Experimental Study on Two-Dimensional Ultrasonic Vibration Grinding of Fine-crystalline Zirconia Ceramics

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Abstract: The grinding performances of zirconia ceramics in workpiece two-dimensional ultrasonic vibration grinding (WTDUVG) and conventional grinding (CG) with diamond wheel were researched experimentally in this work. The effects of WTDUVG on material removal rate, grinding forces, surface microstructures of zirconia ceramic were investigated. Experimental results indicated that: (1) Material removal rate in ultrasonic grinding process is two times as large as that of in conventional grinding. (2)Ultrasonic vibration grinding possessed a much lower main grinding force than that of in CG and the increase in the worktable velocity leaded to a decrease of the grinding force but the grinding force increasing with increasing the grinding depth in WTDUVG and CG. (3) Ultrasonic vibration grinding surface had no spur and build-up edge and its roughness was smaller than CG significantly. (4)Phase transition of ZrO_2 ceramics grinding surface under CG and vibration grinding were analyzed by X-ray diffraction. Researches indicated that two-dimensional vibration grinding could obtain nano finished surface with high efficiency, the phase transition of grinding surface is determined much by material removal mechanism. The paper supplied the theoretical and experimental basis for the grinding of the WTDUVG of ZrO_2 ceramics.

Introduction

ZrO_2 ceramics have attracted attention owing to its outstanding physical, mechanical properties and high wear-resistance, good erosion-resistance. But the fatal brittleness still exists in these materials, and the mechanical reliability is also low. The fine crystalline ceramics was researched popularly at present. Particularly, the fine crystalline ZrO_2 ceramics show a remarkable enhancement of toughness and strength with respect to common ZrO_2 ceramics. Ultrasonic vibration machining has impressed many people with its fine properties of high quality and high precision in machining ceramics. The material removal mechanism, grinding force and surface quality in vibration grinding of ceramics has been widely discussed, but these study concentrated at wheel vibration grinding[1-3], Document 4 discussed the material removing problem on different combined condition when ultrasonic vibration applied to cutter from different direction. In the world, researches mostly focus on elliptical vibration cutting mechanics and its machining effect [5-8], but there were few researches on workpiece two-dimensional vibration grinding research. Based on a series of grinding experiments, some rules of MRR, grinding force and surface Morphology were investigated, According to the acquired data and machining parameters, grinding surface microstructure were discussed in grinding with and without vibration.

Mechanism of two-dimensional ultrasonic vibration grinding

Effect of high frequency modulation on kinematics. A schematic illustration of two-dimensional ultrasonic vibration grinding is shown in Fig.1. The ultrasonic vibration with some amplitude and frequency is applied to workpiece from x, y directions , so the displacement equation of particle A in the workpiece is:

$$\begin{cases} x(t) = A\cos(2\pi ft) + vt \\ y(t) = B\cos(2\pi ft + \varphi) \end{cases} \quad (1)$$

Where, A and B are the two-dimensional vibration amplitudes in x- direction and y-direction respectively, f is the vibration frequency. According to Fig.2, the grain relative motion locus of elliptical spiral in two-dimensional ultrasonic vibration grinding is defined initially , L_T is the offset of workpiece in a vibration period.

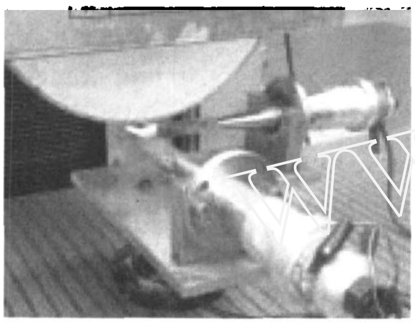


Fig.1. Illustration of the experimental set-up

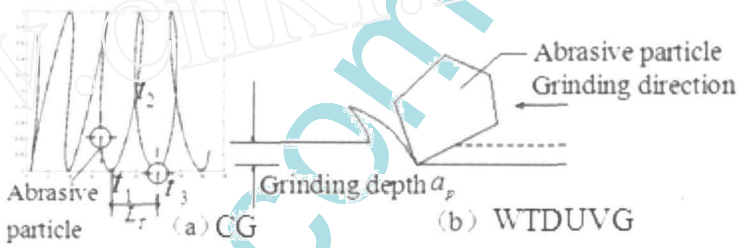


Fig.2. Diagram of a abrasive particle cutting locus in both WTDUVG and CG

Experimental Conditions and Method

Grinding experiments were conducted on a surface grinder GTS6016. The acoustic system was developed with local resonance, and the vibration amplitude plate was employed in the system, the ultrasonic vibration was automatically controlled around a frequency of 20.237 kHz and the amplitude of x,y direction vibration were hold at 11.98μm and 10.22μm.The material removal mass in ultrasonic grinding ZrO_2 was measured by electric balance compared with the traditional method. Workpiece was weighed every 20-minute grinding. Grinding forces were measured by means of an ultraprecision dynamometer SDC-CJ3SA, the outputs of the dynamometer was fed into an AD converter and sampled at a high frequency by a PC. The grinding surface microstructure was observed by AFM (the type is CSPM2000). The phase transformations were measured by X-ray stress diffractometer (the type is D8 Dicover with GADDS).The properties of the ceramics was listed in the Table. 1.

