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Experimental investigations of machining characteristics of SiC in high speed plunge grinding

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Grinding is widely used as a productive technique for finishing ceramic components in the manufacturing industry. However, it is still difficult to achieve a satisfying finishing quality for scarce of comprehensive engineering investigations of damage-free and economical techniques of advanced ceramics. This paper will utilize a high speed grinder to develop the grinding forces, temperature, grinding surface and subsurface features in high speed plunge grinding of SiC. The ductile grinding of SiC under a relatively high grinding speed will be investigated. A set of detecting equipment, including a rotating dynamometer and a grindable thermocouple, will be used to measure the online grinding forces and temperature. Besides, the subsurface damage, chips and ground surface will be examined by SEM micrographs. It has been found that ductile grinding of SiC can be achieved through a combination of the increase of the wheel speed and the control of grinding parameters. Via causing lower force and thermal effects, the critical value for ductile grinding of SiC can be greatly improved under high speed grinding comparing to conventional speed grinding. Moreover, the grinding subsurface integrity will not be adversely effected though improving material removal volumes under high speed grinding.

Key words: High speed grinding (HSG), Silicon carbide, Grinding characteristics, Ductile grinding.

Introduction

Advanced ceramics such as silicon carbide are now being increasingly used in various engineering applications such as bearings, valves, rotors and optical components, etc. However, it is very difficult to machine them because of their great hardness and brittleness. Grinding with diamond wheels [1-3] has become the main processing method that can be expected to achieve the desired dimensional tolerance and surface integrity. The HSG process was characterized by the elevated wheel velocity of above 60 m/s, which dramatically reduces the maximum chip thickness and improves grinding quality comparing to the conventional grinding with a wheel speed of below 40 m/s. Nevertheless, because of the high cost and scarcity of practical research, most studies for grinding characteristics of ceramics were generally conducted at a lower wheel speed [3-6] (below 60m/s). Several important studies aimed at high speed [2,7-10] and low-damage [11, 12] grinding of advanced ceramics, mainly silicon nitride [1, 2], alumina [8] and zirconia [2], favored the potential application of high speed grinding in achieving high quality ceramics grinding.

In material removal processes, the elevation of the wheel speed will result in a smaller chip thickness, thus a decrease of the grinding force. Moreover, the rapid temperature rise is directly related to part quality. An interesting hypothesis [13] proposed by Carl Salomon indicated that at first the temperature rises with increasing wheel speed, but under certain circumstances if the wheel speed is increased enough the temperatures actually begin to fall again. Though there is no consistent conclusion about this hypothesis, lots of practical work in milling [14], turning [15] and grinding [16] of metallic materials have been developed to prove it. But little work has been reported about the discussion of HSG effects on grinding surface temperature of ceramic materials. Therefore, investigations on the exact temperature characteristics for HSG of advanced ceramics are extremely important.

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 [17]. In order to avoid brittle fracture in 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 [18-19] focused on the surface finish only, and rarely involved the mechanism of high-speed grinding to achieve quality and efficiency and the surface integrity. Theoretically, the increment of wheel speed will promote ductile flow by reducing the tendency for brittle fracture. Kovach *et al.* [20] clearly demonstrated that the application of high speed grinding into the machining of advanced ceramics resulted in an improved surface finish. Their

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results also showed a transition from a brittle fracture mode to a low damage ductile grinding mode could be achieved by the increasing of the wheel speed. Similar results were also achieved in the high speed grinding of silicon nitride [21]. T.G Bifano [6] proposed a critical chip thickness model for various brittle materials. However, this model was established under conventional wheel speed and does not apply for high speed grinding, there still lack of a quantitative description of ductile grinding of brittle materials.

The literature review above indicates that most studies for grinding of ceramics are conducted at a low wheel speed and scarcity of comprehensive investigations on practical study of high speed grinding of SiC. Besides, little work has discussed the ductile grinding of SiC under a high wheel speed. This paper is devoted to systematic investigations on the grinding forces, temperature, grinding surface and subsurface features in high speed plunge grinding of SiC utilizing a high speed grinder. A set of detecting equipments, including a rotating dynamometer and a grindable k-type thermocouple, will be used to measure the online grinding forces and temperature. A series of SEM pictures will be used to analyze the subsurface damage, chips and ground surface. This paper will discuss the effects of process parameters on the induced grinding forces and temperature and analyze the influencing sensitivity. Moreover, the effects of grinding wheel speed on the ground surface, subsurface damage and the grinding chips were investigated. Finally, the ductile grinding for SiC under high wheel speed will be proposed and a new critical chip thickness will be achieved through HSG of SiC.

