Int J Adv Manuf Technol (2014) 70:813–819
DOI 10.1007/s00170-013-5297-y

ORIGINAL ARTICLE

# Study on high-speed grinding mechanisms for quality and process efficiency

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Received: 18 April 2013 / Accepted: 5 September 2013 / Published online: 2 October 2013

**Abstract** This paper focuses on the mechanism of high-speed grinding to achieve quality and efficiency for ceramics. The criterion of the brittle–ductile removal transition of ceramics is calculated and analyzed. The effects of the wheel velocity on the specific grinding forces, energy, and specific material removal rates were investigated. The influence of the wheel velocity on the surface integrity was studied in the terms of surface roughness by a 3D optical profilometer, scanning electron microscopy, respectively. The ductile removal mechanism of brittle material was validated experimentally. High quality and efficiency of grinding for SiC can been attained with high-speed grinding due to the understanding of the characteristics and mechanism for ductile grinding of brittle materials with high-speed grinding. Furthermore, based on the high-performance grinding mechanism, reasonable definitions on high-speed grinding are proposed.

**Keywords** High-speed grinding · High-performance grinding · Ductile grinding of brittle materials · Brittle grinding of viscous materials · Definition

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## 1 Introduction

The materials possessing excellent properties such as ceramics are widely used with the rapid developments of aerospace, new energy sources, and high-grade CNC machine tool high technology. However, structure ceramics are also typically difficult-to-cut materials [1].

In the past decades, high-speed grinding has been developed as a finishing process in order to avoid the grinding-induced damage layer on the ceramics [2, 3]. The high-speed machining was proposed by Carl Salomon in 1931. He assumed that at a certain cutting speed, which was 5–10 times higher than that in conventional machining, the chip tool interface temperature will start to decrease [4]. But he did not discuss the cutting speed of the tool for surface temperature beginning to fall and related process parameters. To date, the grinding speed used for industry has been at 120 m/s, therefore the research on high quality and high efficiency of difficult-to-machine materials ground with a wheel speed of 120 m/s has become an extremely important issue. Theoretically, it should promote ductile flow by reducing the tendency for brittle fracture, when the increment of wheel speed will result in a reduction of the maximum undeformed chip thickness and grinding force [2]. As a result, great efforts have been made in the high-speed grinding of advanced ceramics [2, 5]. To avoid brittle fracture grinding, the wheel velocities were increased, leading to an improvement in ground-surface quality when grinding was conducted within the region where ductile flow was prevalent. However, most of the research focused on the surface finish only, and rarely involved the mechanism of high-speed grinding to achieve quality and efficiency and the surface quality.

In this paper, the characteristics and the mechanisms for ductile grinding of brittle materials with high-speed grinding were investigated; reasonable definitions on high-speed grinding on the basis of the high-performance grinding mechanism will be proposed.

## 2 Research on high-performance grinding characteristics for the engineering ceramic

### 2.1 Criterion of the brittle–ductile removal transition of ceramics under low-speed grinding

One parameter which has been used to characterize the penetration depth of each grit is the maximum undeformed chip thickness, $a_{\text{gmax}}$, which can be written as follows [6]:

$$a_{\text{gmax}} = \left[\frac{3}{C\cdot\tan\theta}\cdot\frac{v_w}{v_s}\cdot\sqrt{\frac{a_p}{d_e}}\right]^{1/2} \tag{1}$$

Where $C$ is the active grit density, $\theta$ the semi-included angle of the active grit point and $\theta=60°$ is often used, $v_{\text{w}}$ the workpiece speed and $v_{\text{s}}$ the grinding wheel velocity, and $d_{\text{e}}$ is the equivalent wheel diameter. In the present work, $C=50$ grits/mm$^2$ for the D91 diamond grinding wheel based on the microscope observation of the grinding topography.

