1 Introduction

Silicon carbide (SiC) is an ultra-hard ceramic material possessing highly desirable engineering properties such as high thermal conductivity, chemical inertness, high specific stiffness ($E/\rho$, the ratio of material elastic modulus $E$ and density $\rho$) and high-temperature resistance (Goel et al., 2013). Usually, machining of this kind of hard and brittle materials will inevitably cause microcracks which deteriorate surface quality (Brinksmeier et al., 2010). Abrasive machining of ceramics by means of grinding with diamond wheels is the primary process used in achieving the desired tolerances and surface integrity (Agarwal and Rao, 2010). In order to achieve high quality (Yue et al., 2014) and crack-free products without any 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.

Ductile-regime machining has been studied by many researchers in the last decades. King and Tabor (1954) first observed the ductile-regime machining during frictional wear of rock salts. They realized that although there were some cracks, there was some plastic deformation involved. In the subsequent work, Lawn and Marshall (1979) proposed an empirical formula for the required lower bound of the critical load $P$ and the resulting critical crack length $C$ correlated with the fracture toughness and hardness of the substrate material. Later on, Bifano and Dow (1991) presented a ductile–brittle transition model in which the ductile grinding can be achieved under a certain critical chip thickness value. Venkatachalam et al. (2009) proposed a fracture toughness based model to predict the ductile–brittle transitional undeformed chip thickness in end-turning of silicon wafer. However, all the above works are either in a relative lower machining speed or in micro-machining, high speed grinding in ductile grinding of brittle materials was not frequently reported.

The high speed grinding (HSG) process was characterized by the elevated wheel velocity of above 60 m/s, which dramatically reduces the maximum chip thickness and thus a reduce of grinding forces (Klocke et al., 1997). In the high...
speed grinding, the increased wheel speed will cause the ductile flow by reducing the tendency for brittle fracture (Marinescu et al., 2000). On the other hand, the increased speed will cause the increase of the depth of cut or the feed rate to obtain the higher material removal rate, without deteriorating the ground surface integrity. Through FEM simulation and experiments, Li et al. (2014) show that the actual brittle-ductile transition point for SiC is larger than that derived from the quasi-static condition under a lower grinding speed. However, insufficient practical investigation for ductile grinding of SiC is given in their work, a quantitative description needs to be further discussed.

From the literature review above, it is clear that material removal in ductile-mode machining is accomplished by the plastic deformation whereas material removal in brittle-mode occurs by propagation of cracks due to brittle fracture. This paper is an attempt to provide more practical investigation for ductile grinding of SiC in high speed grinding. A comprehensive observation for ground surface, subsurface and grinding chips is analyzed to explain speed effect on SiC. Based on the SEM observations for ground surface and specific energy analysis under high speed grinding, a new critical chip thickness under high speed grinding will be proposed.

### 2 Experimental Setup

A high speed grinder is used to conduct the grinding experiments. The detailed layout is shown in Fig. 1 (b). In the experiments, the machine spindle is capable of running up to 8000 r/min with a diameter \(d_s\) of 400 mm vitrified diamond wheel. The vitrified diamond grinding wheel has an average grit size of 91 µm, diamond concentration 150 and width 22 mm. Before experiments, the wheel was balanced below a vibration amplitude of 0.02 µm under working speed with a dynamic balancing instrument (Model SB-4500). The workpiece material used for this investigation is reaction-sintered SiC in Fig.1 (a), and its mechanical properties are given in Table 1. It has a diameter \(d_c\) of 60 mm and width \(b\) of 20 mm. The workpiece is divided into two pieces, one is a quarter, the another one is the rest of the part. In this paper, a 5% water-soluble metal cutting fluid was used.

![Fig. 1 SiC workpiece (a) and experiments layout (b)](image)

<table>
<thead>
<tr>
<th>Material properties for SiC</th>
<th>Density (\rho) ([g/cm^3])</th>
<th>Bending strength (\sigma_b) ([MPa])</th>
<th>Hardness (H_i) ([GPa])</th>
<th>Fracture toughness (K_{IC}) ([MPa.m^{1/2}])</th>
<th>Elastic modulus (E) ([GPa])</th>
<th>Poisson rate (\mu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiC</td>
<td>3.22</td>
<td>490</td>
<td>23</td>
<td>3.0</td>
<td>410</td>
<td>0.16</td>
</tr>
</tbody>
</table>

The ground surface and subsurface damage was examined by an environment scanning electron microscope (ESEM)
QUANTA 250 from Czech. A bonded interface sectioning technique (Xu and Jahanmir, 1994) will be exploited to examine the grinding induced subsurface damage. Two parts of the workpiece are polished by a 0.5µm diamond paste to examine subsurface damage 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 (Wu et al., 2016). 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 smaller ground specimens were cleaned with acetone in an ultrasonic bath for at least 20 min, and then gold coated for SEM observations. Another field emission scanning electron microscope (FE-SEM) S-4800 from HITACHI was employed to examine the grinding chips. The grinding chips were collected with a double-sided adhesive placed under the wheel in dry grinding. When grinding, the chips will fall and cling to the adhesive tape. After that a piece of adhesive tape will be used to observe its micro morphology under FE-SEM after gold coated. Moreover, the surface roughness was detected through a Bruker Nano Surface white light interferometer (Npflex).