Table 1 Properties of ceramics usd in the experiments

Ceramics	Flexible strength[MPa]	Fracture toughness[MPa·$m^{1/2}$]	The Vickers hardness[GPa]	The grain size of material [nm]	Density [g/cm ^{3}]
ZrO_2	1150	8	11.1	500	5.71

Experimental results and analyses

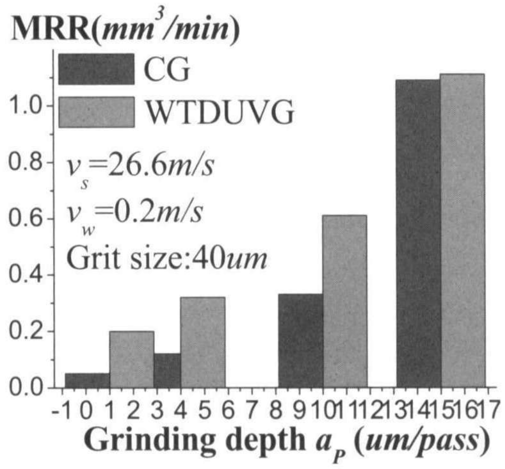


Fig.3. Grinding depth versus MRR

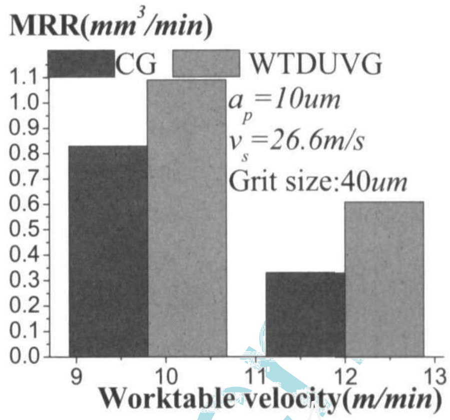


Fig.4. Worktable velocity versus MRR

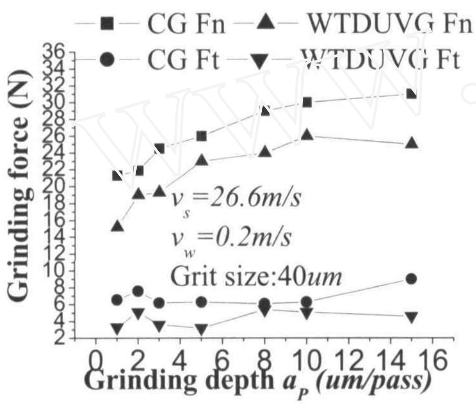


Fig.5. Grinding depth versus grinding force

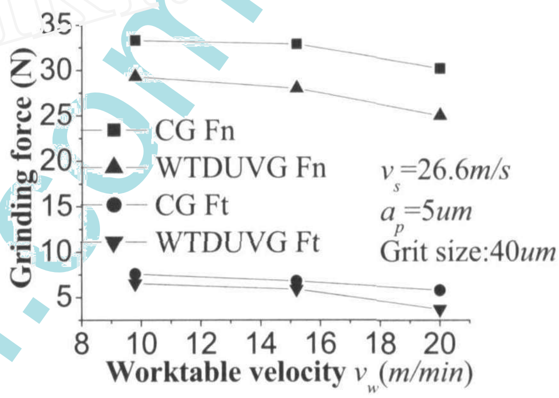


Fig6. Worktable velocity versus grinding force

Influence of grinding depth on MRR. As shown in Fig.3, during the conventional grinding (CG) process material removal rate increases along with the grinding depth, which is involved from that the bigger linear velocity makes the friction between workpiece and wheel intense per unit time and number of effect grains increase. The rule is the same in ultrasonic grinding, but the material removal rate is two times as large as that of conventional grinding. The high grinding efficiency results from the fact that the grains, vibrating with high frequency and certain amplitude, make one side of themselves contact workpiece discontinuously during most of grinding time. Therefore the decrease of friction serves not only for the drop of grinding force, but the improvement of temperature condition in the grinding area. And the effect of the acoustic cavitation of cooling emulsion and peening of detached grains contributes to material removal.

As shown in Fig.4, it can be seen that both the MRR of in WTDUVG and CG will decrease with the increase of worktable velocity.