Experimentation

Grinding experiments were carried out on the MGKS1332/H CNC cylindrical grinding machine. The machine spindle is capable of running up to 8000 rpm with a 400 mm wheel. The spindle drive motor power is 41.9 kw. The workpiece material used for this investigation was SiC, whose properties are given in Table 1. The workpiece specimens have the diameter of 60 mm with the length of 20 mm. A vitrified diamond grinding wheel, with an average grit size of 91 μm, diamond concentration of 150%, diameter 400 mm and width 22 mm, was used. The wheel was balanced below 0.03 μm at the grinding speed with a dynamic balancing instrument (Model SB-4500). A series of shallow plunge grinding experiments will be developed in this paper. The grinding wheel was trued using a diamond truer and dressed using an alumina stick of 200 mesh size for 30s under coolant before every set of test was undertaken. The truing ratio for the grinding wheel is 0.8 under a wheel speed of 80 m/s, the depth of cut 2 μm and the transverse feedrate of 400 mm/min. In this paper, a 5% water-soluble metal cutting fluid was used.

The grinding force and temperature test scheme is illustrated in Fig. 1. The grinding force detecting device is a 3-direction force transducer (Kistler 9347C) mounted in the tailstock. The transducer is collected to a charge amplifier, then the collected signal is sent to the data acquisition system LMS. The grinding contact zone temperature was measured by a grindable thermocouple technique [22]. A column workpiece, as shown in the upper right of Fig. 1, is seperated into two pieces, a quarter part and the rest. A groove, which has a width of 0.5 mm and a depth of 0.1 mm, was made in one side of the quarter part. The surfaces and groove of two parts was further polished through a 0.5 μm diamond paste to remove residual stresses induced by machining. A k-type thermocouple, composed of nickel chrome and nickel silicon foils, was seperated by three mica sheets between the workpiece and foils and then embedded into the groove. The cold junctions of thermocouple was connected to a NI-USB 9213 DAQ card which have a sample rate of 1200s/s and can automatically offset error compensation.

An environment scanning electron microscope (ESEM) QUANTA 250 from Czech was used to examine the ground surface and subsurface damage. A bonded interface sectioning technique [23] was used to examine the grinding induced subsurface damage. Two parts of the workpiece were first polished and then bonded together using a cyanoacrylate-based adhesive. Clamping pressure was applied during bonding to ensure that a thin adhesive layer joint was achieved, which would minimize edge chipping during grinding. The grinding direction was perpendicular to the bonded interface. After grinding the bonded specimens were subsequently separated by heating on a hot plate to soften the adhesive. Before the examination, the ground specimens were cleaned with acetone in an ultrasonic bath for at least 20 min, and then gold coated. Another field

Table 1. Mechanical properties of SiC.

	SiC properties						
	density	Bending strength	Hardness	Fracture toughness	Elastic modulus	Poisson rate	Grain size
	P [g/cm^3]	σ_b [MPa]	H_v [GPa]	K_{IC} [MPa.m$^{1/2}$]	E [GPa]	R [–]	d_g [μm]
SiC	3.05	430	23	3.0	350	0.16	50