Previous research [7] in ductile regime grinding of brittle materials has shown that if the $a_{\text{gmax}}$ value is less than a critical depth of penetration that causes brittle fracture in a material, $d_{\text{c}}$, then the grinding will occur in the ductile regime. So, for the low-speed grinding of SiC, the grinding depth, $a_{\text{p}}$, is normally thinner than 1 μm, in order to get a tiny chip thickness. The $d_{\text{c}}$ value is related to the material properties and can be estimated as follows [7]:

$$d_c = \beta\left(\frac{E}{Hv}\right)\cdot\left(\frac{K_{IC}}{Hv}\right)^2 \tag{2}$$

Where $\beta$ is a constant, $E$ the elastic modulus, $H$v the hardness, and $K_{\text{IC}}$ the fracture toughness. Bifano [8] measured grinding infeed rate corresponding to the brittle–ductile transition of ten materials and figured out the constant $\beta=0.15$. Based on Eq. (2), the values of $d_{\text{c}}$ for the SiC is 0.06 μm (For SiC, $E=415$ GPa, $H\text{v}=23$ GPa, and $K_{\text{IC}}=3.5$ MPa m$^{1/2}$). However, the grinding speed in Bifano's tests was only 26 m/s, and the material properties were assumed to be constant and not influenced by the strain rate and the temperature.

### 2.2 Dependence of the value $d_c$ on the grinding wheel velocity

If the grinding were carried out based on the $d_{\text{c}}$ value calculated by Eq. (2), then the material removal rate shall be limited to a low level in order to avoid the cracks generated on the ground surface. The pursuing of a higher productivity of the grinding of ceramics requires an increment of the critical penetration depth of each grit.

The elevated grinding wheel velocity will inevitably lead to an increment of the strain rate in the cutting area, and a higher contact temperature between the workpiece material and the abrasive grit.

The behavior of the ceramics under high strain rate has been investigated by Ravichandran [9] and Hall [10]. It has been observed that the fracture stress increased with increasing strain rate in monolithic and composite ceramic materials. This tendency is attributed to inertia-dominated dynamic crack growth from preexisting flaws. It is argued that the cracks are initiated athermal, and once the crack initiates, the rate controlling process is considered to be inertia which is suggested to be independent of material properties [9]. Based on this argument, it is suggested that the fracture stress in the high-strain rate regime is given as follows [11]:

$$\sigma \propto \dot{\varepsilon}^{1/3} \tag{3}$$

Where $\sigma$ is the fracture stress and $\dot{\varepsilon}$ is the strain rate. This dependence of fracture stress prevails after a critical strain rate [9]. The critical strain rate for monolithic ceramic materials such as $Al_2O_3$, SiC, and AlN is found to be around 1,000 s$^{-1}$ [9]. Conventional flow curves are valid for strain rates up to 40 s$^{-1}$. The strain rates occurring during the high-speed grinding process are more than 1,000 times higher [12]. In practice, the tensile strength, $\sigma_{\text{t}}$, is often used to characterize the fracture stress. So Eq. (3) can be written as follows:

$$\sigma_t \propto \dot{\varepsilon}^{1/3}. \tag{4}$$

The relationship between fracture toughness, $K_{\text{IC}}$, and tensile strength were paid close attention by many studies [13, 14]. It has been found that for most of the brittle materials, such as rock and clay, the fracture toughness and the tensile strength are linearly correlated. The coefficient will be different depending on the testing materials. Therefore, based on the derivation mentioned above, it could be concluded that the elevated strain rate will lead to a higher fracture toughness, which indicates a ductile tendency of the brittle materials under the shock mechanical loading.

Moreover, the temperature sensitivity of the brittle material also influences the material removal mechanism. It is proved that the grinding temperature will increase with the elevated grinding wheel velocity [15]. The temperature-related physical properties of brittle material depend dominantly on that, whether the material can stand the thermal stress induced by the temperature change or if the bending strength will be overcome. Schneider [16] reported the test results of the bending strength decrease on ceramics at the critical quenching temperature (Fig. 1). The quenching time varied from 3 to 5 s in Schneider's tests, which is longer than the contact time during one grit engagement.

