Int J Adv Manuf Technol (2017) 89:2221–2229
DOI 10.1007/s00170-016-9237-5

ORIGINAL ARTICLE

Strain rate-sensitive analysis for grinding damage of brittle materials

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Received: 4 May 2016 / Accepted: 25 July 2016 / Published online: 10 August 2016
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Abstract Grinding of brittle materials will inevitably cause grinding damages characterized by fracture microcracks, which will greatly affect the grinding integrity. Traditional damage models are just concerned about the material properties and interaction depth between grit and workpiece without considering the dynamic effect on material strength. This paper proposed new damage analysis models which consider the effect of both strain rate and grinding parameters on grinding damages. It is believed that the material strength and dynamic fracture toughness vary under different grinding parameters due to the variation of strain rate brought by the grinding speed and chip thickness. By introducing the grinding-induced strain rate, the new damage models were further updated as the function of the grinding speed and chip thickness. The grinding damage models were verified through different grinding tests. Combining with the surface roughness results, the grinding damages under different grinding speed and damages are fully discussed. Finally, the damage-free grinding was proposed based on the proposed model. It can be concluded that a combination of the grinding speed and reduction of the chip thickness can help achieve damage-free ground surface.

Keywords Grinding damage · High-speed grinding · Silicon carbide · Strain rate · Surface roughness

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1 Introduction

Silicon carbide ceramics are now being widely used in engineering applications such as bearings, valves, and electronics for their high hardness, excellent wear resistance, and extremely high-temperature strength [1]. Diamond grinding [2, 3] is generally considered as the main machining method to obtain a desired dimensional tolerance and surface integrity in precision engineering. However, due to the hard and brittle nature of the brittle materials, machining of this ultra-hard ceramic material will inevitably cause microcracks and surface/subsurface damages [4] which will deteriorate surface quality [5] and further affect the effective use of these materials in structural applications [6]. Therefore, in order to inhibit grinding damages, a good understanding of damage mechanism under different process parameters is necessary.

In the study of brittle material grinding, the indentation fracture mechanics approach likens abrasive-workpiece interactions for grinding of ceramics to small-scale indentation events [7]. In indentation of brittle materials, there exist generally two principal crack systems [8], the lateral and median cracks. They are formed after the plastic deformation between the grit and the workpiece. Lawn et al. [9] developed a theory for describing the evolution of the median/radial crack system in the far field of sharp indenter contacts considering the complex elastic/plastic field beneath the indenter. Lambropoulos et al. [10] presented the theoretical calculation function of lateral and median cracks based on micro-indentation mechanics. Based on Lambropoulos' model, Li et al. [11] and Yao et al. [12] modeled the relationship between subsurface damage and surface roughness of optical materials in grinding processes. Gu et al. [13] established a model for the correlation between the depth of the subsurface cracks and the scratch depth through scratch tests of optical glass BK7. Subsequently, Lin et al. [14] investigated the surface integrity during diamond grinding of BK7. However, the above works

for investigations of grinding damages are mainly conducted under a conventional grinding speed with a static description of induced grinding damages.

The grinding wheel speed was used as a parameter to inhibit surface crack generation [15] in the grinding of brittle materials. Wang et al. [16] developed a new model for the relationship between the grinding damage and grinding parameters in high-speed grinding of brittle materials. But, there is no theoretical explanation or consideration of the strain rate effect brought by the grinding wheel speed and chip thickness. This does not match the real situation of the grinding process. In the high-speed grinding of brittle materials, the increase of the wheel velocity will definitely enhance the strain rate of the material when the grinding wheel interacts with the workpiece. It has been reported that the increase of the strain rate will greatly affect the material mechanical properties, especially for strength [17]. The fracture stress will increase with increasing strain rate in monolithic and composite ceramic materials [17, 18]. Therefore, in order to fully evaluate the damages in grinding processes, the strain rate effect brought by the increased wheel speed should be fully discussed.

From the above literature review, it is obvious that the strain rate has a great effect on the material properties and should be considered in the study of grinding damages. Therefore, this paper is devoted to evaluate the damage mechanism by considering both the grinding parameters and strain rate effect brought by the wheel speed and chip thickness. The indentation fracture mechanics theory was applied to explain the grinding mechanism and obtain general damage models considering the chip thickness. Furthermore, the strain rate was incorporated into the damage model in the function of a combination of grinding speed and chip thickness. Finally, high speed grinding experiments were conducted to verify the proposed damage model through SEM observations of both the surface and subsurface damages. Moreover, 3-D topology surface roughness data were also given to explain the speed and chip thickness effect in grinding processes. A final discussion of damage-free grinding of brittle materials helps to provide more in-depth understanding of grinding mechanism for brittle materials.

