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Brittle–ductile Transition in the Two-dimensional Ultrasonic Vibration Grinding of Nanocomposite Ceramics

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Abstract. Based on impulse theories and indentation fracture mechanics, the motion model of the contact between abrasive particle and workpiece in workpiece two-dimension ultrasonic vibration grinding (WTDUVG) was analyzed, and the critical condition of ultrasonic vibration grinding brittle-ductile transition was analyzed theoretically, furthermore the critical cutting depths of a grain under different grinding conditions were obtained by Matlab programs. In this work, the ultrasonic vibration and conventional diamond grinding of Al_2O_3/ZrO_2 nanoceramics were performed in order to investigate the effect of workpiece ultrasonic vibration on the brittle-ductile transition mechanism, the effect of grit size, worktable speed and grinding depth on the critical depth of cut were studied by grinding experiments. the micro-topography of the grinding surface was observed by AFM and SEM. Experiment indicated that only when the grinding depth less than critical grinding depth, ductile regime grinding of ceramics can be realized, the appropriate grinding parameter on surface finish are suggested.

Introduction

A lot of research results have shown that Al_2O_3/ZrO_2 nanocomposites possesses excellent properties, compared with conventional engineering ceramics, so it has gained increasing attention for applications within the aerospace, defense, aviation and automobiles industries [1]. However, the machining them to the required from and/or finish for their intended applications often poses a serious challenge. Ultrasonic vibration machining has impressed many people with its fine properties of high quality and high precision in machining ceramics [2-3]. Shamoto E ect. [4-6]have reported researches on elliptical vibration cutting mechanics and its machining effect, but it is little for two-dimensional vibration grinding research under workpiece adhered to ultrasonic vibration. At present, many researches are being done on brittle-ductile of conventional grinding (CG) ceramics, but the brittle-ductile transition of nanocomposite is less studies in grinding by the aided of ultrasonic vibration. in order to increase the critical depth of cut, some works on the diamond grinding of brittle materials by applying ultrasonic vibration have been undertaken.

In this work, the ultrasonic vibration diamond grinding of nanocomposites was carried out to investigate the brittle-ductile transition mechanism. The effects of grinding parameters on the the grinding surface micro-topography were studied. The reason for the increase in the critical depth of cut was discussed based on the analysis of the ultrasonic vibration cutting process.

The Critical Ductile Grinding Depth of Two-dimensional Ultrasonic Vibration

According to the study, the removal mechanics of the ceramics material is similar to metal when the grinding depth less than critical value. The ductile regime grinding is generally defined as the fracture rate of the grinding surface is less than 10%. According to the research findings of Marshall and Lawn [7], T. G. Bifano [8] built up the formula of the critical cutting depth of the brittle material. Based on impulse theories and indentation fracture mechanics, the critical cutting depth of a grain of conventional grinding was obtained [9]:

$$a_{gc} = ctg\left(\alpha_0 \big/ 2\right)\sqrt{\frac{2\lambda_0}{\alpha}\left(\frac{K_{1d}}{H}\right)^2}\ . \tag{1}$$

Where $\alpha_0 = 90^0$ is the cone-apex angle of a grain K_{Id} is the dynamic fracture toughness of the ceramics material (GPa); H is the Vickers diamond hardness of the ceramics material (MPa); α =1.8544 is the geometric factor of a grain and $\lambda_0 = (1.0 \sim 1.6)\times 10^4$ is coefficient.

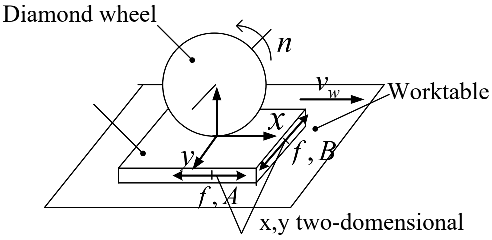


Fig.1 Illustration of the experimental set-up

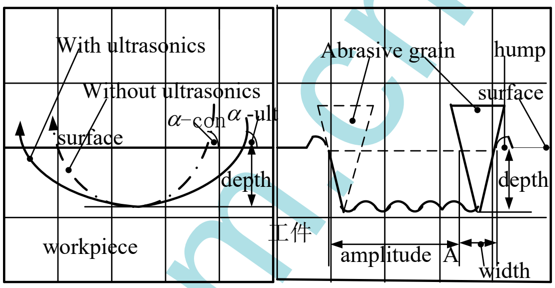


Fig.2 A grain motion model of with and without ultrasonic

According to the grinding mechanics, the ratio of the brittle material removal volume unit time and the number of effective abrasive particles in the working area is the average volume of cutting lay in WTDUVG , so the average cutting thickness of a grain in WTDUVG can be expression:

$$\bar{a}_g\,\bar{b}_g\,l_s = \frac{v_w a_p b}{v_s b N_d}\ . \tag{2}$$

where, $\bar{a}_g$ is the average cutting thickness of a grain, $\bar{b}_g$ is the average cutting width of a grain, l_s is the grinding arc length v_w is the velocity of the workpiece (m/s), a_p is the grinding depth (mm); b is the grinding width of wheel (mm), v_s is the the spindle speed (m/s) and N_d the number of effective abrasive particles in the working area (mm^{-2}).

A schematic illustration of WTDUVG is shown in Fig.1. Ultrasonic vibration with some amplitude and frequency is applied to workpiece from two vertical directions. The motion model of the contact between abrasive particle and workpiece in ultrasonic vibration grinding was analyzed, as shown in Fig.2. The average two-dimensional vibration grinding width unit time of a grain can be regarded as approximate being in the sum of the $\bar{b}_g$ and the vibration amplitude A in y direction. The equation can be simplified to:

$$\bar{a}_g = \left[\frac{v_w}{v_s}a_p\right]\left[N_d\left(\bar{b}_g + A\right)l_s\right]^{-1} \tag{3}$$

M.C.Shaw [10] think that :

$$\bar{b}_g = C\cdot\bar{a}_g\ . \tag{4}$$

where, C is coefficient.

Substituting Eq.(4) into Eq.(3), the $\bar{a}_g$ can be simplified to:

$$\bar{a}_g = \frac{v_w\cdot(a_p\cdot d_{se}^{-1})^{0.5}}{C\cdot v_s\cdot N_d\cdot\bar{a}_{pg} + Av_s\cdot N_d} \tag{5}$$

Substituting Eq.(4) into Eq.(2), the $\bar{a}_g$ can be simplified to: $\bar{a}_{pg} = \left[\frac{v_{pw}}{v_s N_{pd} C}\sqrt{a_p \big/ d_{se}}\right]^{1/2}$

Where, N_d is the number of effective abrasive particles in the working area[11]:

$$N_d = A_g \left[c_1\right]^{2/3} \left[\frac{2}{k_s}\right]^{1/3} \left[\frac{v_x + v_w}{v_s}\right]^{1/3} \left[\frac{a_p}{d_e}\right]^{1/6} \tag{6}$$

where, A_g, c_1 and k_s are coefficient related to wheel. The maximum cutting thickness in WTDUVG can be expression: $a_{g\max} = 2\bar{a}_g$,

Based on the brittle-ductile critical conditions [10]: when the grinding depth a_{gmax} less than critical grinding depth a_{gc}, ductile regime grinding of ceramics can be realized, and $a_{gmax} > a_{gc}$, brittle fracture of the material is removal mechanics.

Experimental Procedure

The experiment was 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 11.98 µm and 10.22 µm. The average grit size of resin diamond wheel is 40 µm and 10, 5 µm, and the density is 3.5 g/cm^3. Grinding forces were measured by means of an ultra-precision dynamometer SDC-CJ3SA, the outputs of the dynamometer was fed into an A/D converter and sampled at a high frequency by a PC. The ground surface microstructure was observed by SEM and AFM (the type is CSPM2000). The Al_2O_3/ZrO_2 nanocomposites (Tsinghua, china) was achieved by using Spark Plasma Sintering (SPS), the excellent mechanical properties of ceramics were listed in the Table 1, and the maximum cutting with of ultrasonic vibration machining were listed in the Table 2.