It was showed that the critical temperature difference for SiC is 380 °C, above which the bending strength retained will be significantly decreased only by 10 % of the initial. Forasmuch as under the condition of high-speed grinding with

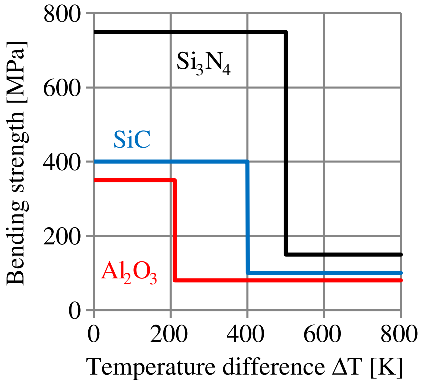


**Fig. 1** Thermal shock influence on the strength of ceramics [15]

cooling spray, the thermal softening effect due to high temperature becomes dominant. The thermal shock sensitivity will lead to a much easier transition from brittle fracture to ductile flow of the material removal mode, especially for the brittle materials.

Therefore, a hypothesis is proposed that the speed effect of high-speed grinding will change the contact behavior between the brittle material and the abrasive grit. On the one side, the fracture stress will be increased with the elevated strain rate. Therefore, the fracture toughness of ceramics can be increased in the condition of high-speed grinding. On the other side, the resultant high temperature by high-speed grinding will lead to lower bending strength of ceramics, so that the penetration depth of each grit can be greatly enlarged without generating fracture cracks.

## 2.3 Validation by the simulation of single grit scratch test

In order to verify the abovementioned analysis, a simulation of single grit scratch test has been done in FEM software. A cone with a rake angle of −37° was employed to simulate the diamond grit with an average grit size of 120 μm. A four-node unit with temperature and displacement coupling was used for the mesh of the workpiece and grit (Fig. 2). The temperature-dependent physical properties of the SiC and diamond were listed in Table 1. The grit material employed in this paper is polycrystalline diamond, whose crystallite size is much larger than the nanopolycrystalline diamond [16].

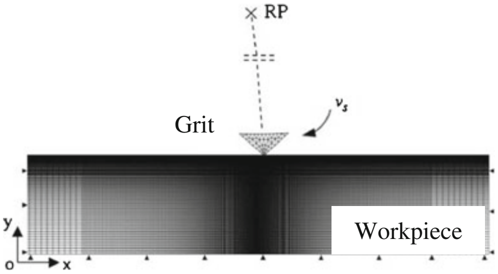


**Fig. 2** Kinematic model of single grit scratch test

The friction boundary condition between the diamond grit and SiC can be expressed as follows:

$$\tau_f = \begin{cases} \mu\sigma_n, \tau_f < \tau_{\max} \\ \tau_{\max}, \tau_f \geq \tau_{\max} \end{cases}. \tag{5}$$

Where $\tau_f$ is friction stress, $\mu$ the friction coefficient, $\sigma_n$ the normal stress, $\tau_{\max}$ the critical shear yield stress, and $\sigma_y$ the yield strength.

The process parameters in the simulation are set as Table 2.

Simulation results demonstrate that keeping the material removal rate as constant, the same proportional increased grinding wheel velocity and the workpiece speed will lead to a thinner maximum undeformed chip thickness. The ductile removal mode will be achieved and no median crack will be generated when the grinding wheel velocity increased from 20 to 80 m/s (Fig. 3a, b). The simulation results show that the temperature on the scratched surface will increase because of the elevated grinding wheel velocity. However, the mechanical loads on the abrasive grit have significant reduces on both normal and tangential directions, due to the thinner maximum undeformed chip thickness (Table 2).

On the other hand, a higher material removal rate can also be achieved when the grinding depth is constant and the workpiece speed is increased proportional with the grinding wheel velocity. In this condition, the maximum undeformed chip thickness is constant when the material removal rate is increased from 1 to 4.16 $mm^3$/mms. The elevated temperature on the scratched surface will soften the SiC, leading to a higher fracture toughness and the ductile tendency of the material behavior. Besides, the mechanical load on the grit is almost the same as that under the low material removal rate. Therefore, no fracture will be generated (Fig. 3a, c) and the grinding process will not deteriorate the surface quality.

Based on the analysis mentioned above, it can be concluded that both the grinding wheel velocity and the maximum undeformed chip thickness have a limitation for the transition from brittle to ductile removal mode. To sum up, ductile grinding of brittle material can be achieved when $a_{\text{gmax}}$ is controlled under a certain value which related to high-speed condition. In this way, not only a good surface quality can be obtained, but also the efficiency of the grinding process can be greatly increased.