1.1 General description of damage formation in grinding processes

In grinding of brittle materials, the interaction between the abrasive grit and workpiece can be regarded as a scratch process [12–14]. The geometrical damage formation schematic can be seen in the Fig. 1. As shown in Fig. 1, two different crack systems will be produced when the grit scratches across the workpiece, the lateral crack and median crack. It is generally believed that brittle materials are removed by the formation of lateral crack beneath the contact compression, at a depth in the plastic zone, followed by the subsequent outward propagation of lateral crack and final emergence to the material surface [16]. The theoretical equation of lateral crack depth C_l can be expressed as a function which is related to the material properties and the interaction depth between the wheel and workpiece [19].

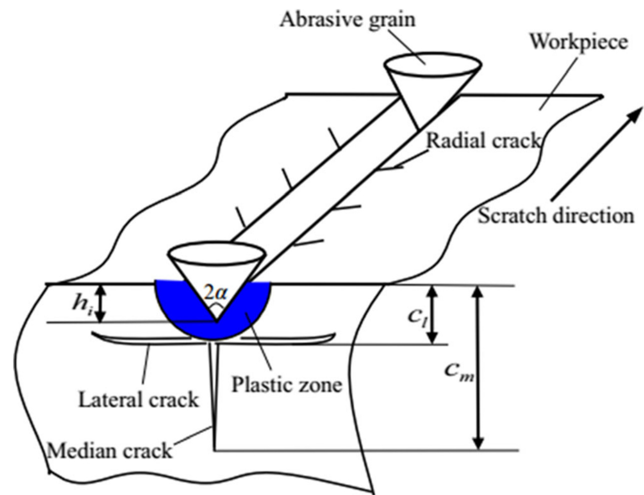

Fig. 1 Grinding damages in the scratch process [12, 16]

$$\mathrm{SD} = C_l = \left[\frac{3(1-2\nu)}{5-4\nu} + \frac{2\sqrt{3}}{\pi(5-4\nu)}\frac{E}{\sigma_c}\cot\alpha\right]^{1/2}\tan\alpha . h_i \quad (1)$$

where E is the elastic modulus, h_i represents the interaction depth between the abrasive grit and the material. In grinding processes, it represents the chip thickness. ν and σ_c, respectively, are the Poisson's ratio and the yield strength in compression test. α is the semi-included angle of the abrasive grain (as illustrated in Fig. 1), it is given 60° [20]. In the grinding process, the lateral crack is generally reflected by the surface crack size, which will greatly affect grinding surface roughness.

The median crack extends perpendicularly to the grinding surface with a sharp indenter, and it is considered as the main type of the subsurface crack [16]. The median crack length is similar to the lateral crack length. The theoretical equation of median crack depth C_m can be given as follows [13].

$$\mathrm{SSD} = C_m = 0.206\frac{(E.H)^{1/3}}{(K_{IC}.\beta)^{2/3}}(\cot\alpha)^{4/9}(\tan\alpha)^{4/3}.h_i{}^{4/3} \quad (2)$$

where H is the scratch hardness, K_{IC} is the fracture toughness and β is a material parameter determined by elastic recovery.

In the grinding process, the interaction depth h_i will not be higher than the maximum undeformed chip thickness h_m and the maximum theoretical damage crack size would be the interaction depth h_i is equal to the chip thickness h_m. The chip

thickness was used to characterize the depth of penetration for a single girt and can be given as follows [21].

$$h_{\mathrm{m}} = \left(\frac{3}{C_d.\tan\alpha}.\frac{V_w}{V_s}.\sqrt{\frac{a_e}{d_e}}\right)^{\frac{1}{2}} \tag{3}$$

where C_{d} represents the active abrasive grits number in unit area. V_{s} and V_{w}, respectively, represents the wheel speed and workpiece peripheral speed a_{e} is the depth of cut, d_{e} is the equivalent diameter, $d_{\mathrm{e}} = d_{\mathrm{s}}.d_{\mathrm{w}}/(d_{\mathrm{s}} + d_{\mathrm{w}})$. d_{w} represents the workpiece diameter and d_{s} is the wheel diameter. The value of C_{d}, in Eq. (2), can be derived as follows [3]:

$$N_{\mathrm{d}} = 4\chi/\left\{{d_{\mathrm{g}}}^2(4\pi/3\omega)^{2/3}\right\} \tag{4}$$

where d_{g} is the equivalent spherical diameter of diamond grit, ω is the volume fraction of diamond in the grinding wheel and volume fraction ω is 0.375 when the grinding wheel in this paper has a density of 150 [22]. χ is the fraction of diamond particles that actively cutting in grinding. The active grits are assumed that one third of the total abrasive particles are actively engaged in cutting [23], or the value of χ is given 1/3.