Influence of the Grinding depth on grinding force. From Fig.5, the grinding force is seen to be sensitive to the change of grinding depth. The curves also show that the value of the normal force in WTDUVG is about 20%～30% less than that in CG. The grinding force in WTDUVG and CG reaches maximum and then trends to reduce when grinding depth reaches 10μm/pass. Later, grinding force shows the phenomenon of fluctuation. The brittle fracture mechanism is the model of material removal, the brittle fracture pull out increase with the increase of grinding width. Low grinding force means large depth of grinding and more brittle fracture. The variation of grinding force in WTDUVG is seen to be sensitive to material removal mechanics.

Influence of the Worktable velocity on grinding force. From the Fig.6, it can be seen that both the force of in WTDUVG and CG will decrease with the increase of worktable velocity. The normal force reduces quickly and tangential force changes very slowly with increasing of worktable velocity in the CG. But in the WTDUVG, the normal force and tangential force have not changed remarkably. The grinding force in WTDUVG is lower than that of CG, the normal force of WTDUVG is remarkable decrease.

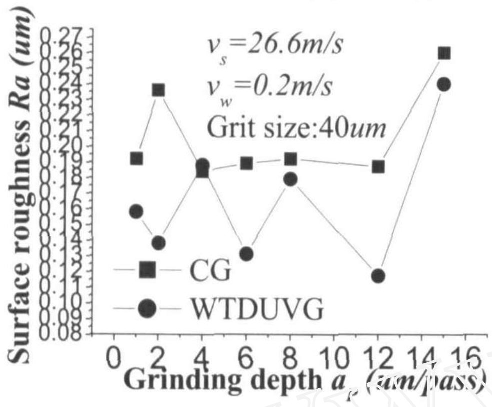


Fig.7. Surface roughness versus a_p

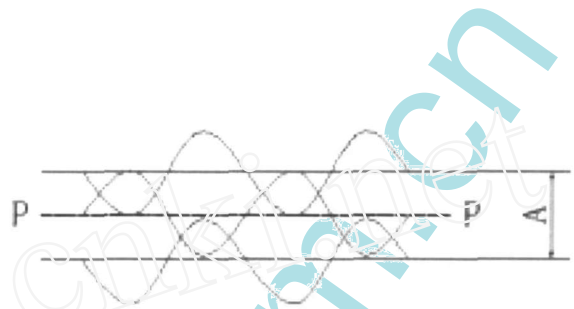
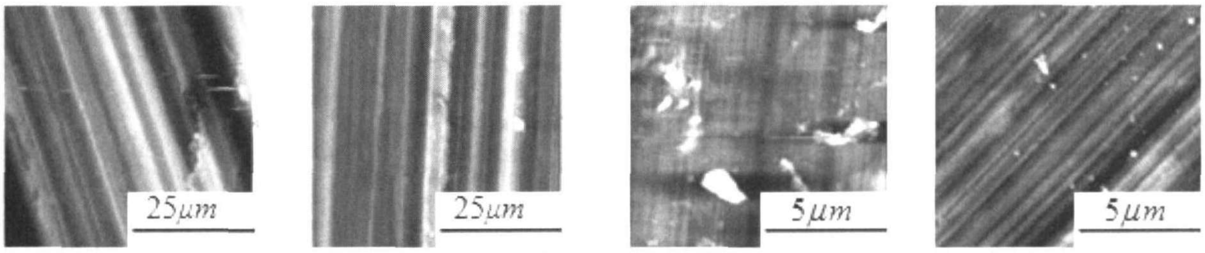


Fig.8. Interference in the crossfeed direction partical in WTDUVG

Influence of Grinding depth on the Surface roughness. As shown in Fig.7, along with the grinding depth the value of the surface roughness both in WTDUVG and CG increases. The surface roughness increased dramatically when grinding depth reaches 12*μm*/pass, the brittle fracture mechanism is the model of material removal. The curves also show that the average value of the surface roughness in WTDUVG is about 20% less than that in CG.

Surface Morphology. AFM images of grinding surface after CG and WTDUVG are shown in Fig.9. After coarse grinding [Fig.9(a) and (b)] show evidences of brittle fracture and ductile, and among the smooth areas are rough patches and holes from pull-out of material by fracture. By the section analysis of AFM, the widths of the conventional grinding grooves in the plastic regions are equal at 4～5*μm*, but the average widths of the grooves under WTDUVG are equal at 8*μm*, which is the reason of efficient material removal of WTDUVG. And the surface roughness of CG is 234.35nm and the surface roughness of WTDUVG is 145.32nm. After polishing with 3.5*μm* diamond grit[Fig.9(c) and (d)], the surface of CG and WTDUVG is dominated by ductile mechanism, some light scratches are visible and there is almost no grain pull-out or fracture, the surface roughness of with vibration grinding is 13.214 nm and the surface roughness of CG is 14.356nm.