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-$ZrO_{2(n)}$	600	7.8	17.5	345	>6.2

Table 2 Maximum grinding depth of ultrasonic vibration machining

Grit size[μm]	Maximum cutting thickness of a grain :a_{gmax} [μm]							
	a_p=1 [μm]		a_p=2 [μm]		a_p=4 [μm]		a_p=6[μm]	
	CG	WTDUVG	CG	WTDUVG	CG	WTDUVG	CG	WTDUVG
40*	—	0.66	1.6	0.68	1.8	0.79	2.0	0.89
40**	—	0.7	1.9	1.2	2.4	1.4	2.6	1.5
10*	0.36	0.18	0.4	0.17	—	—	—	—
5*	0.18	0.09	0.2	0.08	—	—	—	—

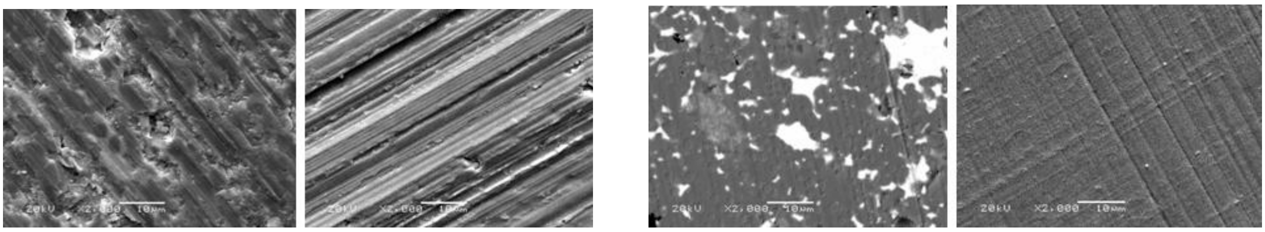
*Grinding conditions: v_s=26.6 m/s, v_w=0.084 m/s, dry grinding

**Grinding conditions: v_s=26.6 m/s, v_w =0.2 m/s , dry grinding

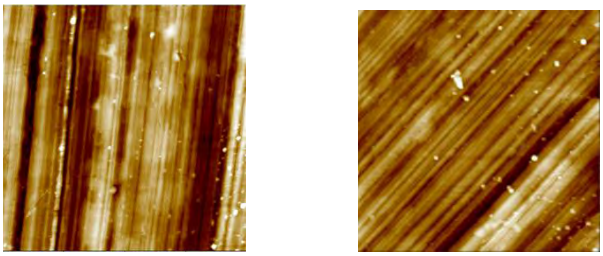
Experimental Results and Discussions

Surface Morphology. The theoretical critical cutting depth of Al_2O_3-$ZrO_{2(n)}$ is the 1.75 micrometer.

Effect of Grit Size on Brittle-ductile Transition. SEM and AFM images of nanocomposite surfaces after grinding are shown in Fig. 3. From the Fig. 3(a), we can see that the surface of grinding is in the completely fracture morphology at this grinding conditions. It can be seen that on the bottom of the grooves of the ceramic composites in CG, there are obvious traces of the grit and the width and depth of the grooves are different, and there is also a great deal of fragmentation along the fringe of the grooves. Of these are due to the unstable and larger CG force.



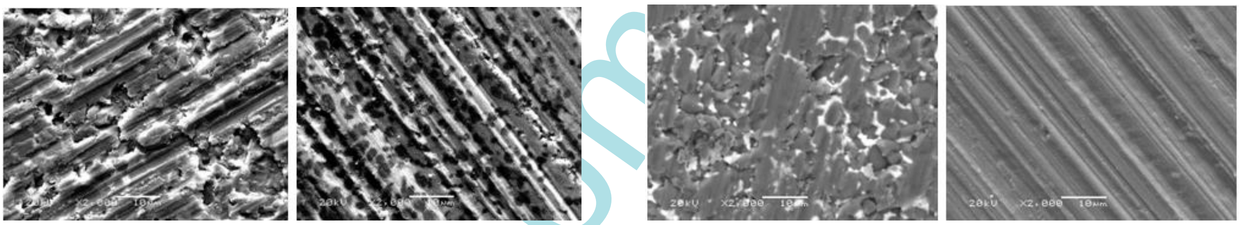
(a) CG Grit size:40μm (b)WTDUVG Grit size:40*μm* (c) CG Grit size:10μm (d) WTDUVG Grit size:10μm