2 Strain rate effect in damage evaluation

In the previous damage model (1) and (2), it can be found that the grinding damage was only dependent on the indentation depth and material properties. However, the machining process is a dynamic process; the variation of strain rate brought by the wheel speed has been proved to have a corresponding effect on the material strength [17, 24, 25]. Therefore, the strain rate effect should be fully considered. It is suggested that the compression failure strength in the high strain rate regime is highly strain rate sensitive and it is given as follows [17, 26]:

$$\sigma_{\mathrm{c}} = \sigma_0 + B\left(\dot{\varepsilon}\right)^{1/3} \tag{5}$$

where $\varepsilon^{\cdot}$ is the strain rate exerted on the material, σ_0 is the static compression strength and B is a constant. The strain rate is used to characterize the deformation velocity of the workpiece material; it is the derivative of the strain to the time. In the high-speed grinding, the increase of the grinding speed will lead to an increase of the strain rate substantially and the strain rate can be calculated through the wheel speed divided by specimen length l_{s}. It can be expressed as follows [27, 28]:

$$\dot{\varepsilon} = \frac{V_{\mathrm{s}}}{l_{\mathrm{s}}} \tag{6}$$

In the grinding process, the specimen length l_{s} is highly related to the grinding wheel type, topology, process parameters and workpiece material. It can be expressed as [17]:

$$l_{\mathrm{s}} = k_1.h_{\mathrm{m}} \tag{7}$$

where k_1 is a constant which is decided by the wheel type, topology, and workpiece material. According to Eqs. (5), (6), and (7), the new description of the strain rate-sensitive compressive strength can be given as follows.

$$\sigma_{\mathrm{c}} = \sigma_0 + B\left(\frac{V_{\mathrm{s}}}{k_1.h_{\mathrm{m}}}\right)^{1/3} \tag{8}$$

For further investigation of the fracture toughness of the brittle materials from dynamic fracture toughness model proposed by Liu et al. [24], the fracture toughness has the following correlation with the strength.

$$\sigma_{\mathrm{c}} = \frac{K_{\mathrm{IC}}}{\sqrt{\pi L(1-\nu^2)}} \tag{9}$$

where L is crack length in static condition, it is a material constant. Therefore, combining Eqs. (8) and (9) and with Eqs. (1) and (2), the damage evaluation model considering the effect of strain rate and grinding parameters can be obtained. For expression simplification, the constant will all be brought out and substituted by a new constant.

$$\begin{cases} C_{\mathrm{l}} = \left[\frac{3(1-2\nu)}{5-4\nu} + \frac{2\sqrt{3}}{\pi(5-4\nu)}\frac{E}{\sigma_0 + \lambda(V_{\mathrm{s}}/h_{\mathrm{m}})^{1/3}}\cot\alpha\right]^{1/2}\tan\alpha.h_{\mathrm{m}} \\ C_{\mathrm{m}} = \frac{(E.H)^{1/3}}{k\left(\sigma_0 + \lambda(V_{\mathrm{s}}/h_{\mathrm{m}})^{1/3}\right)^{2/3}}(\cot\alpha)^{4/9}(\tan\alpha)^{4/3}\cdot{h_{\mathrm{m}}}^{4/3} \end{cases} \tag{10}$$

In the above damage model, k and λ are the material constants and they will be obtained through experiments. From this model, it can be found that both the grinding speed and chip thickness are the main factors that will affect the grinding damages. When the chip thickness is kept constant, the increase of the grinding wheel speed will diminish the grinding damage depth, while when the grinding speed is kept constant, the enhancement of the chip thickness will increase the material removal rate, and thus, the grinding damage will get higher.