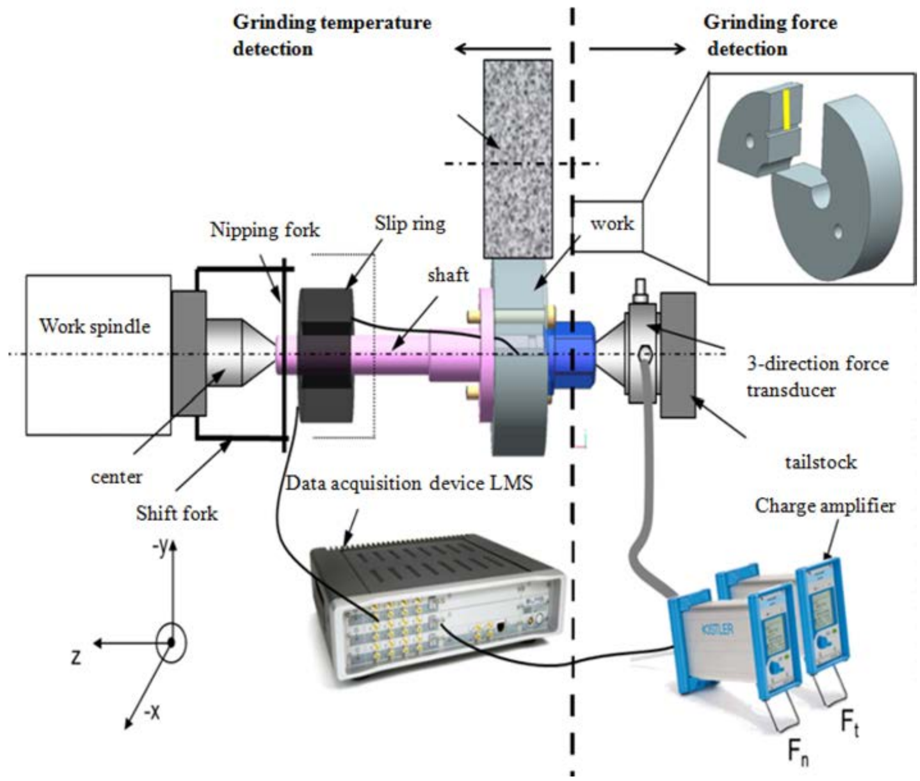

Fig. 1. Grinding test scheme.

emission scanning electron microscope (FE-SEM) S-4800 from HITACHI was used to examine the grinding chips. The grinding chips were collected with a double-sided adhesive putting under the wheel in dry grinding. When grinding, the chips will fall and cling to the adhesive tape. Then a piece of adhesive tape will be used to observe its micro morphology after gold coated.

Results and Discussion

Grinding forces in HSG of SiC

The grinding forces are very important quantitative parameter to characterize the material removal mode in grinding of advanced ceramics. In the high speed grinding (HSG), the measured forces were substantially influenced by the impact of the coolant [24]. Therefore, an additional test was undertaken to measure the coolant induced force in this work. In this test, in order to collect the force data induced by the coolant, the grinding wheel will not interact with the workpiece, but stay close to the workpiece for several seconds without cutting. Then this coolant-induced force will be subtracted from the force data acquired in thecutting process. Furthermore, the dynamometer outputs are the horizontal force Fx and the vertical force Fy. The tangential force Ft and the normal force Fn, respectively, shows a correlation with the experimental result of horizontal force Fx and vertical force Fy in the following equation.

$$\begin{aligned} Fn &= Fx.\sin\theta + Fy.\cos\theta \\ Ft &= Fx.\cos\theta - Fy.\sin\theta \end{aligned} \tag{1}$$

where θ is the included angle between the vertical vector perpendicular to the workpiece and the normal force vector on the grinding zone, written as $\theta = (2/3)\,cos^{-1}1 - 2(a_e/d_s)$, were subsequently separated by heating on a hot plate to soften the adhesive. Before the examination, the ground specimens were cleaned with acetone in an ultrasonic bath for at least 20 min, and then gold coated. Another field emission scanning electron microscope (FE-SEM) S-4800 from HITACHI was used to examine the grinding chips. The grinding chips were collected with a double-sided adhesive putting under the wheel in dry grinding. When grinding, the chips will fall and cling to the adhesive tape. Then a piece of adhesive tape will be used to observe its micro morphology after gold coated.

a_e is the depth of cut (DOC) and d_s is the wheel diameter.

Fig. 2(a) gives the depiction of the effect of grinding speed on the forces and force ratio. It can be seen from this figure that both the tangential force and the normal force decrease with the increase of the grinding speed. This has been proven in previous research [2]. In order to illustrate the machining mechanism, a calculated model of the maximum undeformed chip thickness [19] h_{cu} was given below.

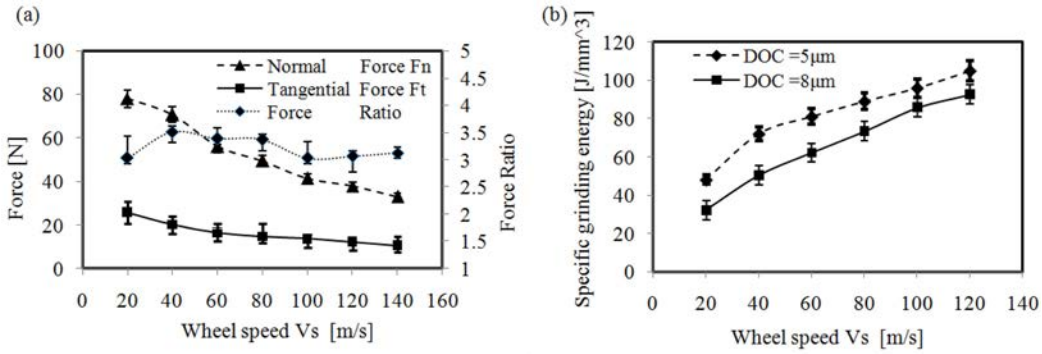

Fig. 2. Measured grinding forces versus the wheel speed.

