processing method for nano ceramics ultraprecise machining, but its primary problem is lower grinding efficiency. Ultrasonic vibration will change ductile domain removal mode of hard brittle material, and enlarge machining range of ductile domain which makes high efficient ultraprecise machining of nano ceramics material simple and feasible. The residual stress of surface is a very important factor in the applying performance of hard brittle material. Grinding cracks of ceramics surface is much related to the surface quality, and residual stress of surface is a prime method for analyzing the cracks [2]. At present, many researches are being done on the residual stress of grinding ceramics, but the distribution of residual stress is less studied in the condition of ultrasonic vibration grinding especially the surface residual stress of nano ceramics grinding. In this paper, it is studied mostly that the surface quality of nano ceramics in condition of ultrasonic vibration grinding and the effect of different grinding styles on residual stress of nano ceramics.

### The Experimental Conditions and Method

The grinding machine was precision instrument grinder. The material of the workpiece is nano ZrO<sub>2</sub> 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<sup>1/2</sup>, granularity is 50-60 nm and the density is 3.96~3.99g/cm<sup>3</sup>. The values of surface roughness were measured by 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). The residual stress was measured by X-ray stress diffractometer (the type is D8 Dicover With GADDS). Ultrasonic generator which has an ability of frequency automatic tracking. The ultrasonic vibration was automatically controlled around a frequency of 20 KHz and the amplitude of vibration was hold at 12 $\mu$ m. The abrasive wheel was dressed (profiled by #200SiC block, sharpened by #400Al<sub>2</sub>O<sub>3</sub> block). Turning the support board of the ultrasonic vibration device could test the effect of different vibration direction on grinding character.

## Experiments and Discussions

**The Effect of Grinding Speed on Surface Roughness.** Fig. 1. shows the effect of the wheel speed on the surface quality. From the Fig.1, when the linear speed of the wheel increases, the roughness of grinding surface tends to reduce. The wheel linear speed has a great influence on surface roughness in convention grinding. The value of surface roughness is much lower when vibration direction is vertical to the wheel speed than the one when vibration direction is parallel to the wheel speed. The roughness of grinding surface tends to reduce along with increasing of the wheel speed, the possible reason is that the cutting burthen of the single grain is low and breaking depth of wokpiece surface reduces with increasing of the grinding speed.

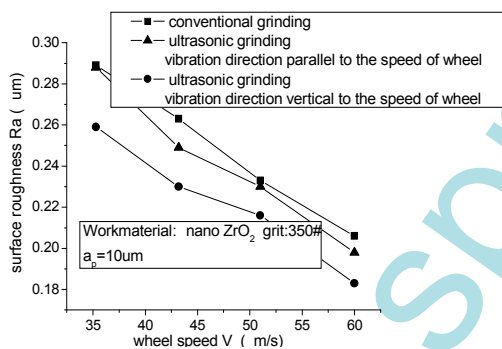


Fig.1 The effect of the wheel velocity on the surface roughness Ra

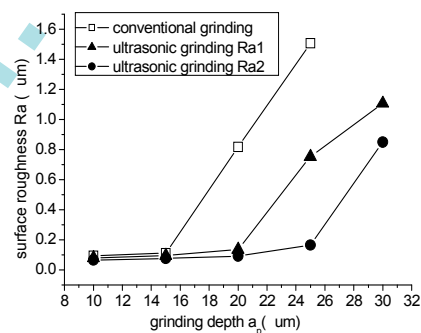


Fig.2 The effect of the grinding depth on the surface roughness Ra

**The Effect of Grinding Depth on The Surface Roughness.** In ultra-precision machining, it is believed that grinding depth has the direct relation to grinding efficiency, but the surface quality will descend as grinding depth increases [3]. Fig.2 shows the effect of the grinding depth on surface quality, where Ra<sub>1</sub> is the surface roughness when the vibration direction is parallel to the speed of wheel and Ra<sub>2</sub> is the roughness when vibration direction is normal to the speed of wheel. From Fig.2, with the increase of grinding depth, the surface roughness of convention and ultrasonic grinding all have an increscent trend. In conventional grinding, the surface roughness increases sharply when the grinding depth is above 15 $\mu$ m. Concaves on workpiece surface are obvious observed, and brittle destruction appears on workpiece surface as shown in Fig.3. From above, it is estimated that the critical grinding depth is about 15 $\mu$ m in this situation. And the same result will be obtained in the ultrasonic vibration grinding, the critical grinding depth is about 25 $\mu$ m when vibration direction is normal to the speed of wheel and the critical grinding depth is about 20 $\mu$ m when vibration direction is parallel to the speed of wheel. The critical ductile grinding shape is shown in Fig.4 when vibration direction is vertical to wheel speed, and a few traces of brittle destruction can be observed on the grinding surface. Fig.5 is the surface of conventional grinding at a grinding depth of 10 $\mu$ m in ductile grinding model. Fig.6 is an ultrasonic ductile grinding surface which vibration direction is normal to the wheel speed at a grinding depth of 15 $\mu$ m. It can be seen that the vein of surface is still better than the one in conventional grinding. From above, the critical ductile grinding depth in ultrasonic

vibration grinding is much greater than that in conventional grinding, so we can obtain precision surface by using ultrasonic vibration grinding with high efficiency.