3 Results and discussions

3.1 Speed effect on grinding quality

The maximum undeformed chip thickness $h_{cu}$ is a very important indicator to characterize the grinding process. Generally, it represents the theoretical penetration depth of a single grit. It is written as follows (Zhu et al., 2014):

$$h_{cu} = \left( \frac{3}{C_d \tan \Phi} \right) \left( \frac{V_w}{V_s} \right) \frac{d_e}{d_c}$$

(1)

where $C_d$ is the dynamic grit number in unit area, $\Phi$ the semi-included angle of the active grit and for calculation simplicity, $\Phi = 60^\circ$ is used (Li et al., 2014), $a_e$ the depth of cut, $V_w$ the workpiece speed and $V_s$ the grinding wheel speed, and $d_e$ is the equivalent wheel diameter, $d_c = d_s d_w / (d_s + d_w)$, $d_s$ the workpiece diameter, $d_w$ the wheel diameter. In this paper, $C_d$ is 50 grits/mm$^2$ for the D91 diamond grinding wheel based on the microscope observation of the grinding topography. The material removal volume can be calculated through the product of the depth of cut $a_e$ and the workpiece speed $V_w$.

The typical SEM micrographs of subsurface damage of SiC under high speed grinding are shown in Fig.2. The subsurface damage was shown on the polished surface, which is perpendicular to the grinding direction and parallel to the ground surface. From formula (1), it is obvious that the material removal volumes can be greatly enhanced when the grinding wheel speed increases at a constant maximum undeformed chip thickness value. Therefore, it can be found from the SEM results that the subsurface damage layer is getting thinner when the wheel speed increases, from 95 µm to 41 µm, while the chip thickness $h_{cu}$ keeps constant. Moreover, two kinds of subsurface damage can be found from the damage fracture micrographs, fracture cracks and shearing chipping. The fracture cracks are featured by fracture debris and irregular fracture surface. However, the shearing chipping will more probably show the regular and uniform shearing plane in the subsurface.

The Figure 2(a) has fracture cracks close to the ground surface, while a large shearing chipping area comes into being after fracture cracks, which means that fracture cracks occur first followed by a large shearing chipping during the grinding process. The enlarged Figure 2(d) shows clearly that the damage layer is composed by both the fracture cracks and shearing chipping. For Figure 2(b) and enlarged Figure 2(e), the subsurface damage is mainly formed by fracture cracks, the shearing chipping almost cannot be found. While for the Figure 2(c) and enlarged Figure 2(f), the subsurface damage is mainly occupied by shearing chipping.
Microscopic observations of the grinding chips can provide more direct evidence about high speed effect on grinding mechanisms. FE-SEM micrographs of grinding chips collected for SiC are shown in Fig. 3. When it is under a relatively lower grinding speed (20 m/s), the chips mainly consist of relatively small particles debris (Fig. 3 (a)) which appear to be fractured from the workpiece by fracture cracking. However, much bigger and regular particles (Fig. 3 (b)) are generated by shearing chipping when at a higher grinding speed (140 m/s). The plate-like particles in high speed grinding typically have grinding striations on one side as seen in Fig. 3 (b). The striations may have been generated either immediately before the particle fractured from the workpiece or during the preceding grinding pass. Therefore, it can be summarized...
that a higher grinding speed will most probably produce more regular grinding chips with plastic striations for brittle materials like SiC.

![Image](image1.png)

Fig.3 FE-SEM examination for grinding chips, (a) \( V_s = 20 \text{ m/s}, h_w = 0.52 \mu\text{m} \); (b) \( V_s = 140 \text{ m/s}, h_w = 0.52 \mu\text{m} \); the right figures are enlarged pictures.

![Image](image2.png)

Fig.4 Surface Roughness Characterization by while light interferometer, \( h_w = 0.52 \mu\text{m} \); (a) \( V_s = 20 \text{ m/s} \); (b) \( V_s = 80 \text{ m/s} \); (c) \( V_s = 140 \text{ m/s} \).

Surface roughness is another important factor in assessing machining quality under various grinding speed. In this paper, the surface roughness measurement of the cylindrical workpiece was conducted by a Bruker Nano Surface white light interferometer (Npflex). The interference wave will first be detected at the top surface of the cylindrical workpiece when the lens approaches the workpiece, then the interference wave will spread to the whole measurement cylindrical surface. After collecting all the interference data, the surface roughness will be obtained after the cylindrical surface was post-processed to a flat surface through the measurement software.