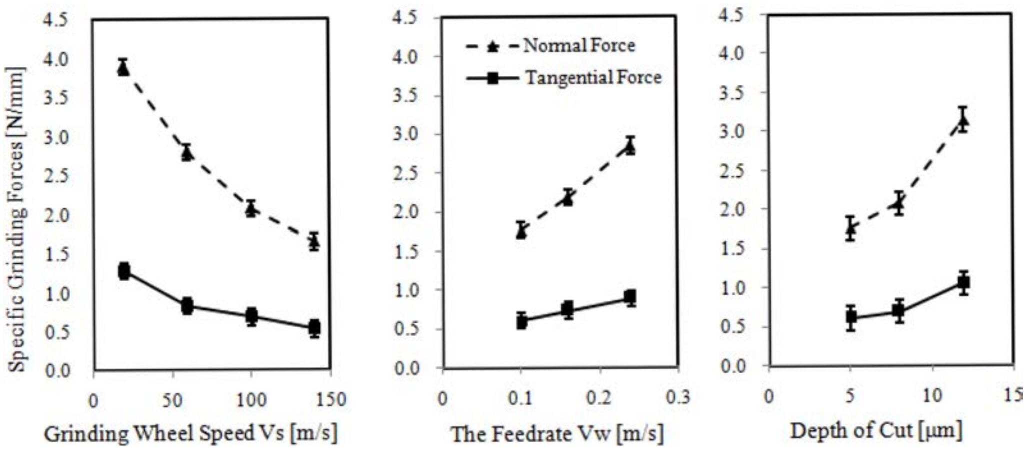

Fig. 3. Sensitivity analysis of process parameters.

$$h_{cu}=\left(\frac{3}{C_d.\tan\psi}\cdot\frac{V_w}{V_s}\sqrt{\frac{a_e}{d_e}}\right)^{\frac{1}{2}} \quad (2)$$

where C_d is the number of active grits in unit square area. Ψ is the vertex angle of single grit, and for calculation simplicity, the half vertex angle $\Psi/2$ is 60 ^{o} [2]. d_e is the equivalent diameter, $d_e=d_s.d_w/(d_s+d_w)$, , d_w the workpiece diameter. V_s and V_w, respectively, are the wheel speed and feedrate (workpiece cylindrical linear speed). It can be easily found from equation (2) that the increase of the grinding speed will lead to a decrease of the chip thickness h_{cu}. Combined with the Fig. 2(a), the smaller the chips, the lower the grinding forces will be produced. Moreover, the decrease gradient of the normal force is higher than the tangential force when the grinding speed increases. This is because that the normal force does not produce any work, while the tangential force is the main indicator to decide the grinding energy consumed in the cutting process. The increase of wheel speed changes the material removal mode, which is more inclined to ductile removal not brittle fracture. Therefore, the tangential force does not decrease as much as the normal force. For further illustration of this idea, the specific grinding energy is given in Fig. 2(b). It can be seen from this figure that the specific grinding energy increases with the increase of the wheel speed. Which means more grinding energy will be used to remove unit volume of material when the wheel speed increases. Moreover, the smaller the depth of cut is, the higher specific grinding energy is produced.

Fig. 3 gives a further sensitivity analysis of process parameters, including the wheel speed, the depth of cut and the workpiece feedrate. It can be found from this figure that the increase of the depth of cut and the workpiece feedrate will cause an increase of both the normal force and the tangential force for the increase of material removal volumes and the chip thickness h_{cu}, which is opposite to the wheel speed. Moreover, when the wheel speed lift from 20 m/s to 140 m/s (7 times' increment), the grinding forces only decline 2.5 times. While for the depth of cut and the feedrate, the increase of these two parameters will bring almost equal increase of grinding force. Therefore, the depth of cut and feedrate show a higher positive sensitivity in resulted grinding forces than the wheel speed, which shows a negative linear sensitivity.

HSG effects on temperature for SiC

In order to investigate the temperature characteristic of HSG for SiC, s series of experiments are developed. Fig. 4 shows the dry grinding temperature trendency under different wheel velocities while keeping the

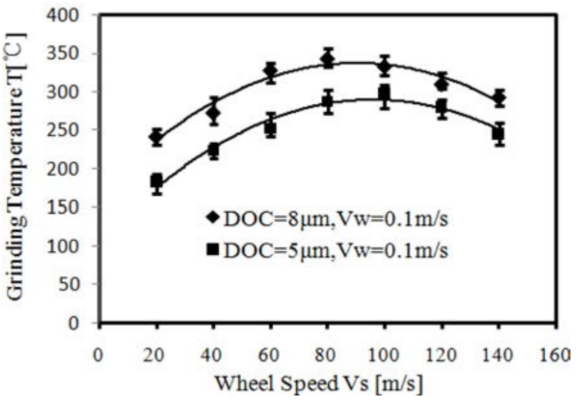

Fig. 4. HSG temperature characteristics for SiC in dry grinding.