Fig.3 Conventional grinding ( $a_p=15\mu\text{m}$ )

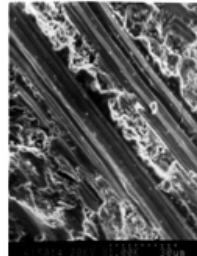


Fig.4 Vibration grinding ( $a_p=25\mu\text{m}$ )



Fig.5 Conventional grinding ( $a_p=10\mu\text{m}$ )



Fig.6 Vibration grinding ( $a_p=15\mu\text{m}$ )

**The Effect of Wheel Granularity on Surface Roughness.** From Fig.7, the surface roughness value gets lower obviously with the decreasing of wheel granularity. The effect on surface roughness in ultrasonic vibration grinding is less than that in conventional grinding by using very fine grains. Resin combined wheel is used in the experiment; therefore, the surface quality depends on directly whether the wheel is blocked up or not. The surface roughness in ultrasonic vibration grinding is better than that in conventional grinding, because the very high acceleration in ultrasonic vibration grinding makes the block-up in wheel surface difficult to form.

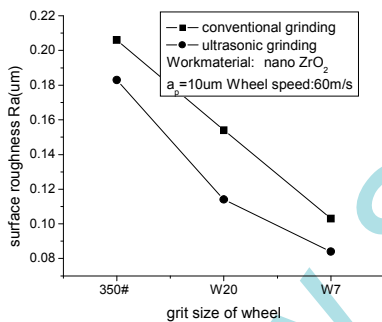


Fig.7 The effect of the wheel granularity on the surface roughness

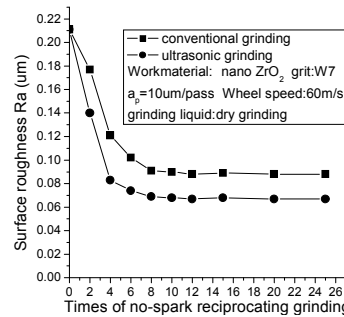


Fig.8 The effect of the times of no-spark reciprocating grinding on the surface roughness

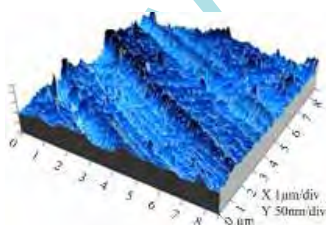


Fig.9 The 3D plot after no-spark grinding 4 times with ultrasonic vibration

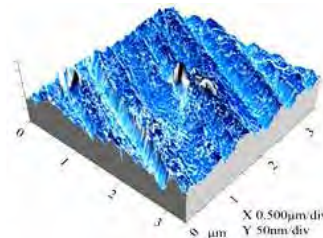


Fig.10 The 3D plot after no-spark grinding 6-10 times with ultrasonic vibration

**The Effect of the No-spark Grinding Times on Surface Roughness.** Fig.8 shows that the surface roughness reduces with increasing of no-spark grinding times. The surface roughness will achieve its minimum 88nm when the no-spark grinding times reaches 12 in conventional grinding and afterward the surface roughness will not change with increasing of no-spark grinding times. But in ultrasonic vibration grinding, the surface roughness decreases quickly by using the same no-spark grinding times as that in conventional grinding, and the surface roughness achieves its minimum 60nm when the no-spark grinding times reaches 6-10. Then the roughness remains constant with increasing of grinding times. Fig.9 shows that the surface of nano  $\text{ZrO}_2$  ceramics has obtained the

level of nanometer after no-spark grinding. The value of surface roughness Ra is about 65 nm by the measuring of AFM. Fig.10 shows that the surface sharp peaks lessening obviously and the channel mark being narrower and shallower after no-spark grinding for 6-10 times, and its surface roughness Ra is about 60 nm. From above, no-spark grinding times are imperative to ameliorate surface roughness Ra of ceramics.

**Study on the Surface Residual Stress of the Ultrasonic Vibration Grinding Nano ZrO<sub>2</sub> Ceramics.** During the process of grinding, the surface residual stress has a great influence on machining quality and breaking strength of the workpiece. The residual stress of the specimen is measured by the means of  $\sin^2 \psi$  [4]. When the value of  $2\theta - \sin^2 \psi$  is got, a line whose slope M could be fitted by the above values. So the residual stress could be computed as follows [5].

$$\sigma = \left[ -\frac{E}{2(1+\gamma)} \cot \theta_0 \cdot \frac{K}{180} \right] \cdot M \quad (1)$$