3 Experiments

The experimental conditions are given in Table 1. The grinding machine spindle is capable of running up to 8000 rpm with a 400-mm wheel. The spindle drive motor power can reach up to 41.9 kw. The reaction-sintered SiC in Table 2 was used for investigation. And, the workpiece specimens have a diameter of Φ60 mm with a width of 20 mm. The grinding wheel was

Table 1 Grinding conditions

Type	Content
Machine tool	CNC cylindrical grinding machine MGKS1332/H
Grinding wheel	Vitrified Diamond Wheel D91 V+ 2046 J1SC-23 C150 E
Wheel width	22 mm
Machining mode	Plunge Up grinding
Wheel speed	20–150 m/s
Workpiece speed	300–1200 mm/min
Depth of cut	2–20 μm
Cooling	Water-based emulsion 5 % at the speed of 10 L/min
Wheel spindle balancing system	Model SB-4500 under 0.03 μm

balanced below 0.03 μm at the grinding speed with a dynamic balancing instrument (Model-SB-4500) installed on the spindle. The grinding wheel was trued using a diamond truer and dressed using an alumina stick of 200-mesh size for 30s under a coolant before every set of test was undertaken. The grinding surface and subsurface damages were observed through an environment scanning electron microscope (ESEM) QUANTA 250 from Czech. Before observation, the workpiece was first polished and then cleaned with acetone in an ultrasonic bath for at least 20 min. Moreover, the surface roughness was measured through a Bruker Nano Surface white light interferometer (Npflex). In Fig. 2, the detailed experiments were established on a cylindrical grinding machine. In this figure, the specimen was given in Fig. 2(a). The quarter part was used to observe the surface and subsurface damages. The contact area between the two parts was the polished area for subsurface damage observation on a scanning electron microscope.

4 Results and discussions

4.1 Grinding damages under different grinding speed and chip thickness

From formulas (1) and (2) in chapter 2, the grinding damages were only dependent on the material properties and chip thickness between the grit and workpiece, which means that if the chip thickness is kept constant, the grinding damages will not change when the wheel speed varies. From the SEM results in Fig. 3, this does not fit the real observation results. Therefore, the surface and subsurface damages considering both the chip thickness and grinding speed were given in the SEM topology pictures in Fig. 3. It can be found from Fig. 3a, b that when the wheel speed increases, the surface damage crack size will get inhibited and the damage area will get smaller; more plastic striations can be found in Fig. 3b compared with fracture cracks in Fig. 3a. This is because the increase of the grinding speed will promote the strain rate in the grinding process, which will further enhance the material strength. Thus, a reduction of the surface damage is quite easy to understand from damage model in formula (9). However, the chip thickness shows a different influence on the surface damage in Fig. 3c. Comparing with Fig. 3b at a chip thickness of 0.52 μm, the surface fracture cracks in Fig. 3c get much bigger. This can be understandable from formula (9) that the increase of the chip thickness will increase the interaction depth between the grit and workpiece, which will cause a higher grinding force and, thus, more severe damages.

For the subsurface damages, the grinding speed and chip thickness shows the same physics with the surface damage. In Fig. 3d–f, the direction for (e) is different with (d) and (f) because the placed position of specimen is different. Two small parts in Fig. 1a were placed against together to keep flat when doing the SEM tests. In Fig. 3, in order to clearly measure the crack size of surface/subsurface damage, different magnifications for SEM figures were applied. The wheel speed effect in Fig. 3d, e shows that the increase of grinding speed can be used to inhabit the subsurface damage. While the chip thickness has a negative effect on the subsurface damages

Table 2 Mechanical properties for SiC

Material properties for SiC						
		Density ρ [g/cm^3]	Compressive strength σ_c [MPa]	Hardness H [GPa]	Fracture toughness K_{1C} [MPa.m$^{1/2}$]	Elastic modulus E [GPa]
SiC	3.22	2600	23	3.0	410	0.16

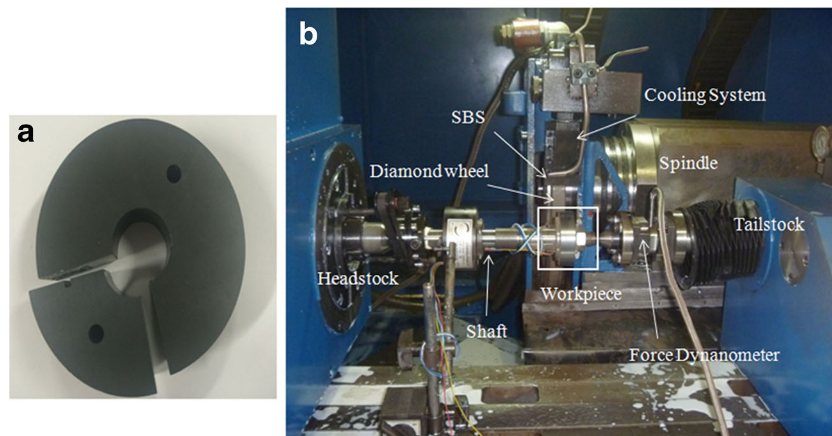

Fig. 2 SiC workpiece (**a**) and experiments setup (**b**)