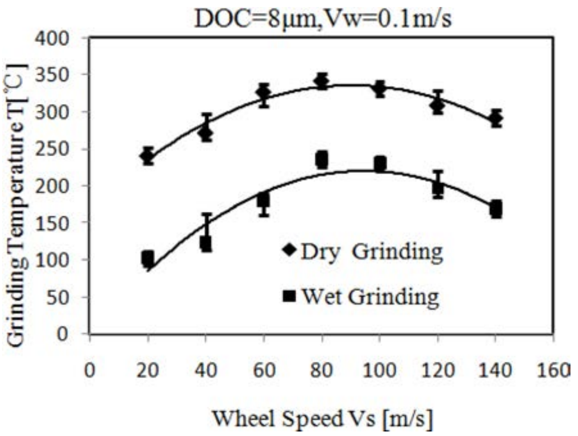

Fig. 5. Comparisons between dry and wet grinding.

depth of cut and feedrate constant. It can be seen from this figure that the surface temperature rises with the elevation of the wheel speed V_s when V_s is below 80m/s, after that the temperature drops down. This is partially because the faster the cutting action, the less time there is for the heat to enter the workpiece. And the heat is more likely to be taken away by the chips as the wheel passes through the workpiece at high speed. The new chip is generated before the heat produced by the former one conducted into the workpiece. At the speed of 20 m/s and 140 m/s, the grinding temperature is about 60-80% of temperature values at the speed of 80 m/s or 100 m/s (the depth of cut is 5ìm). Which means more than 20% of the mechanical heat-induced temperature rise can be reduced through the increase of wheel speed.

Coolants are widely used to reduce machining induced force and temperature and achieve better machining quality. Fig. 5 is the comparison between dry and wet grinding (5% water-soluble metal cutting fluid) temperature characteristics. For wet grinding, the grinding temperature is about 70% of dry grinding and it shows the same trend with dry grinding.

The effects of the depth of cut and feedrate on grinding temperature are illustrated in Fig. 6. From this figure, we can see the grinding temperature shows a positive linear

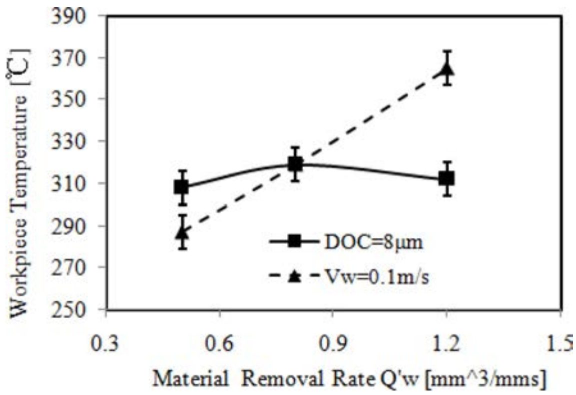

Fig. 6. MRR vesus grinding temperature.

relationship when the depth of cut increases (the feedrate keeps constant, while the MRR increase). While for the feedrate, the grinding temperature does not show any dramatic leap like the depth of cut. Both the elevation of the depth of cut and the feedrate will bring an increment of material removal rate (MMR), while the increase of workpiece feedrate will lead to a higher rotational speed of the workpiece, which will help to take more grinding induced energy away, thus it is not likely to induce an increase of the grinding temperature. However, the increase of depth of cut purely brings a higher MMR, which means more energy will be needed to bring the increased material volumes.

Therefore, we can judge from the above analysis that the depth of cut shows a higher linear sensitivity than the wheel speed and feedrate. However, the increase of the wheel speed will cause a quadratic sensitivity for the grinding temperature. Moreover, in the high speed grinding of SiC, the increase of the feedrate will help to quicken the heat dissipation, thus controlling a possible high temperature.