$\theta_0$  – Bragg angle

$E \cdot \gamma$  – elastic modulus and Poisson's ratio

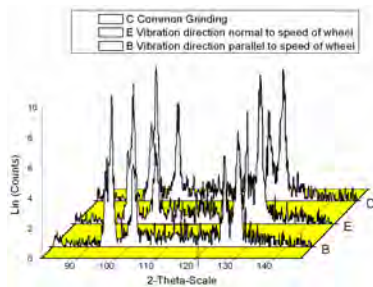


Fig.11 XRD spectra chart of ceramics surface under different grinding conditions

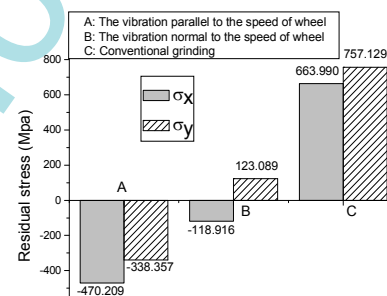


Fig.12 The effect of grinding method on residual stress

The influence to residual stress of nano ZrO<sub>2</sub> ceramics surface varies much by adopting different grinding styles. The XRD diffraction spectrum of the surface which is got by different grinding styles is showed in Fig 11. The residual stress of specimen surface is obtained by analyzing X-ray diffraction angle of different inclination angel  $\psi$  to the sample surface. The surface residual stress distribution of different grinding styles are shown in Fig 12. Three states of grinding are all in the field of ductile grinding in Fig.12 and the grinding depth is 10 $\mu$ m. Fig.12 mark A is the residual stress of the sample surface when the vibration direction is parallel to the wheel speed and Fig.12 mark B indicates that of the sample when the vibration direction is vertical to the wheel speed. Fig.12 mark C is the residual stress of the sample surface in the condition of convention ductile grinding. Of which,  $\sigma_x$  is the residual stress which parallel to grinding direction while  $\sigma_y$  is residual stress which vertical to grinding direction. During the convention grinding,  $\sigma_x$  and  $\sigma_y$  of nano ZrO<sub>2</sub> ceramics surface are both tensile stress. But *Katsumi* et al [6] got the compression stress when they measured common ZrO<sub>2</sub> ceramics grinding surface by way of XRD, the cause maybe pertinent to various aspects as follows: the size and distance of crystal lattice, the phase transformation of nano ceramics in the real experiment. For common ZrO<sub>2</sub> ceramics, its granularity is about micron, and its rapture extends mainly along the crystal lattice fracture. While, for the nano ZrO<sub>2</sub> ceramics which is sintered by use of nano grains, the rapture mode mainly is transgranular fracture. For the nano ZrO<sub>2</sub> ceramics which is made by vacuum heat pressing, both intergranular and intracrystalline structures exist in it. Two apparent effects could be emerged due to the co-action of the two structures: transgranular fracture and multiple crystal boundaries. The form of interior-crystal structure can strengthen the crystal boundary and ameliorate stress distribution. Besides, hypo-boundary which is formed by intergranular structure can contribute much to the improving of mechanical performance. High stress



emerges in the hypo-boundary because of the distribution of heated expansion coefficient and elastic modulus between the matrix and nano phase, therefore, many new dislocations and various dislocation configurations come into being as a result of stress concentration. So in conventional grinding of nano  $ZrO_2$  ceramics, main cracks may expand along intracrystalline rather than along crystal boundary which is extended mode of common  $ZrO_2$  ceramics, thus, residual tensile stress is produced in the surface.

In ultrasonic vibration grinding, high frequency vibration is performed on the workpiece, so, the grinding process is not continuous and the grinding temperature decreased much. Besides, a little machining distortion are emerged around blades of grain which makes crystal grain organization changes little in the surface and has almost the same organization as that in the interior of workpiece. Therefore, machining deteriorative layer becomes very thin which caused minor residual compressive stress obtained in the surface ultimately. The influence to residual stress varied with different vibration direction. Compressive stress is obtained in the surface when the vibration direction is parallel to wheel speed and the absolute value of residual stress decreases much when vibration direction is vertical to wheel speed, where  $\sigma_x$  is compressive stress and  $\sigma_y$  is tensile stress. The cause is that grinding force which vibration direction is parallel to wheel speed is greater than the one which vibration direction is vertical to wheel speed, besides, grinding temperature is much higher which causes the phase transition stress of  $t-ZrO_2 \rightarrow m-ZrO_2$ . Local bulk will change as a result of the emerging of phase transition stress and thus compressive stress increases.

### Conclusions

The roughness of grinding surface tends to reduce along with the increasing of the linear speed. In ultrasonic vibration grinding, the effect of wheel linear speed on surface roughness is not as dramatic as that in conventional grinding. Ultrasonic machining could remarkable increase critical ductile depth of hard brittle material, and it could obtain ultra-precision surface with high efficiency.

In ultrasonic vibration grinding in which vibration direction is vertical to wheel speed, the surface quality is still better than the one in which vibration direction is parallel to wheel speed. The influence of wheel granularity on surface quality is profound. In order to obtain ideal roughness, it is imperative to perform no-spark grinding on workpiece, and no-spark grinding times should be 6–10 optimally.

Surface residual stress is tensile when nano  $ZrO_2$  ceramics is ground in traditional method. Compressive stress is obtained on the surface when vibration direction is parallel to wheel speed and the value of residual stress decreases much when vibration direction is vertical to wheel speed, where  $\sigma_x$  is compressive stress and  $\sigma_y$  is tensile stress.

### Acknowledgments

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