in Fig. 3e and f. That is to say, in order to improve the surface quality and reduce grinding damages, the increase of grinding speed combined with the decrease of the chip thickness can be adopted. In order to calibrate and verify the reasonability of the strain rate sensitive damage model in formula (9), a group of experimental results are given in Table 3. In this table, the SD and SSD values are average data of three different tests. Based on the first five groups of experimental data in Table 3, the constants k and λ in formula (9) can be calculated. It is 0.07 for k and 0.3 for λ. In this table, the error of experimental value over the predicted value are given to show the prediction accuracy. The results show that the predicted values from formula (9) match very well with the experimental results. This proves that both the strain rate effect and interaction depth should be considered in the damage analysis.

4.2 Grinding surface roughness

Surface roughness is one of the most important factors in assessing the quality of a machined surface. In the grinding of brittle materials, it is inevitable to cause grinding damages. These damages are the main factors that affect the surface roughness. Therefore, the surface roughness can be used as a parameter to characterize and indicate the grinding damage. In this paper, a 3-D Bruker Nano Surface white light interferometer (Npflex)

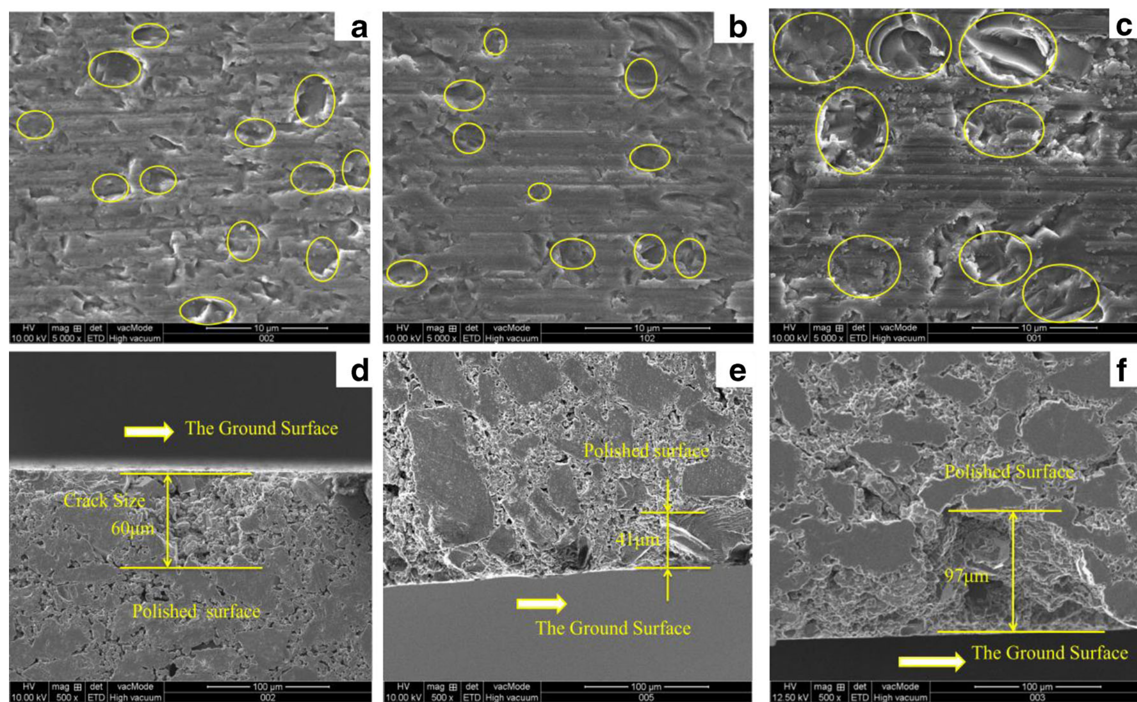

Fig. 3 Surface/subsurface damage SEM topology for SiC at **a** and **d** $V_s = 80$ m/s, hm = 0.52 μm; **b** and **e** $V_s = 140$ m/s, hm = 0.52 μm; **c** and **f** Vs = 140 m/s, hm = 1.04 μm; **a**–**c** ×5000; and **d**–**f** ×500

