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Experimental Research on Surface Integrity of Ceramic Nanocomposites in Two-Dimensional Ultrasonic Vibration Grinding

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Abstract. The grain cutting trace of elliptical spiral in workpiece two-dimensional ultrasonic vibration grinding(WTDUVG) is defined, the reason of machining accuracy improvement by applying two-dimensional ultrasonic vibration is discussed. Adopting two-dimensional ultrasonic composite processing, the influences of grinding depth, worktable velocity, wheel granularity on the surface roughness of Al_2O_3/ZrO_2 ceramic nanocomposites were described. Experimental results of AFM microstructure show that the material removal model in WTDUVG is dominated by ductile flow of material, some crystal refinement, the crush powder and grain pull-out are visible and there is almost no fracture. Furthermore, the surface roughness in WTDUVG with coarse grit is about 30～40% less than that in CG under identical grinding condition; the qualitative analysis of X-diffraction results indicated that the surface phases are composed of α-Al_2O_3, t-ZrO_2 and small quality m-ZrO_2, there are amorphous phase in the surface both with and without vibration grinding. M-zirconia phase transitions rule in vibration and conventional grinding was found. Under definitive grinding conditions, the material removal mechanism of inelastic deformation is the principal removal mechanism of Al_2O_3/ZrO_2 ceramic nanocomposites, the grit size of diamond wheel and vibration grinding mode have important influence on material removal mechanism of ceramic nanocomposites.

Introduction

A lot of research results have shown that Al_2O_3/ZrO_2 nanocomposites possess excellent properties compared with conventional engineering ceramics, so it has gained increasing attention for applications within the aerospace, defense, aviation and automobiles industries [1]. It is necessary to investigate material removal mechanism of ceramic nanocomposites. Ultrasonic vibration machining has impressed many people with its super properties of high quality and high precision in machining ceramics[2,3]. Shamoto E[4-6] have reported researches on elliptical vibration cutting mechanics and its machining effect , but it is little for two-dimensional vibration grinding (WTDUVG) research under workpiece adhered to ultrasonic vibration. At present, many researches are being done on residual stress of grinding brittle material, but the residual stress of nanocomposites is less studies in grinding by the aided of ultrasonic vibration. In this paper, based on the defined elliptical cycloid in WTDUVG, the surface integrity of nanocomposites and the effect of grinding styles on the phase transformation and residual stress after the two-dimensional ultrasonic grinding and polishing with coarse and fine diamond grit are studied.

Mechanism of two-dimensional ultrasonic grinding

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 of workpiece, so the displacement equation of particle A in the workpiece is:

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

Where, A and B are the two-dimensional vibration amplitudes in x- direction and y-direction respectively, f is the vibration frequency. When the relative velocity of wheel to workpiece is v, the relative motion locus of a grain to workpiece is elliptical spiral, the elliptical spiral locus is defined initially in this paper, L_T is the offset of workpiece in a vibration period T. As Fig.2, the equation of elliptical spiral is:

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

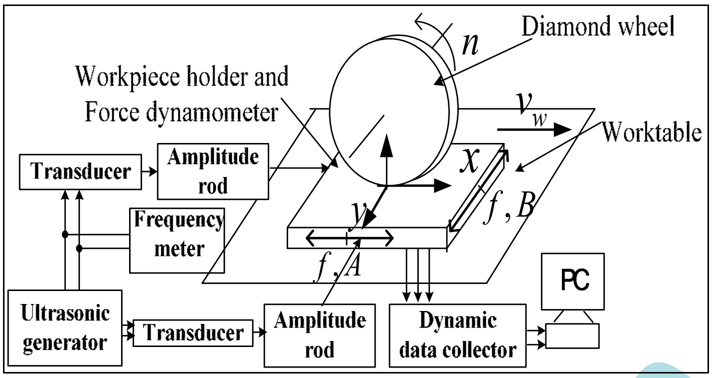


Fig.1. Diagram of WTDUVG and signal collection

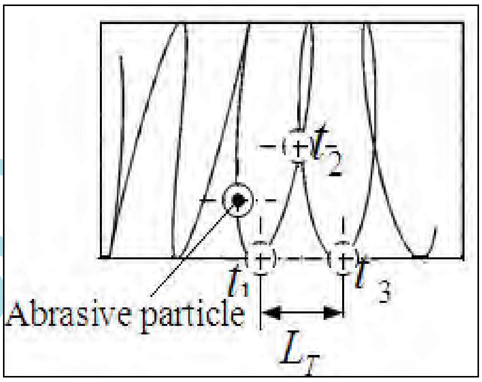


Fig.2. Grain cutting locus in WTUVG

Experimental conditions and method

The experiment was carried out on a precision surface grinder GTS6016. The acoustic system was developed with local resonance theory, the ultrasonic vibration was automatically controlled around a frequency of 20.237 KHz and the amplitudes of x, y direction vibration were hold at 11.98μm and 10.22μm.The average grit size of resin diamond wheel is 40-50μm and 10μm, and the density is 3.5g/cm^3. The material removal mass Al_2O_3/ZrO_2 was measured by electric balance. Grinding forces were measured by means of a ultraprecision dynamometer SDC-CJ3SA, the output of the dynamometer was fed into an A/D converter and sampled at a high frequency by a PC. The grinding surface microstructure was observed by SEM and AFM (the type is CSPM2000). The Al_2O_3/ZrO_2 nanocomposites produced by Tsinghua university was achieved by using Spark Plasma Sintering (SPS), the excellent mechanical properties of ceramic composites were listed in Table 1.

Table 1 Properties of Al_2O_3/ZrO_2 nanocomposites

Ceramics	Flexible strength[MPa]	Fracture toughness[MPa$\cdot m^{1/2}$]	Vickers hardness[Gpa]	Young's modulus[Gpa]	Density [g/cm^3]
Al_2O_3/ZrO_2	600	7.6	24	345	>6.2

Experimental results and discussions

Influence of grinding depth on the surface roughness. As shown in Fig.3, along with the increase of grinding depth, the value of the surface roughness both in WTDUVG and CG increases. Especially, the surface roughness increased dramatically when grinding depth reaches 3μm/pass, and at this time the brittle fracture mechanism is the main material removal model. The curves also show that the value of the surface roughness in WTDUVG is about 20% less than that in CG.

Influence of worktable velocity on surface roughness. Fig.4 clearly demonstrates that the surface roughness increase along with the worktable velocity both in CG and WTDUVG. The experiments proved that the vibration grinding surface had no spur and build-up edge and the surface roughness was smaller than conventional grinding significantly.

