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Modeling of High Efficiency Removal in the Grinding of Aluminal/ZrO_2 Nanocomposites with the Aid of Two-dimensional Ultrasonic Vibration

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Abstract: Based on the single abrasive particle motion locus of elliptical spiral in two-dimensional ultrasonic vibration grinding (WTDUVG), the theoretical model representing the material removal rate are deduced and verified, and the reason of high efficiency material removal by applying two-dimensional ultrasonic vibration is analyzed. Finally, experimental researches on material removal rate of ceramics were carried out using coarse grit diamond wheel both with and without workpiece two-dimensional ultrasonic vibration assistance grinding. Experimental results indicated that (1) Material removal rate (MRR) in vibration grinding process is about 1.5 times as large as that of in conventional grinding, the experimental results are in good agreement with the calculated ones. (2)The material removal rate increases along with increases of the grinding depth and workpiece velocity both in with and without vibration grinding. (3)The vibration grinding surface had no spur and build-up edge and its surface roughness was smaller than CG significantly. Surface quality of WTDUVG is superior to that of conventional grinding, it is easy for ultrasonic vibration grinding that material removal mechanism is ductile regime grinding.

Introduction

A lot of investigations have been carried out in ultrasonic vibration machining of ceramics all over the world. The material removal mechanism, grinding force and surface integrity in vibration grinding of ceramics has been widely discussed, but it is difficult to quantification study the machining mechanism because of the complexity of the grinding process and removal mode of ceramic materials and these studies concentrated at Vertical modulation machining with abrasive slurry and fixed abrasive tool [1-6]. 1997, T.C.Lee has researched the mechanism of the ultrasonic machining of ceramic composites, the models representing the shocking force and the material removal rate are deduced and verified based on the indentation fracture mechanics[4]. In 1998, one of this paper authors has researched machining mechanism and device of power ultrasonic honing, on the basis of impulse theory, the material removal synthesis theory modeling of ultrasonic honing of hard-brittle materials was established[5]. Z.J.Pei has proposed an approach to modeling the Ductile-mode removal in rotary ultrasonic machining of ceramics [6]. Shamoto E.[1]have reported researches on elliptical vibration cutting mechanics and its machining effect，but there were few reports about the mathematical model of material removal rate in workpiece two-dimensional vibration grinding.

In this paper, based on the works mentioned above, the author studied on material removal rate in work two-dimensional ultrasonic vibration grinding with diamond wheel. The MRR model of work ultrasonic vibration was established. Based on a series of grinding experiments, some rules of MRR are investigated, the effect of the grinding parameters on the MRR and the surface roughness with and without vibration of ceramics were analyzed.

Theoretical model of the grinding velocity in WTDUVG

A schematic illustration of two-dimensional ultrasonic vibration grinding is shown in Fig.1. Ultrasonic vibration with some amplitude and frequency is applied to workpiece from two vertical directions. The relative motion locus of a grain to workpiece is

$$\begin{cases} x(t) = A\cos(2\pi ft) + v_w \cdot t \\ y(t) = B\cos(2\pi ft + \varphi) \end{cases} . \qquad (1)$$

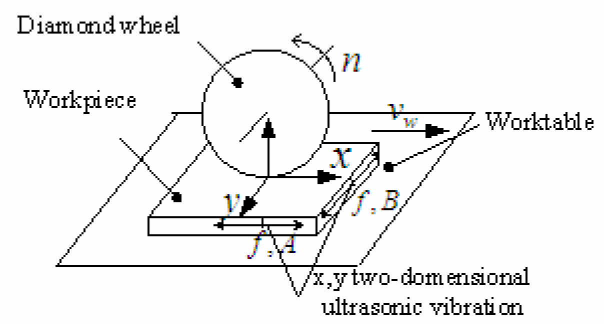

Fig.1. Illustration of the experimental set-up

The relative motion speed of the abrasive particle to workpiece is

$$\begin{cases} v_x = \dot{x}(t) = -2\pi fA\sin(2\pi ft) + v_w \\ v_y = \dot{y}(t) = -2\pi fB\sin(2\pi ft + \varphi) \end{cases} . \qquad (2)$$

Where, *A* and *B* are the two-dimensional vibration amplitudes in *x*-direction and *y*-direction respectively, *f* is the vibration frequency and v_w is the workpiece velocity (*m/s*).

Synthesis theory model of material removal in WTDUVG of ceramics

On the basis of indentation fracture mechanics, the indentation of brittle material by a small indenter will obviously cause localized deformation and the initiation of the median and lateral cracks, the initiation and propagation of median as well as lateral cracks are considered to contribute greatly to the material removal process in machining of ceramics. As shown in Fig.2, the initiation and propagation of lateral cracks lead finally to chipping of the ceramics.