Table 3 Experimental results and its error with predicted value

Experimental No.	Wheel speed V_s (m/s)	Chip thickness h_m (μm)	Experimental SD (μm)	Error with predicted value (%)	Experimental SSD (μm)	Error with predicted value (%)
1	80	0.52	3.7	6	58	13
2	140	0.52	3.5	3	39	2
3	140	1.04	7.2	3	94	12
4	80	0.68	5.2	5	70	3
5	80	0.81	5.9	6	103	4
6	140	0.16	1.1	12	7	11
7	140	0.31	1.7	5	23	8
8	20	0.89	6.8	3	114	7

was used to measure the surface roughness value. The 3-D topology of the surface roughness and the values are given in Fig. 4. In this group of figures, the effect of grinding speed and chip thickness will be discussed. It can be seen from the Fig. 4a, b that when the grinding speed increases from 80 to 140 m/s, the surface roughness drops from 0.297 to 0.187 μm. Moreover, the surface topology at a higher grinding speed (140 m/s) has better surface finish and less pits and grooves than the picture in the lower speed (80 m/s). Figure 4b–d can explain the chip thickness effect on the surface roughness. The surface roughness at chip thickness of 1.04 μm is 0.317 μm (Fig. 4c), while it is 0.187 μm at a chip thickness of 0.52 μm (Fig. 4b) and 0.165 μm at chip thickness of 0.32 μm (Fig. 4d). The above results from the surface roughness show the same mechanism from the grinding damage. Therefore, it can be concluded that the increase of the grinding speed helps to inhabit the grinding damages and improve the surface quality. However, the reduction of the chip thickness helps increase the surface quality. Thus, in order to achieve higher surface quality, it can be suggested that a combination of the increase of the grinding speed and control of the chip thickness can be adopted.

4.3 Discussions of the damage-free grinding for SiC

In order to achieve damage-free and high-quality products without post processing, ductile-regime machining was put forward for brittle materials. This kind of machining mode can generate the chips through a mode of plastic deformation rather than fracture, and thus, a higher accuracy of the machined surface can be obtained. Bifano et al.[27] have proposed that ductile grinding

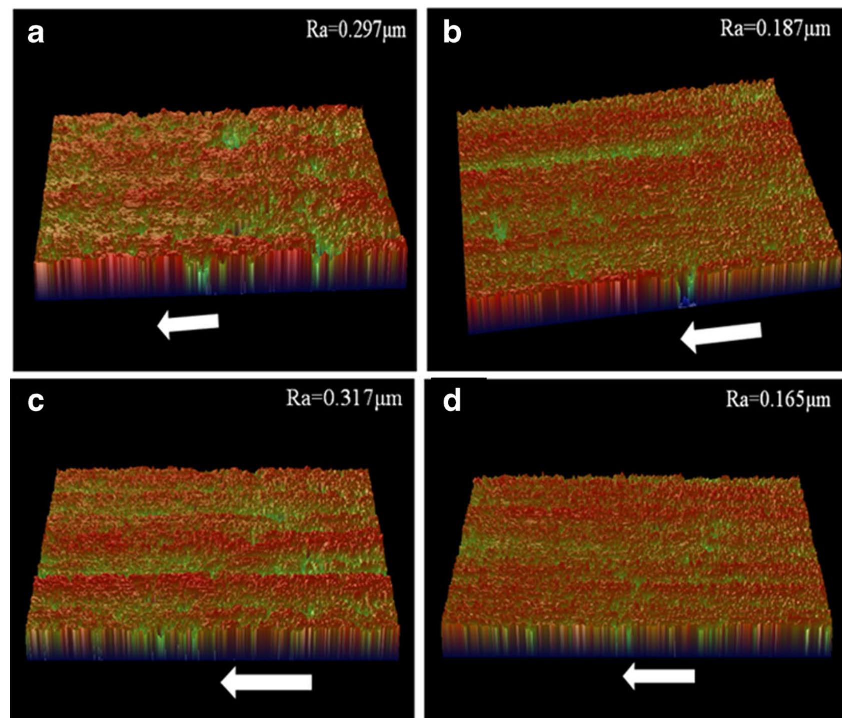

Fig. 4 Gound surface morphology of SiC. **a** $V_s = 80$ m/s, hm = 0.52 μm. **b** 140 m/s, hm = 0.52 μm. **c** $V_s = 140$ m/s, hm = 1.04 μm. **d** $V_s = 140$ m/s, hm = 0.32 μm. The *arrows* indicate the grinding direction