## 2.4 Experiment on the ductile removal mode of brittle material

The aforementioned hypothesis was further examined by the high-speed grinding test with SiC. Grinding experiments were performed on the MGKS 1330/H CNC outer cylindrical-grinding machine in Shanghai Machine Tool Works Ltd. The resolution of the grinder feed is 0.2 μm. A ceramic-bonded diamond-grinding wheel D91 was used with the average grit size of 91 μm and the concentration of 6.6 Carat/

**Table 1** Physical properties of SiC and diamond grit

| Material | Density [kg/m$^3$] | Elastic modulus [GPa] | Poisson's ratio | Shear modulus [MPa] | Coefficient of thermal expansion [℃] | | Thermal conductivity [W·(m·K)$^{-1}$] | | Specific heat [J/(kg·K)] |
|---|---|---|---|---|---|---|---|---|---|
| SiC | 3215 | 415 | 0.075 | 1.93e+05 | 4.7e-06 | | 20℃ | 220 | 669 |
| | | | | | | | 1000℃ | 50 | |
| Diamond | 3560 | 900 | 0.2 | 9.75e+05 | 20℃ | 0.8E-06 | 146 | | 502 |
| | | | | | 100℃ | 0.4E-06 | | | |

cm$^3$. The wheel has a diameter of 400 mm and a width of 15 mm.

The workpieces have the diameter of Φ100 mm with the length of 22 mm. The ground surfaces cleaned with alcohol were examined by using an optical microscope equipped with a scanning electron microscopy (SEM). The surface roughness values were measured using a 3D optical profilometer. Each data point for grinding forces is the average of three measurements and the average of seven measurements for surface roughness. Error of repeated experiments is less than 10 %.

Figure 4 shows the normal and tangential grinding forces per unit length, F'$_n$ and F'$_t$, obtained under different conditions for the grinding of SiC. It can be seen that the normal and tangential force components decrease with the increasing of the peripheral wheel speed, which should be attributed to the reduction in the maximum undeformed chip thickness at higher grinding speeds (Fig. 4).

The reduced maximum undeformed chip thickness will lead to the transition from microfracture to micro cutting. Furthermore, keeping the speed ratio as q=250, the specific normal and tangential grinding forces scaled relatively steady at about 25 and 8 N/mm, respectively, almost regardless of the specific material removal rate (Fig. 5).

The surface roughness measured along the grinding direction and perpendicular thereto is presented in Fig. 6. It shows that the surface roughness, under the wet grinding and dry grinding, can be improved at a higher grinding wheel speed. An interesting phenomenon is that the ground surfaces with cooling spray have a better surface roughness in comparison with that under the same grinding parameters, but without cooling. As discussed in Sect. 2.2, the thermal shock sensitivity can change the strength of the brittle–elastic materials, especially under the grinding conditions with the coupling of thermal and mechanical loads in the contact area. The higher the grinding wheel velocity is, the higher the grinding temperature rises. So that the quenching effect leads to a thermal stress concentration in the surface layer and the toughness of the material will be overcome. Therefore, the chip formation will take place in the ductile regime with cutting. Moreover, in condition of wet grinding, the roughness value perpendicular to the grinding direction is obviously higher than that parallel thereto, which indicates the plastic deformation occurred. Under the ductile removal mode, the plowing effect leads to the anisotropy of the surface roughness, which is in accordance with Mamalis on the precision grinding of advanced ceramics [1].

In addition, the ground surfaces were also checked in more detail by the 3D optical profiling microscope, and the images are shown in Fig. 7. The profile images show that under the same maximum undeformed chip thickness, brittle–ductile transition can be recognized during grinding of SiC when the wheel speed increased from 20 to 120 m/s.

