Modeling of grinding chip thickness distribution based on material removal mode in grinding of SiC ceramics

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Abstract
Grinding chip thickness is an important parameter to reflect the grinding efficiency and investigate the grinding mechanism. Modeling of the chip thickness is generally based on a certain stochastic distribution model, like Uniform, Gaussian or Rayleigh distribution. This paper is devoted to establish the real grinding chip thickness distribution model for brittle materials based on the material removal mode: coexistence of ductile and brittle removal mode. A grid calculation method will provide a quantitative data of ductile removal surface to validate the chip thickness model. The results show that the grinding chip thickness for Silicon Carbide ceramics is more close to the Rayleigh model with an average error of 3.25% compared with 11.74% of Gaussian model. Finally, grinding experiments were conducted to reveal the Rayleigh model-based grinding temperature characteristics, surface roughness and topography. It was found that ductile-oriented ground surface with a lower surface roughness value was increased with the enhancement of the ductile surface percentage and a substantial suppression of surface crack and damage generation.

Keywords : Chip thickness, Rayleigh distribution, Brittle materials, Ductile grinding, Grid calculation technique

1 Introduction

Grinding process is a precision machining method in high surface finish applications, such as aerospace engineering, medical engineering, electronic semiconductor engineering, etc. Grinding is a particular material removal process featured by continuous grain-workpiece interactions by different irregular abrasive grains with large negative rake angles (Liao et al., 2018; Zhu et al., 2019 and Wu et al., 2019). Moreover, the abrasive grains on the grinding wheel have different topography, which will certainly lead to a different chip thickness for every single grain. In grinding process, the grinding chip thickness is a very important parameter to analyze the grinding kinetics (Muhammad et al., 2013 and Zhu et al., 2020), material removal mechanism (Xiao et al., 2015; Ding et al., 2020 and Song et al., 2020), chipping mechanism (Rapheal et al., 2013 and Kang et al., 2019) and so on. However, most research works are based on a certain constant average chip thickness (Yang et al., 2017 and Jiang et al., 2020) or undeformed maximum chip thickness (Dai et al., 2015) related to process parameters and wheel topography, which does not conform to the real situation of random grits’ grinding process. Therefore, precisely modeling the chip thickness with a probability distribution would be of great significance for efficient modeling and analysis of grinding mechanism.

In order to match the stochastic feature of abrasive grains, grinding chip thickness has been assumed to conform to different probability distributions. Rayleigh distribution was first proposed statistically by Younis et al. (1984) through Monte Carlo techniques. After that, Hecker et al. (2003) modeled the grinding force based on an assumption of Rayleigh chip thickness distribution. In the subsequent work, more work about the modeling of grinding force and grinding kinetics are based on a Rayleigh chip thickness assumption (Shao et al., 2015 and Wu et al., 2016). However, the Rayleigh chip thickness model was not validated experimentally until Hecker et al. (2007), whose work was based
2 Chip thickness model

2.1 Grinding kinetics

The grinding chip thickness is a theoretical parameter to analyze the grinding trajectory and quantitatively assess the grinding efficiency and quality. For a single grain, the theoretical undeformed grinding chip was depicted in Fig.1. From the Fig.1, it can be found that the chip is produced by a relative movement of both the wheel rotation and workpiece rotation. As the abrasive grains have typical random feature on the wheel surface, the chip thickness for different grain is obviously different. Thus, the maximum undeformed chip thickness will be discussed with the surface roughness value and topography.

Based on the above literature review, this paper is devoted to model the real chip thickness in grinding of brittle materials based on the material removal mode. Grinding chip thickness of brittle materials will be modeled through a stochastic distribution model, which will be validated through the calculation of ductile removal surface percentage with grid calculation method. The proposed model, Gaussian and Rayleigh, will be validated respectively. Then, the Rayleigh-based temperature characteristics in the contact arc length were analyzed. Finally, the ductile-based grinding will be discussed with the surface roughness value and topography.

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In modeling of chip thickness, there are generally two different distributions that are widely used in research work, Rayleigh distribution and Gaussian distribution. This paper will compare the two models and decide which is closer to the real situation in grinding process, the two models are depicted in Fig.2. Moreover, in order to calculate the probability of ductile grinding surface, another criterion for ductile grinding in grinding of brittle materials are also depicted in Fig.2. Wu et al. (2016) have established a critical criterion for ductile grinding considering both effects of the material’s properties and process parameters. The critical criterion \( d_{nc} \) could also be expressed by the critical grain depth of cut, it was given as:

\[
d_{nc} = \beta \left[ a_0 + b_0 \ln \left( \frac{V_s}{h_{cu}} \right) \right]^2 \left( \frac{E}{H_Y} \right)^{-\frac{K_{IC}}{H_Y}}
\]

(4)

where \( E, H_Y \) and \( K_{IC} \) are the elastic modulus, hardness and fracture toughness respectively. \( \beta, a_0 \) and \( b_0 \) are the constants.