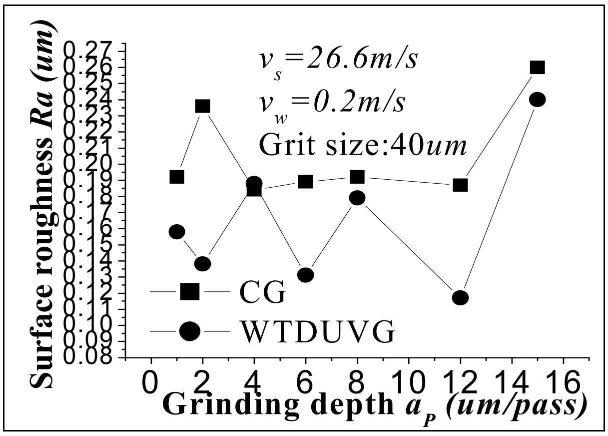


Fig.3. Surface roughness versus a_p

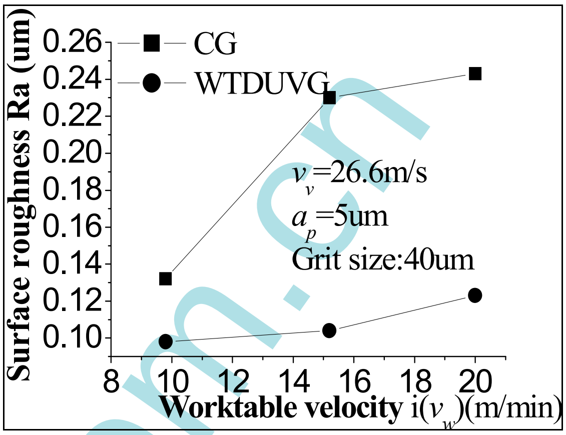
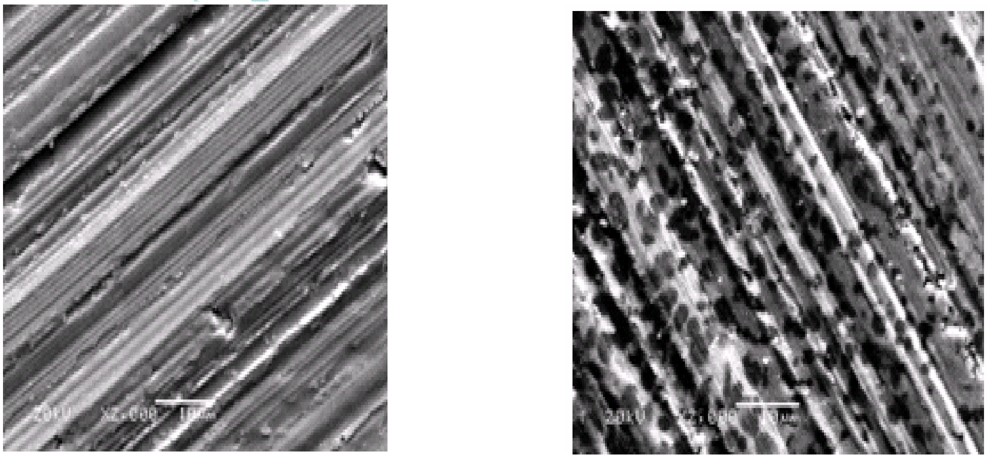


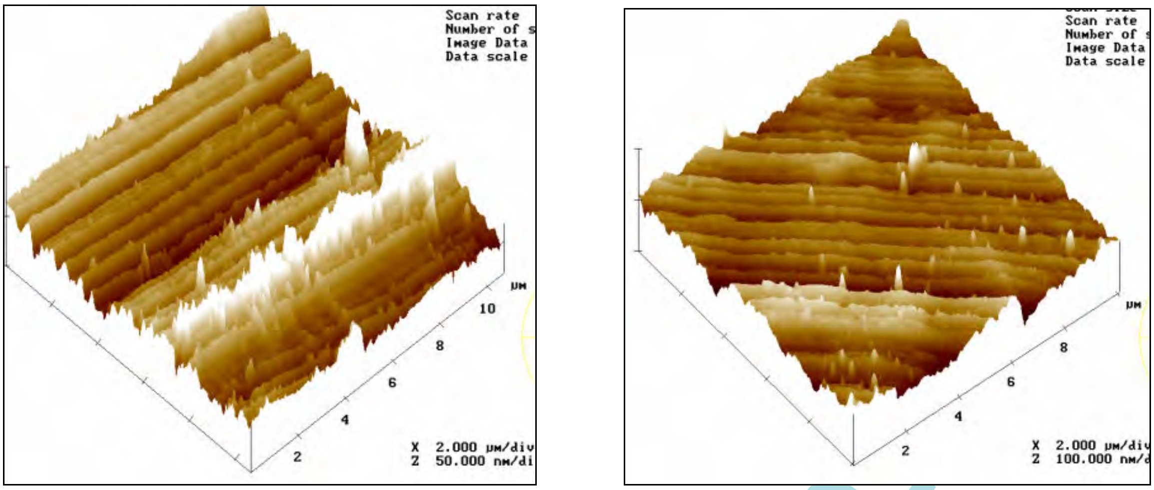
Fig.4. Surface roughness versus v_s

Effect of grit size on the surface roughness. In Fig.3, grinding surface roughness are given for CG and WTDUVG at wheel speed of 26.6m/s, worktable velocity of 12 m/min, and grinding depth of 5μm. Roughness analysis of AFM photographs shown in Fig.5 indicate that the surface roughness in CG is 176.35nm and the surface roughness in two-dimensional ultrasonic vibration grinding with coarse grit wheel is 136.23nm. In Fig.5(c)(d), After polishing with grinding wheel of 10μm grit size under identical grinding condition, the surface roughness in CG is 6.214nm and the surface roughness in WTDUVG is 3.356nm, Experimental results show that with two-dimensional modulation, the surface roughness is about 45% of that in CG.

The conclusion that two-dimensional modulation can reduce the surface roughness is based on the fact that ground surface texture has dominant influence on roughness in the cross feed direction. During ultrasonic 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.