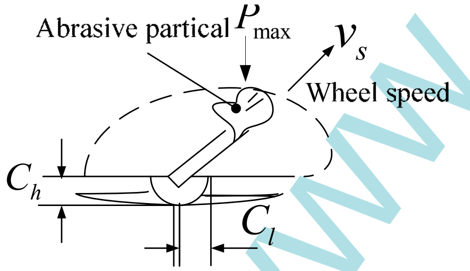

Fig.2. Diagram of chip formation

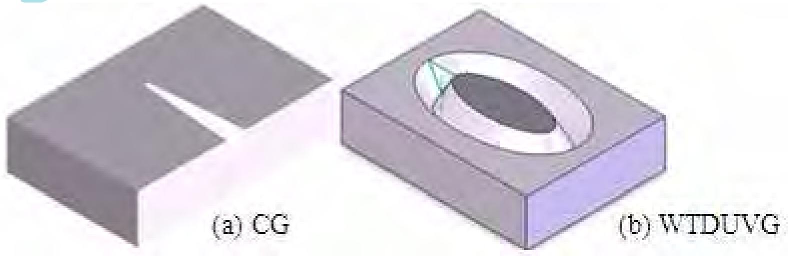
(a) CG (b) WTDUVG

Fig.3. Material removal volume of a grain

Micro-brittle fracture can be caused on the surface of ceramics when $P_{\max} \geq P_L^*$ [7]. For the size of the lateral crack C_l[8]and the depth of the lateral crack C_h[9], the following equation has been derived:

$$C_l = \xi_1 \left(\frac{P_{\max}}{K_{IC}} \right)^{\frac{3}{4}}, \quad C_h = \xi_2 (P_{\max} / H_v)^{1/2} . \qquad (3)$$

Where, P_{max} is the maximal normal grinding force of the workpiece; K_{IC} is the fracture toughness of the workpiece; H_v is the Vickers-hardness of the workpiece and ξ_1, ξ_2 are coefficient.

It is conclude from these results that the size of the lateral crack grows with an increase in the load and with a decrease in the fracture toughness of the workpiece. Investigations on the indentation described so far provide useful information for understanding the practical ultrasonic machining process of ceramic composites.

According to the test results of ceramic indentation, a model of material removal of a single abrasive has been established, as shown in Fig.3.The material will be removed if the lateral cracks extend to the workpiece surface or if the lateral cracks of two adjacent indentations meet. The volume can be regarded as being in the volume form of a crater. The material removed by one grain in some *t* becomes:

$$V = \frac{1}{3} C_L \cdot C_h \cdot L \cdot \tag{4}$$

Where *L* is the distance of single grain during some *t*. Base on the relative motion locus of a grain Eq. (1), the movement track in WTDUVG of a single diamond grain is approximate expression:

$$L = \int_l ds = \int_0^t \sqrt{(x')^2 + (y')^2}\, dt \, . \tag{5}$$

Where, Z_w is the material removal rate（mm^3/min ）and *K* are coefficient.

As shown in Fig.3（a）, material removal rate Z_w in CG of a single diamond grain is approximate expression:

$$Z_w = \frac{V \cdot N_d}{t} = N_{CGd} K (P_{CGm} / K_{IC})^{3/4} (P_{CGm} / H_v)^{1/2} \cdot v_w \, . \tag{6}$$

Substituting Eq.（2）（3）（5）into Eq.（4）, the material removal rate Z_w can be simplified to Fig.3（b）:

$$Z_{WTDw} = \frac{N_{WTDd}}{t} K (P_{WTDm} / K_{IC})^{3/4} (P_{WTDm} / H_v)^{1/2} \int_0^t \sqrt{(v_w - 2\pi fA \sin \omega t)^2 + [2\pi fB \sin(2\pi ft + \varphi)]^2}\, dt (7)$$

And N_d is the number of effective abrasive particles in the working area[10]:

$$N_d = A_g [c_1]^{2/3} \left[\frac{2}{k_s}\right]^{1/3} \left[\frac{v_w}{v_s}\right]^{1/3} \left[\frac{a_p}{d_{se}}\right]^{1/6} .$$

Where, A_g,c_1 and k_s are coefficient related to wheel.