At the conventional wheel speed, it dominantly has a higher tendency to produce brittle fracture along with the interface of crystalline grains. These brittle fractures will leave pits and protrusions on the ground surface (Fig. 8a, b). Specifically, the ground surface is characterized as (1) brittle fractures and (2) grains dislodgement under the condition of $v_s$=20 m/s and $v_w$=4.8 m/min. The grinding is under the brittle removal mode. As illustrated on Fig. 3, the median cracks can be obviously recognized underneath the scratched surface in the simulation. With increasing wheel speeds, the maximum undeformed chip thickness becomes thinner, leading to a lower tangential grinding force. As a result, the ceramic SiC has an inclination to be ductile removed, significantly improving the surface roughness (Fig. 8c, d). In this occasion, the mechanical load is the major cause for the transition from brittle fracture to the ductile removal mode (Table 2). When keeping the grinding depth as constant, the

**Table 2** Physical properties of SiC and diamond grit

| Single grit scratch parameters | | | | | | Simulation results | | |
|---|---|---|---|---|---|---|---|---|
| $Q'_w$ (mm$^3$/mms) | $a_p$ (mm/U) | $v_w$ (m/s) | $v_s$ (m/s) | $d_w$ (mm) | $a_{gmax}$ (μm) | T (°C) | $F_{Gn}$ (N) | $F_{Gt}$ (N) |
| 1 | 0.013 | 0.08 | 20 | 100 | 0.93 | 104 | 25 | 13 |
| 1 | 0.0038 | 0.267 | 80 | 100 | 0.63 | 150 | 5 | 10 |
| 4.16 | 0.013 | 0.32 | 80 | 100 | 0.93 | 400 | 20 | 10 |

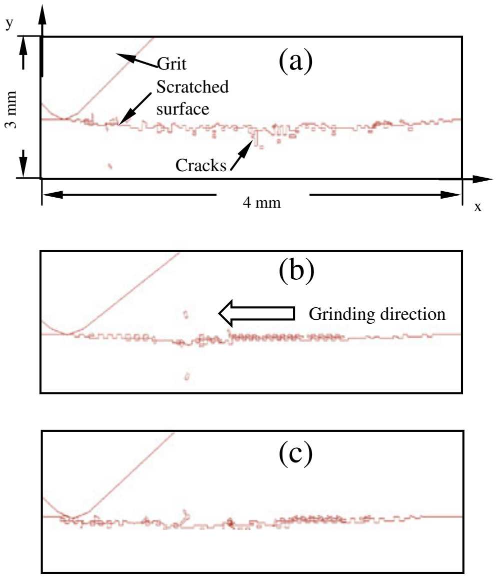


**Fig. 3** Brittle and ductile removal mode by grinding of SiC. ($v_s$=20 m/s, $a_p$=0.013 mm, $Q'_w$=1 mm$^3$/mms, $a_{gmax}$=0.93 μm; (**b**) $v_s$=80 m/s, $a_p$= 0.0038 mm, $Q'_w$=1 mm$^3$/mms, $a_{gmax}$=0.63 μm; $v_s$=80 m/s, $a_p$= 0.013 mm, $Q'_w$=4.16 mm$^3$/mms, $a_{gmax}$=0.93 μm)

same proportional increment of the workpiece speed with the elevated grinding wheel velocity leads to a constant maximum undeformed chip thickness. As illustrated in Fig. 5, the resultant increase of the material removal rate does not give rise to a higher grinding force. In combination with the higher fracture toughness of ceramics under the condition of high-speed grinding, the ground surface also presents ductile grooves when the material removal rate is 4.16 mm$^3$/mms. Also, SEM results are in accordance with the single grit scratch simulation (Fig. 8a, c). Under the condition of $v_s$=80 m/s, $v_w$=19.2 m/min, the plastic deformation can be recognized on the ground surface, although brittle fracture still occurs. With the elevated grinding wheel velocity and the proportionally increased workpiece speed, a semi-ductile removal mode can be achieved.