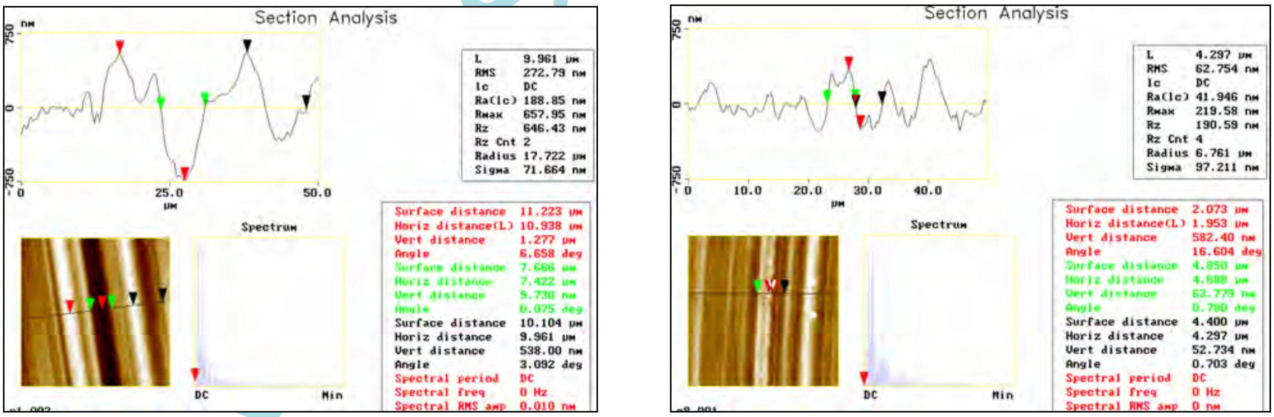
(a)Coarse CG (b) Coarse WTDUVG



(c) Fine CG (d) Fine WTDUG

Fig.5. Surface of ceramics nanocomposit specimen after CG and WTDUVG

Surface Morphology. The SEM photographs are given in Fig. 5(a)(b). 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. As for the surfaces in WTDUVG, there are no cutting traces of cutter but obvious dense fine pits can be seen from the SEM photographs. AFM images of nanocomposite surface after CG and WTDUVG are shown in Fig.6. By the section analysis of AFM, the width of the conventional grinding grooves in the plastic regions is equal to 3μm [Fig.6(a)], but the average width of the grooves under WTDUVG are equal to 8μm [Fig.6(b)], which is the reason of high efficient material removal of WTDUVG. After polishing with 10μm diamond grit, the CG surface shows features characteristic of both brittle fracture and local ductile flow[Fig.5(c)], but the surface of WTDUVG is dominated by ductile mechanism, some light scratches are visible and there is almost no grain pull-out or fracture[Fig.5(d)].



L 9.961 µm
RMS 272.79 nm
Ic DC
Ra(Ic) 188.85 nm
Rmax 657.95 nm
Rz 646.43 nm
Rz Cnt 2
Radius 17.722 µm
Sigma 71.664 nm
Surface distance 11.223 µm
Horiz distance(L) 10.938 µm
Vert distance 1.277 µm
Angle 6.658 deg
Surface distance 7.666 µm
Horiz distance 7.422 µm
Vert distance 9.730 nm
Angle 0.075 deg
Surface distance 10.104 µm
Horiz distance 9.961 µm
Vert distance 538.00 nm
Angle 3.092 deg
Spectral period DC
Spectral freq 0 Hz
Spectral RMS amp 0.010 nm

L 4.297 µm
RMS 62.754 nm
Ic DC
Ra(Ic) 41.946 nm
Rmax 219.58 nm
Rz 190.59 nm
Rz Cnt 4
Radius 6.761 µm
Sigma 97.211 nm
Surface distance 2.073 µm
Horiz distance(L) 1.953 µm
Vert distance 582.40 nm
Angle 16.604 deg
Surface distance 4.850 µm
Horiz distance 4.688 µm
Vert distance 63.779 nm
Angle 0.780 deg
Surface distance 4.400 µm
Horiz distance 4.297 µm
Vert distance 52.734 nm
Angle 0.703 deg
Spectral period DC
Spectral freq 0 Hz
Spectral RMS amp 0 nm

(a) CG (b) WTDUVG

Fig.6. AFM micrographs of grinding surface

(Grinding condition: 40μm grit, v_s=26.6m/s,v_w=12m/min, a_p=5μm)

M-ZrO$_2$ Phase Transition. The qualitative analysis of X-diffraction results indicated that the surface phases are composed of α-Al$_2$O$_3$, t-ZrO$_2$ and small quality m-ZrO$_2$, there are no amorphous phase generating in surface both with and without ultrasonic grinding. The XRD diffraction spectrums are shown in Fig.7.