So the number of effective abrasive particles with two-dimensional vibration grinding is:

$$N_{WTDd} = \left[v_x / v_w \right]^{\frac{1}{3}} N_{CGd} = \left[1 - \frac{A \cdot 2\pi f}{v_w} \sin(2\pi ft) \right]^{\frac{1}{3}} N_{CGd} \, . \tag{8}$$

The ratio of MRR in WTDUVG and CG under identical grinding conditions can be expression:

$$\lambda = \frac{Z_{WTDw}}{Z_{CGw}} = \frac{1}{v_w t} \left[1 - \frac{A \cdot 2\pi f}{v_w} \sin(2\pi ft) \right]^{\frac{1}{3}} \left(\frac{P_{WTDm}}{P_{CGm}}\right)^{5/4} \int_0^t \sqrt{[v_w - 2\pi fA \sin(2\pi ft)]^2 + [2\pi fB \sin(2\pi ft + \varphi)]^2}\, dt (9)$$

Where, the time that single abrasive particle passes through the arc length is showed as follows:

$$t=\frac{l_s}{v_s}=\frac{\sqrt{a_p d_{se}}}{v_s}\quad . \tag{10}$$

Where, d_{se} is the diameter of wheel (*mm*), a_p is the grinding depth (μm) and l_s is the cutting arc length of a abrasive particle in the surface of workpiece (μm) and v_s is the spindle speed (*m/s*). It is obviously predicted by Eq.(9) that the material removal rate will increase with increase of the loadP_{WTDm}, P_{CGm} , the amplitude of vibration A,B, and the particle size of the abrasive. Experiment indicated that the grinding force in WTDUVG is about 20% less than that in CG.

Experimental Conditions and Method

Experiments were carried out on a precision surface grinder GTS6016. The acoustic system was developed with local resonance, 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 average grit size of resin diamond wheel is 40μm, and the density is 3.5g/cm^3. The material removal mass was measured by electric balance. The grinding surface microstructure was observed by AFM (the type is CSPM2000) and SEM (the type is JSM-5610LV). The diamond wheel was dressed (profiled and sharpened by #80 SiC oilstone slip). The Al_2O_3-ZrO_2 nanocomposites (Tsinghua, china) was achieved by using Spark Plasma Sintering(SPS), the excellent mechanical properties of ceramic composites and fine-crystal ZrO_2 were listed in the Table. 1.

Table. 1 Properties of materials

Ceramics	Flexible strength[MPa]	Fracture toughness[MPa·$m^{1/2}$]	Vickers hardness[GPa]	Young's modulus[GPa]	Density [g/cm^3]
Al_2O_3-ZrO_2	600	7.6	17.5	345	>6.2
ZrO_2	1150	8～9	11.1	200	>6.0

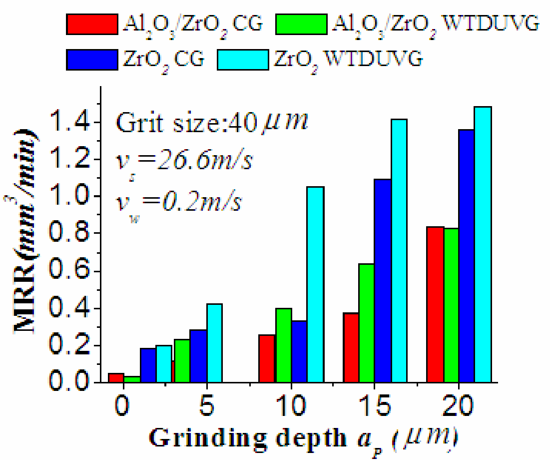

Fig.4. Grinding depth versus MRR

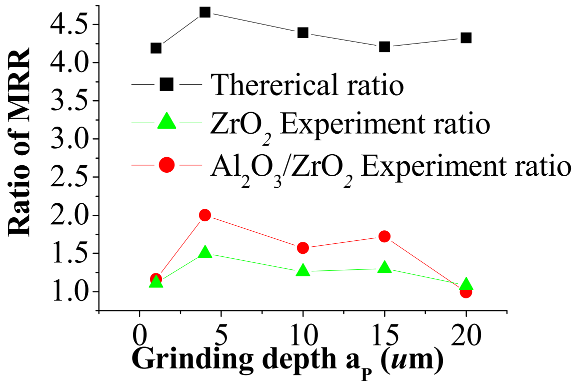

Fig.5. Ratio of MRR versus a_p

Experiments and Discussions

Effect of the grinding depth on the material removal rate. Experiments were carried out under the conditions of spindle speed v_s=26.6*m/s*, v_w=0.2*m/s* and a_p=1,4,10.15,20*μm*.Experiment results shows that the material removal rate（MRR） tends to increase with increase of the grinding depth, as shown in Fig.4. and Fig.5. the theoretical material removal rate of Al_2O_3/ZrO_2 in two-dimensional ultrasonic grinding process is 1.488 times as large as that of in CG, and the average experiment ratio of ZrO_2 MRR is 1.25, under identical grinding conditions, the theoretical MRR in WTDUVG is the 4.3 times as large as that of in CG. The experiment results demonstrated that the theoretical mathematical model of material removal rate is corrected. The high efficiency material removal results from the fact that the grains and amplitude of vibration, 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.