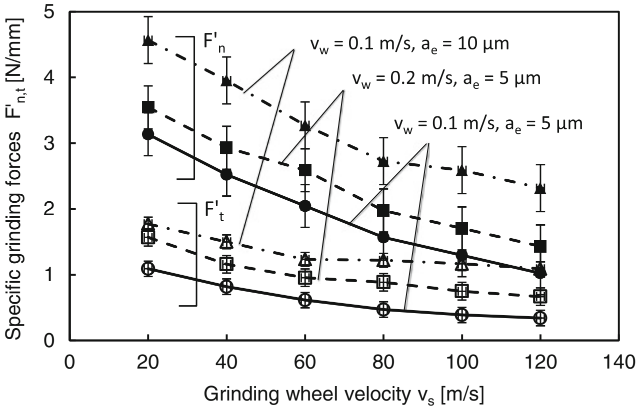


**Fig. 4** The effect of the wheel velocity on the specific grinding forces at $v_w$=0.1 or 0.2 m/s and $a_e$=5 or 10 μm

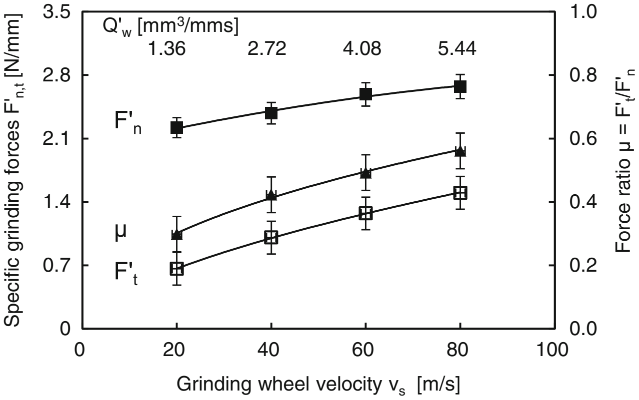


**Fig. 5** The effect of the wheel velocity and specific material removal rate on the specific grinding forces under $v_s/v_w$=250 and $a_e$=0.013 mm

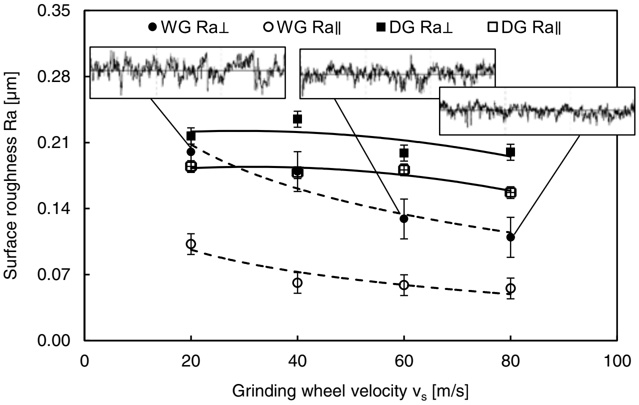


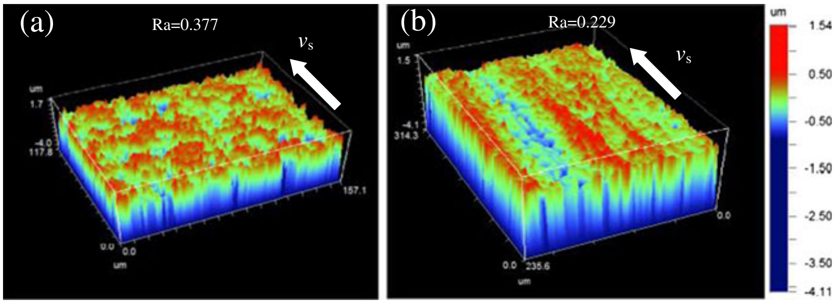
**Fig. 6** Surface roughness under the wet grinding (*WG*) and dry grinding (*DG*) as a function of grinding wheel speed

## 3 Definition on high-speed grinding for grinding target

In the past, it is called high-speed grinding that grinding wheel speed equals to 45 m/s or above. Currently, in most of the industry, it is called high-speed grinding that grinding wheel speed equals to 60 m/s or above. However, in the academic areas, grinding wheel speed is equal to 120 m/s or higher. It is called super high-speed grinding when grinding wheel speed is equal to 150 m/s or above. There are two problems with the above definition as follows: (1) It involves only the wheel speed, without involving the other parameters of the grinding process; (2) It does not involve grinding goals on quality, efficiency, and cost.