Experimental results show that with two-dimensional modulation, the surface roughness is about 67% of that without modulation. The conclusion that two-dimensional modulation can reduce the surface roughness is based on this fact that ground surface texture has dominant roughness in the cross feed direction in the surface grinding process High-frequency vibration movement of the workpiece in the *x-y* plane reduces the surface roughness in the crossfeed direction and therefore reduce the overall surface roughness（Fig.8）.



(a)Coarse CG (b) Coarse WTDUVG (c) Fine CG (d) Fine WTDUVG

Fig.9. AFM micrographs of grinding surface (a),(b)Coarse Grinding condition:v_s=26.6m/s,v_w=0.2m/s, a_p=10μm) (c),(d)Polishing condition:v_s=26.6m/s,v_w=0.084m/s, a_p=1μm

M-ZrO_2 Phase Transition. The qualitative analysis of X-diffraction results indicated that the surface phases are composed of t-ZrO_2 and small quality m-ZrO_2, there are non-crystal in surface both with and without vibration grinding. The XRD diffraction spectrums are showed in Fig.10. Phase transition rate of specimen surface is obtained by semi－quantify (S-Q) data analysis method. The measured surface phase transition values are summarized in table 2 for fine-crystalline zirconia ceramics under CG and WTDUVG. For the m-ZrO_2, the phase transition rate reaches 16.8% after conventional grinding with coarse grit diamond wheel and decreases after vibration grinding with identical grinding conditions, with the WTDUVG, the level of phase transition was 7.9%. XRD methods of phase transition measurement found a significant change in the ceramics of different grinding method with decreasing in WTDUVG. In WTDUVG, high frequency vibration is performed on the workpiece, so the grinding process is not continuous and the grinding force, grinding temperature decreased much, besides, the surface of WTDUVG show ductile surface behavior. The ductile is associated with extensive dislocation activity near the surface, the depth of the deformed zone depends on the size of the grinding particles used. Therefore, the phase transition of ZrO_2 grinding surface is determined much by material removal mechanism. For the WTDUVG, transformation toughening is easy to ZrO_2 ceramics.

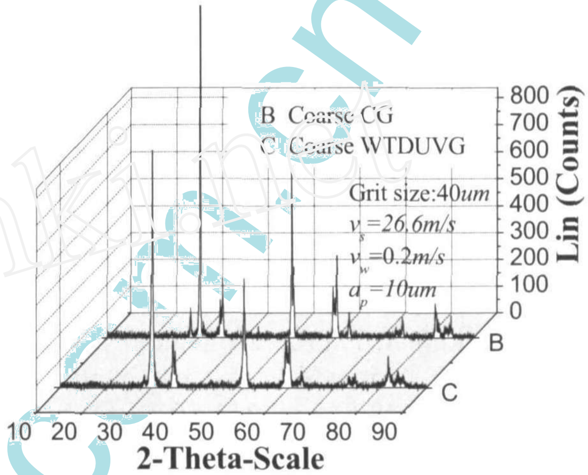


Fig.10. XRD spectra chart of grinding surface

Table 2 Phase transition of fine-crystalline zirconia ceramics

Grinding conditions	Coarse grit, v_s=26.6m/s,v_w=0.2m/s, a_p=10μm				
Grinding mode	CG			WTDUVG	
Phase composition	t-ZrO_2 (011)	m-ZrO_2 (111)	m-ZrO_2 $(11\bar{1})$	t-ZrO_2 (011)	m-ZrO_2 $(11\bar{1})$
Phase transition (%)	83.2	3.3	13.5	92.1	7.9

Conclusions

1) Material removal rate in ultrasonic grinding process is two times as large as that of in conventional grinding.

2) Ultrasonic vibration grinding possesses a much lower normal grinding force than that in CG. Furthermore, the grinding force increasing with increasing the grinding depth in both CG and WTDUVG. The variation of grinding force fits well with the material removal mechanism, it is easy for vibration grinding that material removal mechanism is ductile regime grinding.

3) Under a ductile regime grinding, the value of the surface roughness in WTDUVG rises slightly with the grinding depth .The surface roughness in WTDUVG is smaller than in CG under the same condition.

4) Experiment indicated that because of the unstable grinding process in CG, the surface can easily produce some defects such as burrs, built-up edges and so on, so that the quality of surface becomes very poor, while ultrasonic grinding can reduce the influence of tearing, plastic deformation and built-up edge in grinding, and restrain flutter, so as to make the grinding process more stable. And, the phase transition of ZrO_2 ceramics surface is related much with material removal mechanism.

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