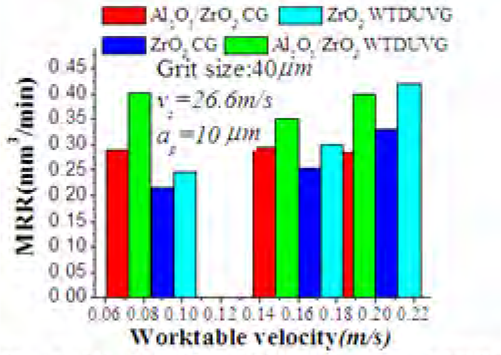

Fig.6. Worktable velocity versus MRR

Effect of the worktable velocity on material removal rate. From the Fig.6, it can be seen that both the MRR of in WTDUVG and CG will increases with the increase of worktable velocity. The average experiment ration of MRR of Al_2O_3/ZrO_2 and ZrO_2 in two-dimensional ultrasonic grinding process is 1.15～1.4 times as large as that of in CG, under identical grinding conditions, but the theoretical MRR in WTDUVG is the 1.3 times as large as that of in CG. The experiment results proved that the theoretical mathematical model of material removal rate is corrected.

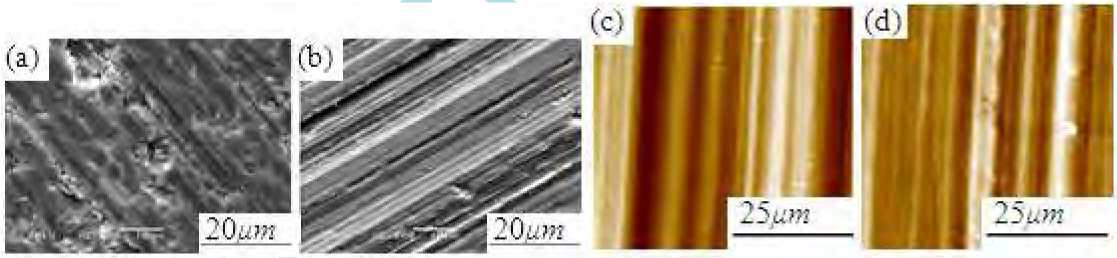

Fig.7. Surface morphology of CG and WTDUVG: (a) and (b) Al_2O_3/ZrO_2 , (c)and (d) ZrO_2 ,(a) and (c) CG, (b)and (d) WTDUVG Grinding conditions: v_s=26.6*m/s*, v_w=0.2*m/s* and a_p=4*μm*

Effect of the parameters on the surface Morphology. SEM and AFM images of ceramic nanocomposites and ZrO_2 surface after CG and WTDUVG are shown in Fig.7. After coarse grinding [Fig.7(a) and (b)] both with and without vibration show evidence of brittle fracture and ductile, and among the smooth areas are rough patches and holes from pull-out of material by fracture, 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 7～8*μm*,which is the reason of efficient material removal of WTDUVG. As Fig.7(c) and (d), ZrO_2 grinding surface morphology show evidence of ductile, so the experimental MRR of ZrO_2 is proximity the theoretical values(As Fig.5).The widths of the WTDUVG grinding grooves in the plastic regions are equal to 1.5 times of the average grooves under CG. In the present of two-dimensional modulation, experiment results found that the ground the surface roughness of ZrO_2 and Al_2O_3/ZrO_2 workpiece is reduced by 30%～

35%. The conclusion that two-dimensional modulation can reduce the surface roughness in the feed and crossfeed direction 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 crossfeed direction reduces the surface roughness in this direction and therefore reduce the overall surface roughness, furthermore, the two-dimensional vibration modulation can reduce average plastic deformation force, causes a self-dressing and self-cleaning effect, so the surface quality of WTDUVG is better than that of CG under identical grinding conditions.

Conclusions

1）The material removal rate in ultrasonic grinding process is 1.2～1.5 times as large as that of in conventional grinding, the experiment results of material rate removal approximate equals to theoretical MRR and it increases along with increasing of grinding depth and workpiece velocity both in with and without ultrasonic grinding.

2）The ductile regime grinding surface roughness in WTDUVG rises slightly with the grinding depth, and the surface roughness in WTDUVG is smaller than that of in CG under the same condition.

3）Through experiments, it was found 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. Surface quality of WTDUVG is superior to that of conventional grinding, it is easy for ultrasonic vibration grinding that material removal mechanism is ductile regime grinding.

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