Therefore, in addition to high-grinding wheels speed, the definition may also need to take into account the comprehensive performance on quality, efficiency, and cost in view of the importance to the overall grinding system competitiveness. According to the contemporary advanced typical grinder and grinding wheel, the definition of high-speed grinding can be made by different material properties and its high-performance grinding characteristics. According to Schaudt and Junker, the highest speed of grinder wheel is 200 m/s, and

**Fig. 7** Ground surface morphology of SiC under $a_p$= 13 μm, **a** $v_s$=20 m/s, $v_w$=4.8 m/min, **b** $v_s$=120 m/s, $v_w$=28.8 m/min

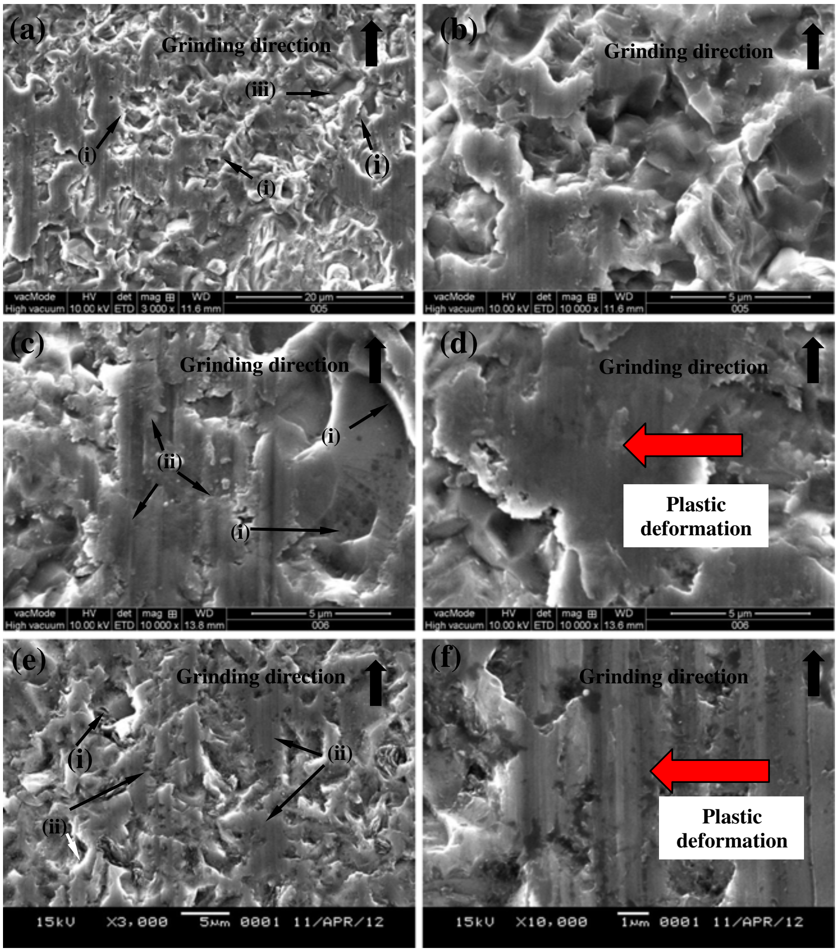


high-speed microfeed precision is 0.2 μm [17]. Take WINTER grinding wheel for an example, the maximum line speed of CBN wheel is 200 m/s, but diamond wheel is only 80 m/s because of high temperature leading to diamond carbonization (http://www.schleifring.net/en/brands/schaudt.html).

High-speed grinding of brittle materials can be defined, when its wheel speed $v_s \geq 80$ m/s and ultra-high-speed grinding is $v_s \geq 120$ m/s. The reasons of the definition listed are as follows:

1. The brittle material ductile grinding undeformed chip thickness is characterized in that the maximum threshold value and the maximum undeformed chip thickness can be effectively reduced by increasing the wheel speed.
2. The grinding brittle materials subject to the limitations of the current wheel speed. $v_{\mathrm{smax(brittle\ materials)}}=\min[v_{\mathrm{smax\ (diamond\ grinding\ wheel)}}, v_{\mathrm{smax\ (high\text{-}speed\ grinder)}}]=80$ m/s.
3. The better grinding quality be obtained using diamond grinding wheel when $v_s$ equals to 120 m/s. However, a