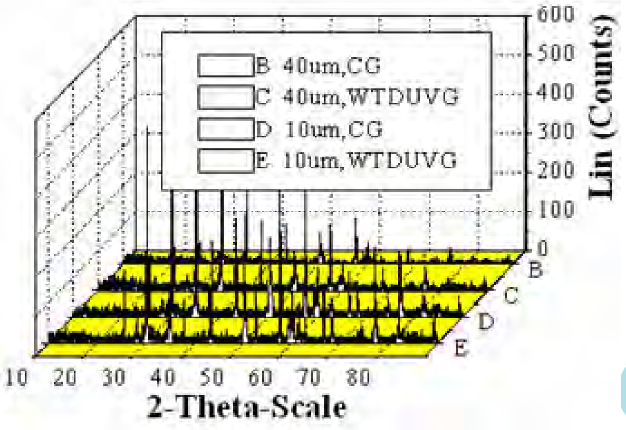


Fig.7 XRD spectra chart of grinding surface

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 Al_2O_3/ZrO_2 ceramic nanocomposites under CG and WTDUVG.

Table 2 Phase transition of Al_2O_3/ZrO_2 nanocomposites

Grinding conditions	Coarse grit, $v_s = 26.6 m/s$, v_w=0.2m/s, a_p=1μm						Fine grit		
	CG			WTDUVG			WTDUVG		
Phase composition	t-ZrO_2 (011)	m-ZrO_2 ($11\bar{1}$)	α-Al_2O_3 (104)	t-ZrO_2 (011)	m-ZrO_2 ($11\bar{1}$)	α- Al_2O_3 (104)	t-ZrO_2 (011)	m-ZrO_2 ($11\bar{1}$)	α- Al_2O_3 (104)
Phase transition	46.9%	6.2%	46.9%	47.9%	4.1%	47.9%	46.9%	6.2%	46.9%

From Table 2, it can be seen that the m-ZrO_2 transition rate of nanocomposites reaches 6.2%l after conventional grinding with coarse grit diamond wheel vs. 4.1%l after ultrasonic grinding under identical grinding conditions. That is to say, martensite phase transition rate of Al_2O_3/ZrO_2 nanocomposite in WTDUVG is smaller than that in CG. Moreover, grit size of ceramics material nearly has no real effect on phase transition in WTDUVG. In WTDUVG, high frequency vibration is performed on the workpiece, so the grinding process is not continuous and the grinding force and grinding temperature will decrease much. Besides, stress state in grinding area will change due to cavitating action of ultrasonic vibration and intermittent contact between abrasive particle and material. So tetragonal phase of ZrO_2 in ground surface is easy to produce in WTDUVG, which further heighten material's fracture toughness. Meanwhile, the surface in WTDUVG shows ductile behaviour which is associated with extensive dislocation activity near the surface and the size of abrasive particle. Therefore, the phase transition of Al_2O_3/ZrO_2 nanocomposites surface in WTDUVG is determined much by material removal mechanism.

Conclusions

The following conclusions can be obtained:

1. The surface roughness in two-dimensional ultrasonic vibration grinding with coarse grit is about 30～40% less than that in convebtional grinding under identical grinding condition. Surface quality of Al_2O_3/ZrO_2 nanocomposites in WTDUVG is superior to that in CG.
2. Ground surface of Al_2O_3/ZrO_2 nanocomposites in WTDUVG shows obvious local plastic flow characteristic under all conditions studied. While in CG, ductile surface produces only when

polishing with fine diamond grit, and some brittle fractures and pulled out grains can be seen if using coarse grit .

3. M-ZrO_2 phase transition rate of Al_2O_3/ZrO_2 nanocomposite in WTDUVG is smaller than that in CG and t-ZrO_2 phase in ground surface of Al_2O_3/ZrO_2 nanocomposites is easy to produce in WTDUVG, which further heighten material's fracture toughness. The phase transition of Al_2O_3/ZrO_2 nanocomposites surface in WTDUVG is determined much by material removal mechanism.

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