Grinding subsurface damage and chips

In the high speed grinding, the wheel speed shows a great effect in subsurface damage of advanced ceramics. The typical SEM micrographs of subsurface damage are shown in Fig.7. From this SEM examination, it can be judged that the subsurface damage layer is getting thinner, from 95ìm to 41 ìm, when the wheel speed increase from 20m/s to 140m/s while keeping the chip thickness h_{cu} constant. Moreover, with the increase of the wheel speed, the material removal rate is getting higher when h_{cu} keeps constant. From the damage fracture micrographs, two kinds of subsurface damage can be found, fracture cracks and shearing chipping. The Fig.7(a) shows fracture cracks close to the grinding surface, while a large shearing chipping area forms after fracture cracks, which means that fracture cracks occur first followed by a large shearing chipping during the grinding process. For Fig.7(b), the subsurface damage is mainly fracture cracks, the shearing chipping does not form. While for the Fig.7(c), the subsurface

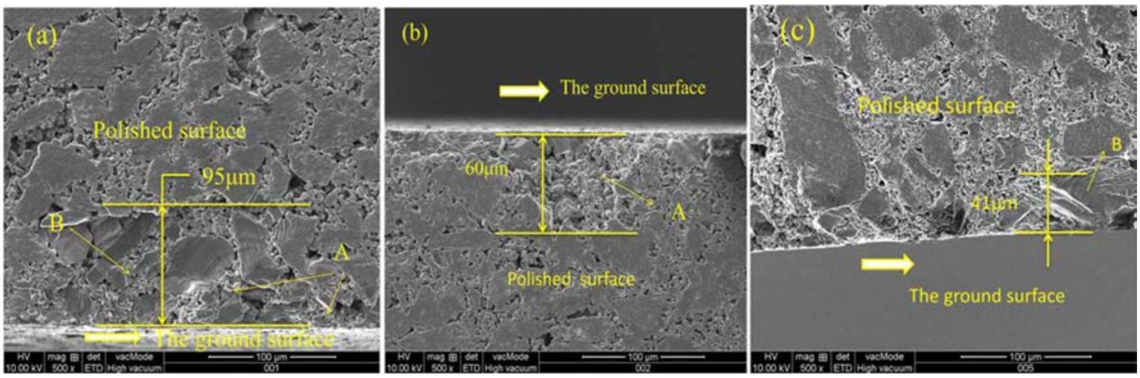

Fig. 7. Subsurface damage SEM micrographs, h_{cu} = 0.52ìm, (a) Vs = 20m/s; (b) Vs = 80m/s; (c) Vs = 140m/s. And A represents the fracture cracks, B the shearing chipping.

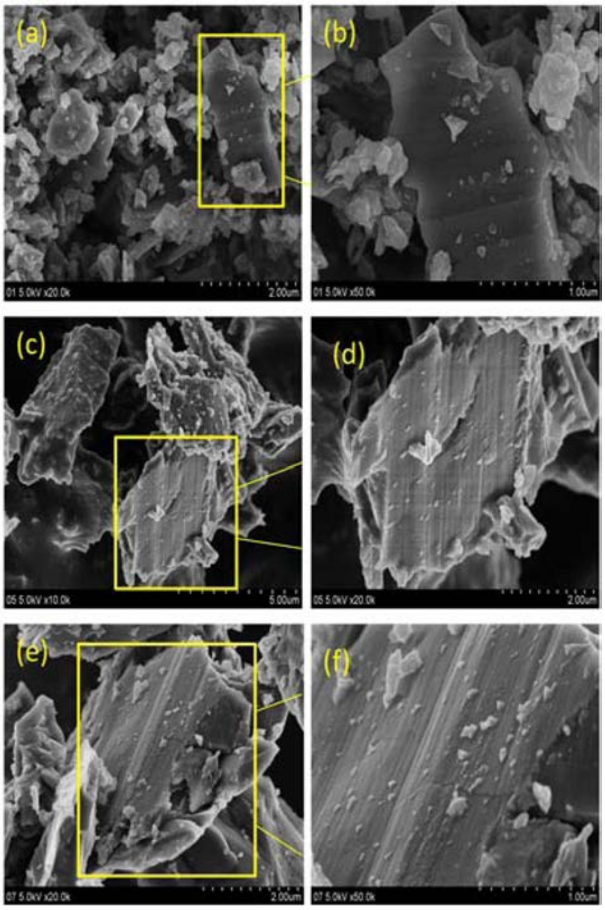

Fig. 8. Grinding chips for SEM examination,(a)Vs = 20 m/s, h_{cu} = 0.52 μm; (c)Vs = 140 m/s,h_{cu} = 0.52 μm; (e)Vs = 140 m/s, h_{cu} = 1.04 μm. (b), (d) and (f) are enlarged pictures.

damage is only occupied by shearing chipping. That is to say, the increase of the wheel speed will help to achieve higher material removal volumes while not deteriorating the subsurface quality.