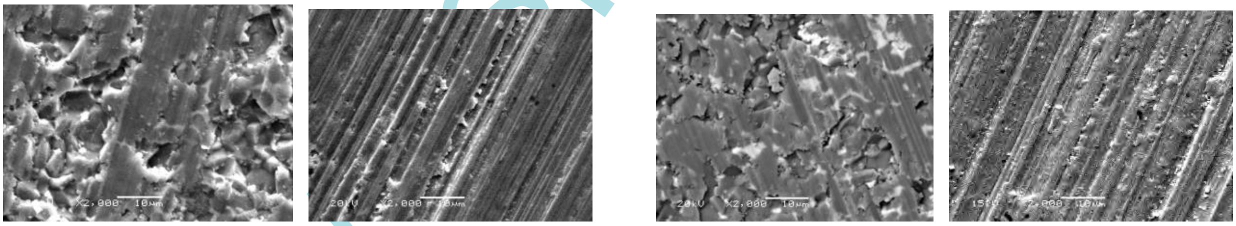
(e) CG Grit size:5μm (f) WTDUVG Grit size:5μm

Fig.3 SEM and AFM micro-topography of the grinding surface of $Al_2O_3/ZrO_{2(n)}$ ceramics under v_s=26.6m/s, a_p=1μm,v_w=0.084m/s

After coarse grinding [Fig.3 (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. After grinding with 10 μm diamond grit and polishing with 5 μm diamond grit, the surface of both CG and WTDUVG are dominated by ductile mechanism, some light scratches are visible and there is almost no grain pull-out or fracture. The SEM photographs are gives in Fig.3 (a) (b).



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



(e)CG (f) WTDUVG (g) CG (h) WTDUVG

Fig.4 SEM micro-topography of the grinding surface of ceramics under w=40 μm, v_s=26.6 m/s,(a)(b) v_w=0.084 m/s, a_p=2 μm;(c)(d) v_w=0.2 m/s, a_p=2 μm;(e)(f)v_w=0.084 m/s, a_p=4 μm;(g)(h)v_w=0.084 m/s, a_p=6 μm

Effect of Worktable Speed on Brittle-Ductile Transition. In order to examine the effect of the worktable speed on the brittle-ductile transition, the surface ground at a worktable speed of 0.2 m/s, Compared with the surfaces ground at worktable speed 0.084 m/s [Fig.4(a)-(d)], the surface in Fig.4(c)(d) appear to be covered with significantly more brittle fracture . Because of the number of effective abrasive particles in the working area increases with the larger of worktable speed, the maximum cutting thickness increased, As Fig.4(c) shows that brittle regime grinding of ceramics can be realized, when the maximum cutting thickness of a grain more than critical depth of cut.

Effect of Grinding Depth on Brittle-ductile Transition. SEM images of nanocomposite surfaces after the critical ductile grinding are shown in Fig.4. As Fig.4(a) shows ground surface groove mark of material is interrupted, and the fracture and pull-out of surface were seen at a conventional grinding depth of 2μm. As shown in figure 5(h), the critical grinding depth is 6*μm*, at this moment it is also the ductile grinding. the ductile grinding depth of nanocomposite is higher than that of conventional grinding, it is because that its ultrasonic vibration direction and its grinding force reduce under the ultrasonic vibration grinding.

During the experiment, the critical ductile grinding depth of $Al_2O_3/ZrO_{2(n)}$ ceramics is about 1.5 μm under CG and 6μm under ultrasonic vibration grinding. This experiment has proved that theoretical critical grinding depth has some relation with other factors besides characters of materials and cutting parameter. Specially, the processing method must be considered, such as ultrasonic compound machining which remove material with high energy.

Summary

Based on a grain motion model of with and without ultrasonic, the critical condition of ultrasonic vibration grinding brittle-ductile transition was analyzed theoretically. The equations for the maximum cutting thickness of a grain of vibration grinding deduced and verified. Furtheremore, The effects on the brittle-ductile transition of grinding parameters have been discussed. Experiment indicated that only when the maximum cutting thickness of a grain less than critical depth of cut, ductile regime grinding of ceramics can be realized, the ultrasonic vibration grinding method , grit size, workpiece velocity and grinding depth have been important effect on the brittle-ductile transition. Surface quality of vibration grinding 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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