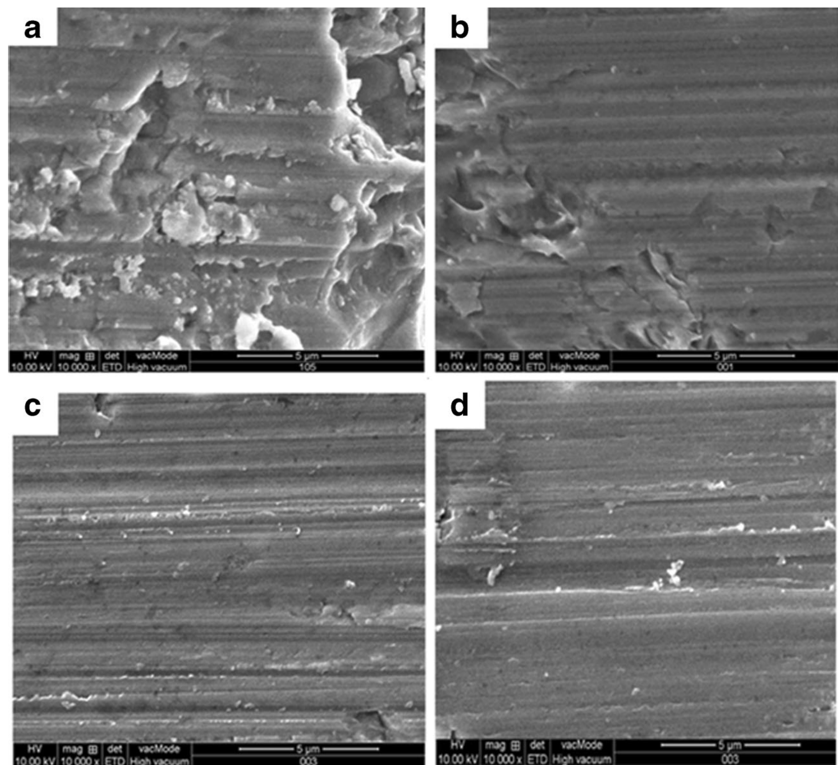

Fig. 5 Damage-free grinding of SiC under a higher grinding speed (140 m/s). **a** hm = 1.8 μm,60 % fracture. **b** hm = 1.04 μm, 32 % fracture. **c** hm = 0.32 μm, 8 % fracture. **d** hm = 0.16 μm, 4 % fracture

could be achieved in the machining of brittle materials when the chip thickness is small enough. And the critical depth for ductile grinding d_c was given [27]:

$$d_c = \beta\left(\frac{E}{H}\right).\left(\frac{K_{1C}}{H}\right)^2 \quad (11)$$

where β is a constant ($\beta = 0.15$ [27]), E is the elastic modulus, and H is the hardness. The experiments in this model were conducted under a constant grinding speed of 26.2 m/s. It can be found that this model is fully dependent on the material properties. Moreover, the critical value for ductile grinding of SiC is 0.045 μm, which means that only when the chip thickness h_m is not higher than 0.045 μm, the ductile grinding of SiC can be realized. According to this model, the ductile grinding can only be obtained at a very low chip thickness and very small material removal rate. It is very inefficient. However, in the previous chapters of this paper, it has been verified that different grinding parameters will cause the variation of the material strength and the fracture toughness. Thus, the grinding parameters should be considered in this model.

In chapter 5.1, it has been proved that the increase of the grinding speed will reduce the grinding damages. Thus, in order to obtain the damage-free surface, a higher grinding speed under low chip thickness should be adopted. Figure 5 gives the SEM observation results under different chip thickness. In this figure, a grid-counting technique [3, 27] was adopted to calculate the facture surface percentage. In this method, the whole SEM picture was divided into hundreds of squares. Then, the fracture surface proportion can be obtained through a selection of the fractured squares. It can be easily seen that the ground surface shows less grinding debris and fracture region with the decrease of h_m, from 1.8 to 0.16 μm. When the h_m is 1.8 μm, the fracture surface consists of 60 % of the whole ground surface, then a slightly decrease to 32 % for 1.04 μm. However, when h_m decrease from 1.04 μm to 0.32 μm,