Microscopic observations of the grinding chips can provide direct evidence about the prevailing grinding mechanisms. SEM micrographs of grinding chips collected for SiC are shown in Fig.8. The chips consist mostly of relatively small particles debris (Fig. 8 (a, b)) which appear to be fractured from the workpiece by fracture cracking, and much finer and regular particles (Fig. 8 (c, d)) which are generated by shearing chipping. The plate-like particles typically have grinding striations on one side as seen in Fig. 8 (d). The striations may have been generated either immediately before the particle fractured from the workpiece or during the preceding grinding pass. In Fig. 8 (c, d) and (e, f) the high impact by the elevated wheel speed broke the grains and changed chip profile in comparison with that at the low wheel speed (Fig.(a, b)). However, when the chip thickness h_{cu} reaches high enough, the chips will fracture again, this can be found in Fig. 8(f). These and numerous other SEM observations indicate that the increase of the grinding speed will help to form fine and regular debris when the chip thickness h_{cu} were controlled into a certain reasonable extent.

The ground surface and Ductile Grinding of SiC

Surface roughness is one of the most important factors in assessing the quality of a ground component. Fig. 9 is the ground surface morphology of SiC achieved by Coherence Scanning Interferometry under different wheel speed. It is obvious that the surface fracture cracks reduce with the increase of the wheel speed, while the plastic striations become more apparent and smooth. Which means that the ductile grinding became more prevalent and fracture surface decreased when the wheel speed increase Moreover, the surface roughness get a substantial improvement, from 0.341 μm (20 m/s) to 0.267 μm (80 m/s)and then 0.182 μm (140 m/s).

In previous research [6], Bifano have indicated that in the machining of brittle materials ductile grinding could be achieved when the maximum undeformed chip thickness is less than a critical chip thickness. The critical chip thickness for ductile grinding, dc, is given by [6]:

$$dc=\beta\left(\frac{E}{H}\right)\cdot\left(\frac{K_{IC}}{H}\right)^{2} \tag{3}$$

where β is a constant (β = 0.15 when surface fracture is

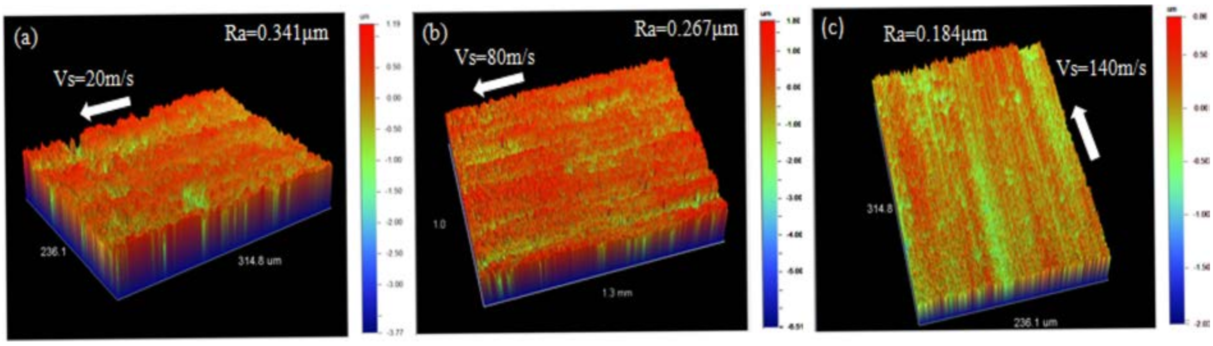

Fig. 9. Gound surface morphology of SiC under various wheel speed.

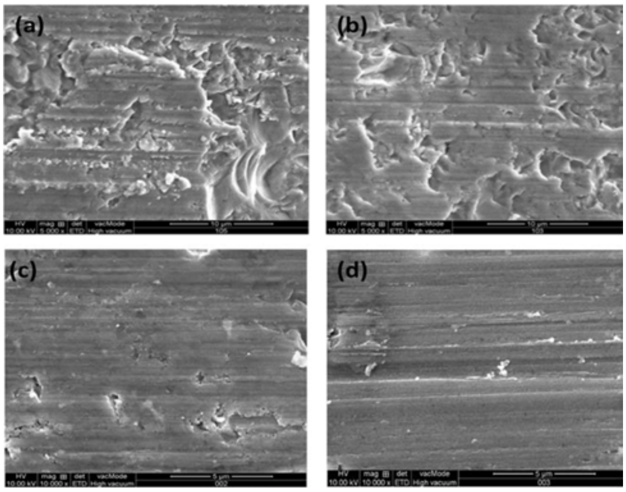

Fig. 10. The ground surface SEM micrographs, Vs = 140 m/s, (a) hcu = 1.8 μm, 40% fracture; (b) hcu = 1.04 μm, 32% fracture; (c) hcu = s0.31 μm, 8% fracture; (d) hcu = 0.16 μm, 4% fracture.