**Fig. 8** Ground surface characteristics of SiC under **a**, **b** $v_s$=20 m/s, $v_w$=4.8 m/min, $a_e$= 13 μm; **c**, **d** $v_s$=80 m/s, $v_w$= 16 m/min, $a_e$=3.8 μm; **e**, **f** $v_s$= 80 m/s, $v_w$=19.2 m/min, $a_e$= 13 μm. **b**, **d**, **f** are close-up views of (**a**, **c**, **e**), respectively. (*i*) Brittle fractures, (*ii*) smeared area by plastic deformation, and (*iii*) grains dislodgement



large number of test results need to be further examined in order to determine the durability of the grinding wheel.

## 4 Summary

This paper proved that the speed effect of high-speed grinding will change the contact behavior between the brittle material and the abrasive grit, so that the penetration depth of each grit can be greatly enlarged without fracture cracks generation. Compared with the criterion purposed by earlier researches for the brittle–ductile regime grinding, the results of simulation and experiment of this paper show that actual transition point is larger than that derive from the quasi-static condition. With the elevated grinding wheel velocity, higher grinding productivity of brittle material can be achieved without brittle fracture on the ground surface. In the end, the definition on high-speed grinding for grinding target is provided.

**Acknowledgments** This work is supported in part by the National Basic Research Program of China (2009CB724403) and the National High Technology Research and Development Program of China (2012AA041309).

## References

1. Mamalis AG, Kundrak J, Gyani K (2002) On the precision grinding of advanced ceramics. Int J Adv Manuf Technol 20(4):255–258
2. Ramesh K, Yeo SH, Gowri S (2001) Experimental evaluation of super high-speed grinding of advanced ceramics. Int J Adv Manuf Technol 17(2):87–92
3. Hwang TW, Malkin S (1999) Grinding mechanisms and energy balance for ceramics. J Manuf Sci E-T ASME 121(4):623–631
4. Schulz H, Moriwaki T (1992) High-speed machining. CIRP Ann Manuf Technol 41(2):637–643
5. Hwang TW, Evans CJ, Malkin S (2000) An investigation of high-speed grinding with electroplated diamond wheels. CIRP Annals Manuf Technol 49(1):245–248
6. Malkin S, Guo C (1989) Grinding technology: theory and applications of machining with abrasives. Ellis Horwood Press, Chichester, England
7. Bifano TG (1988) Ductile-Regime Grinding of Brittle Materials. Dissertation, North Carolina State University
8. Bifano TG, Dow TA, Scattergood RO (1991) Ductile-regime grinding: a new technology for machining brittle materials. J Manuf Sci E-T ASME 113(2):184–189
9. Ravichandran G, Subhash G (1995) A micromechanical model for high strain rate behavior of ceramics. Int J Solids Struct 32(17,18): 2627–2646
10. Hall IW, Guden M (1998) High strain rate behavior of a SiC particulate reinforced Al2O3 ceramic matrix composite. Scr Mater 38(4): 667–674
11. Grady DE, Lipkin J (1980) Criteria for impulsive rock fracture. Geophys Res Lett 7(4):255–258
12. Klocke F, Beck T, Hoppe S, Krieg T, Müller N, Nöthe T, Raedt HW, Sweeney K (2001) Examples of FEM application in manufacturing technology. J Mater Process Technol 120(1–3):450–457
13. Wang JJ, Zhu JG, Chiu CF, Zhang H (2007) Experimental study on fracture toughness and tensile strength of a clay. Eng Geol 94(1–2): 65–75
14. Zhang ZX (2002) An empirical relation between mode I fracture toughness and the tensile strength of rock. Int J Rock Mech Min 39(3):401–406
15. Huang H (2009) High-speed grinding of advanced ceramics: a review. Key Eng Mat 404
16. Schneider GA (1989) Thermoschockverhalten von Hochleistungskeramik. Dissertation, University of Stuttgart
17. Couvy H, Lahiri D, Chen J, Agarwal A, Sen G (2011) Nanohardness and Young's modulus of nanopolycrystalline diamond. Scr Mater 64(11):1019–1022