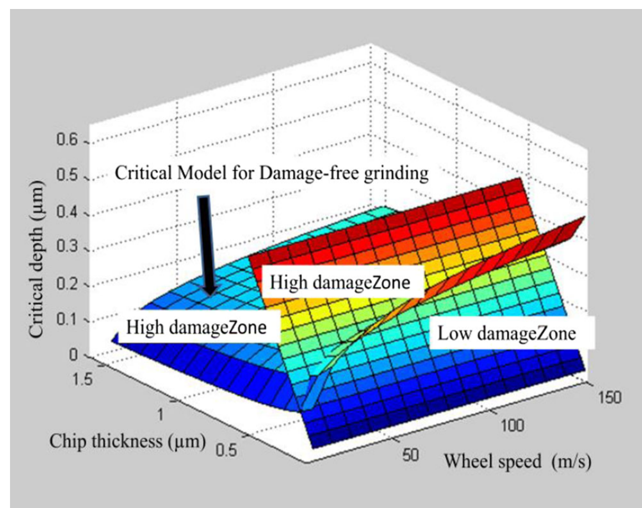

Fig. 6 3-D model for damage-free grinding considering the effect of grinding speed and chip thickness

the ground debris and fracture surface shows a substantially reduction, from 32 to 8 %. After that, when h_m continues to decrease, the ground surface shows a less grinding fracture. This can clearly conclude that the damage-free grinding of brittle materials can be realized at a combination of higher grinding speed and low grinding chip thickness. And, this chip thickness is much higher than the critical depth of 0.045 μm in equation (11). Thus, the material removal rate can be greatly improved.

The new model was established by substituting the fracture toughness K_{1C} in equation (9) and compressive strength σ_c in equation (8) into the model (11). Then the new critical model for silicon carbide can be given as follows:

$$d_{nc} = \beta' \left(\frac{E}{H}\right)\left(\frac{\sigma_0 + 0.3(V_s/h_m)^{1/3}}{H}\right)^2 \tag{12}$$

where d_{nc} represents the new chip thickness model considering the strain rate sensitivity. β' is the material constant. According to the calibration of model (10), the constant β' can be given 0.4 for SiC.

Based on the new critical chip thickness model (12), the three dimensions (3-D) description for the new critical depth model considering the grinding speed and chip thickness was plotted in Fig. 6. In Fig. 6, the curved surface is the critical value for the predictive damage-free model, while the plane is the criterion that the chip thickness h_m is equal or below to the critical value. It is obvious that the increase of the wheel speed will lead to an increase of the critical value, while the chip thickness shows a negative trend. Moreover, the damage-free zone is under the new critical model curved surface when the chip thickness h_m is equal or smaller than the critical value, and it is indicated in the outward part of the space intersection between the two surfaces. The remains are the zones that may cause high surface damages.

5 Conclusions

Grinding damages in brittle materials are always the main factors that affect the machining quality. This is because that it is inevitable to cause microcracks in machining of the brittle materials for their high hardness and low fracture toughness nature. The traditional damage models were constructed based on the material properties, and it was generally thought to be only dependent on grinding parameters. Based on the strain rate-sensitive analysis of brittle materials, this paper proposed new damage analysis models which consider the effect of both strain rate and grinding parameters on grinding damages. By introducing the strain rate brought by the grinding speed and chip thickness, the new damage models were further updated as a function of the grinding speed and chip thickness. Thus, the new grinding damage models considering both the effect of strain rate and interaction depth were established. Experiments on the SEM observations and surface roughness results are used to verify the proposed model. Moreover, the new critical chip thickness model of damage-free grinding are discussed to provide further application of high-quality grinding.

The following conclusion can be drawn from this paper:

1. The increase of the grinding wheel speed can diminish the grinding damage for SiC while not deteriorating subsurface damage. Moreover, the surface roughness keeps a stable improvement with the increase of wheel speed and more plastic deformation not fracture cracks in the ground surface can be observed under a higher grinding speed.
2. The reduction of the chip thickness will help to improve the surface quality and achieve damage-free surface by reducing the surface damages. Moreover, the subsurface damage is lesser when the chip thickness decreases.
3. In the study of damage-free grinding of brittle materials, the critical depth for ductile grinding of SiC can be greatly improved through a combination of the increase of the wheel speed and the control of chip thickness. This will also help to substantially increase the material removal rate while not sacrificing the machining quality.

Funding This work is supported by the National Major Projects (2013ZX04001-141), National High Technology Research and Development Program of China (2012AA041309), Innovation Funds of Donghua University (CUSF-DH-D-2015100) and Morris M. Bryan Jr. Professorship for Advanced Manufacturing Systems in Georgia Institute of Technology. The authors wish to record their gratitude to their generous supports.

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