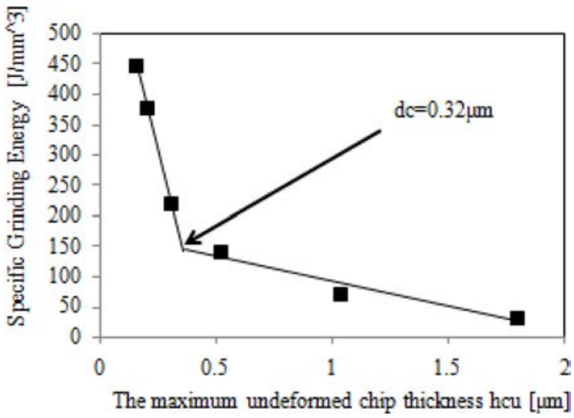

Fig. 11. Specific grinding energy vesus hcu (Vs=140m/s).

below 10%), E the elastic modulus, H the hardness and K_{IC} the mode I fracture toughness. Based on the equation (3) and the mechanical properties in table 1, the critical value for SiC is about 0.04, which means when the hcu is less than 0.04 μm, a ductile grinding of SiC will be achieved. However, the critical model are established under a conventional wheel speed (Vs = 26.2 m/s) and did not consider the impact of wheel speed, which has been shown in Fig. 9.

In order to investigate ductile grinding of SiC under high wheel speed, the ground surface of SEM micrographs are given in Fig. 10. These pictures are all conducted at the wheel speed of 140 m/s. A grid counting technique was devised to quantify the real percentage of surface fracture. From the Fig. 10, it can be seen that a brittle-ductile transition was achieved when the maximum undeformed chip thickness decrease from 1.8 μm to 0.16 μm. In Fig. 10(a), the ground surface shows a very high percentage of fracture (40%) and a lot of debris covers on the ground surface. When h_{cu} decreases to 1.04 μm (Fig. 10(b)), the grinding debris vanished and fracture surface get a further reduce to 32%. However, when h_{cu} drop down to 0.31 or below (Fig.10(c,d)), the ground surface are mainly occupied by plastic striations and a minor surface fracture (less than 10%) are achieved. It is obvious that ductile grinding of SiC is more likely to be obtained under a high wheel speed and the critical chip thickness could be greatly improved under a higher speed than a conventional speed conducted by Bifano [6].

It is known that the specific grinding energy associated with ductile removal is much higher than that with brittle fracture. Fig.11 is the depiction of specific grinding energy under different chip thickness when Vs = 140 m/s. From this figure, it can be easily found that the specific grinding energy substantially decrease with the increase of h_{cu}, which indicates the occurrence of transition from energy consumption occurs. Based on the Fig. 10, a ductile grinding of SiC was achieved during this energy variation. In the further investigation, it can be seen that a dramatic shift occurs when h_{cu} is close to 0.32 μm. When h_{cu} is below or above this critical value, the specific energy shows a good linear variation. Therefore, it can be concluded that the critical chip thickness dc will be greatly improved in high speed grinding of SiC. And when the wheel speed is 140 m/s, the critical value for ductile grinding of SiC is around 0.32 μm.

Conclusions

This experimental study has developed the grinding forces, temperature, grinding surface and subsurface features in high speed plunge grinding of SiC. A set of detecting equipments, including a rotating dynamometer and a grindable thermocouple, were used to measure the online grinding forces and temperature. Besides, the subsurface damage, chips and ground surface will be examined by SEM micrographs. The conclusions can be summarized as follows.

Although both the tangential force and normal force decreased with the increase of the wheel speed, the downtrend for tangential force is lower than the normal force. This is because the increase of the wheel speed reduces the chip thickness h_{cu} and the removal mode is more inclined to a ductile grinding. In addition, the DOC and feedrate shows a higher sensitivity to grinding forces than the wheel speed.

While for the grinding temperature, the increase of grinding wheel speed will cause a temperature shift point when the wheel speed is close to 80 m/s. Moreover, the increase of the feedrate will better control machining heat than the increase of depth of cut.

Although improving material removal volumes, the grinding subsurface will not be deteriorated under high speed grinding. This can also be found in the grinding chips.

It has been found ductile grinding of SiC can be achieved through a combination of the increase of the wheel speed and the control of grinding parameters. The critical value for ductile grinding of SiC will be greatly improved under high speed grinding comparing to conventional speed grinding. And when the wheel speed is 140 m/s, the critical value for ductile grinding is around 0.32 μm.

Acknowledgments

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