![Image](image3.png)

Figure 4 is the ground surface 3-D morphology for SiC. It is obvious that the surface irregular 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 lifts. From the illustrated pictures, the surface roughness gets a substantial improvement, from 0.357 \( \mu\text{m} \) (20 m/s) to 0.286 \( \mu\text{m} \) (80 m/s) and then 0.195 \( \mu\text{m} \) (140 m/s). Moreover, the increase of the wheel speed helps greatly increase material removal volumes while without deteriorating surface quality.
### 3.2 Ductile grinding of SiC under high speed grinding

Bifano and Dow (1991) have revealed that ductile grinding could be achieved in the machining of brittle materials when the maximum undeformed chip thickness \( h_{cu} \) is less than a critical chip thickness \( d_c \). And the critical chip thickness for ductile grinding \( d_c \) is given by the following equation.

\[
d_c = \beta \left( \frac{E_m}{H_f} \right) \left( \frac{K_{IC}}{H_f} \right)^2
\]

(2)

where \( \beta \) is a constant, \( E_m \) the elastic modulus, \( H_f \) the hardness and \( K_{IC} \) the mode 1 fracture toughness. According to a series of grinding experiments on different brittle materials, the constant \( \beta \) is obtained and \( \beta=0.15 \) for SiC. Based on the above equation (2) and the mechanical properties in Table 1, the calculated critical value for SiC is about 0.04 μm, which means that when the maximum undeformed chip thickness \( h_{cu} \) is less than 0.04 μm, a ductile grinding of SiC can be achieved. However, this calculation critical model in Bifano’s work are established under a conventional wheel speed \( (V_s=26.2 \text{ m/s}) \) and did not consider the impact of wheel speed, which has been discussed in Chapter 3.1.

In order to investigate ductile grinding of SiC under a higher material removal rate, a series of high speed grinding \( (V_s=140 \text{ m/s}) \) experiments was undertaken. The SEM ground surface micrographs were given below. A grid calculation technique (Bifano and Dow, 1991) was devised to quantify the real percentage of surface fracture. Along with the SEM investigations, the specific grinding energy \( E \), which represents the consumed energy in unit material removal volume, was used to clarify the ductile grinding mechanism for SiC. The specific grinding energy \( E \) can be obtained through the equation (3).

\[
E = \frac{F_t V_s}{a_s V_m b}
\]

(3)

where \( F_t \) represents the tangential grinding force, \( b \) is the width of workpiece.

From the following SEM investigations in Fig. 5, it can be easily seen that the ground surface shows less grinding debris and fracture region with the decrease of \( h_{cu} \), from 1.8 μm to 0.16 μm. When the \( h_{cu} \) is 1.8 μm, the fracture surface consists of 40% of the whole ground surface, then a slightly decrease to 32% for 1.04 μm. However, when \( h_{cu} \) decrease from 1.04μm to 0.31μm, the ground debris and fracture surface shows a substantially improvement, from 32% to 8%. After that, when \( h_{cu} \) was given a further decrease, the ground surface shows a lesser grinding fracture. This can give a clear conclusion that the material removal mode has changed. This can be further proved through the characteristics of the specific grinding energy.

It is known that the specific grinding energy associated with ductile removal is much higher than that with brittle fracture (Malkin and Hwang, 1996). Fig.5 gives the detailed depiction of specific grinding energy under different \( h_{cu} \) when \( V_s \) keeps a high grinding speed of 140 m/s. From this figure, it can be easily found that the specific grinding energy substantially decrease with the increase of \( h_{cu} \), from 450 J/mm\(^3\) for 0.16 μm to 25 J/mm\(^3\) for 1.8 μm. Similar to the SEM results, the grinding energy shows a slightly change when \( h_{cu} \) changes from 1.8 μm to 1.04 μm, while it decrease to 0.31μm, the specific grinding energy shows a little increase, which reveals that a different removal mode occurs during this period. In the further investigation, when \( h_{cu} \) is smaller than 0.31μm, the more grinding energy expenditure are produced. Therefore, through a curve fitting method, a critical value can be obtained when \( h_{cu} \) is close to 0.32 μm, where shows a dramatic energy shift. 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 \( d_c \) will be greatly improved in high speed grinding of SiC. And when the wheel speed \( V_s \) is 140 m/s, the critical value for ductile grinding of SiC is around 0.32 μm, which shows a substantial increase compared with the critical value of 0.04 μm obtained by Bifano and Dow (1991) in a relatively low grinding speed. Moreover, in high speed grinding, a higher material removal can be obtained than conventional grinding speed.
Fig. 5 Ductile grinding of SiC under high speed grinding (140 m/s) ① $h_{cu} = 1.8 \mu m$, 40% fracture; ② $h_{cu} = 1.04 \mu m$, 32% fracture; ③ $h_{cu} = 0.31 \mu m$, 8% fracture; ④ $h_{cu} = 0.16 \mu m$, 4% fracture.

4. Conclusions

This paper conducted a series of high speed grinding experiments to investigate ductile grinding of SiC and led to the following conclusions:

1. Compared with the conventional grinding, the high speed grinding can diminish the subsurface damage for SiC while not deteriorating subsurface damage. With the increase of the wheel speed, the material is more tended to be shearing chipping while not fracture cracks. This can also be concluded from the grinding chips.

2. While maintaining the maximum chip thickness $h_{cu}$ constant, the surface roughness keeps a stable improvement with the increase of wheel speed. Moreover, more plastic striations not fracture cracks are observed under a higher grinding speed.

3. The experimental results shows that 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 can be greatly improved under high speed grinding comparing to conventional speed grinding.
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References