2.2 Rayleigh chip thickness distribution

When the chip thickness is assumed to conform to the Rayleigh chip thickness model, it can be modeled as (Hecker et al., 2007):

\[
f_R(h) = \begin{cases} 
\frac{(h / \sigma_r)^2 e^{-h^2/2 \sigma_r^2}}{\sqrt{2\pi} \sigma_r^2} & h \geq 0 \\
0 & h < 0 
\end{cases}
\]

(5)

where \( \sigma_r \) is a parameter that can fully define the probability function. In this model, the chip thickness model will be valid when \( \int f(h) dh = 1 \). Through the integral calculation, the expected value \( E(h) \) and standard deviation \( SD(h) \) are as follows:
In grinding process, the material volume removed by abrasive grains was equal to the lost material volume of workpiece (Wu et al., 2017). Therefore, it can be expressed by:

$$E(A_{\text{total}})V_S = V_a a_r b$$  \hspace{1cm} (7)

$$A_{\text{total}} = A_{\text{chip}} N_d$$  \hspace{1cm} (8)

$$A_{\text{chip}} = h^2 \tan \theta$$  \hspace{1cm} (9)

where $A_{\text{total}}$ is the total chip cross section that all the engaged grains interact with the workpiece in the contact arc length. While $A_{\text{chip}}$ represents the chip triangular cross section for a single grit. Thus, the expected value $E(A_{\text{total}})$ can be given as:

$$E(A_{\text{total}}) = N_d E(A_{\text{chip}}) = N_d E(h^2) \tan \theta$$  \hspace{1cm} (10)

Then, based on the above equations (7)-(10), the parameter $\sigma_r$ can be obtained:

$$\sigma_r = \sqrt{\frac{a_e v_w}{2v_i N_d l_g \tan \theta}}$$  \hspace{1cm} (11)

Based on the equation (4) and (5), the probability for ductile grinding can be calculated as follows:

$$\delta_r = \int_0^{d_{av}} f_k(h)dh = 1 - e^{-\frac{d_{av}^2}{2\sigma_r^2}}$$  \hspace{1cm} (12)

### 2.3 Gaussian chip thickness model

For the Gaussian chip thickness distribution, the model can be mathematically expressed as (Li et al., 2017):

$$f_G(h) = \begin{cases} 
\frac{1}{\sqrt{2\pi\sigma_g}} e^{-\frac{(h-h_c)^2}{2\sigma_g^2}}, & h \geq 0 \\
0, & h < 0 
\end{cases}$$  \hspace{1cm} (13)

In this model, the chip thickness will be conformed to this model at an average chip thickness of $h$ and variance of $\sigma^2$. According to the mathematic basics, the correlation between the chip thickness variance $D(h)$ and expected value $E(h)$ can be given as:

$$D(h) = E(h^2) - (E(h))^2$$  \hspace{1cm} (14)

where $E(h^2)$ is the expected of the variable $h^2$. It can be obtained through the calculation of Equations (7)-(10).

$$E(h^2) = \frac{V_a a_r b}{V_i N_d \tan \theta}$$  \hspace{1cm} (15)

Moreover, the theoretical maximum chip thickness is $h_{cu}$, considering about the feature of the Gaussian distribution, the expected value of the chip thickness can be expressed as half of the maximum undeformed chip thickness:

$$E(h) = \bar{h} = \frac{h_{cu}}{2}$$  \hspace{1cm} (16)

Thus, the Equations (15) and (16) can be substituted into (14), and $D(h) = \sigma_g^2$, the parameter $\sigma_g$ can be calculated as:
\[
\sigma_g = \sqrt{\frac{a_y v_w}{V_N N_d l_y \tan \theta} - \frac{h_{uw}^2}{4}} \tag{17}
\]

Based on the Gaussian distribution, the probability of ductile grinding could be expressed as:

\[
\delta_g = \int_{d_{uw}}^{d_{uw}} f_G(h)dh = \frac{1}{\sqrt{2\pi}\sigma_g} \int_{d_{uw}}^{d_{uw}} e^{-\frac{(d_{uw} - h_{cw})^2}{2\sigma_g^2}} dh \tag{18}
\]

In order to simplify the calculation, the above equation can be transformed to the below normal distribution, which can be given as:

\[
Y = \frac{d_{uw} - h_{cw}}{\sigma_g} \sim N(0,1) \tag{19}
\]

3 Experimental setup

3.1 Grinding experiments setup

The grinding experiments were carried out on a cylindrical CNC grinder MGKS1332/H. The wheel speed of this machine could reach up to 150 m/s with a 400 mm diameter wheel. The detailed layout and configuration can be found in Fig. 3 and Table 1.

![Experimental Setup](image)

Fig. 3 Experiments setup. (b) is the partial enlarged of (a)

| Table 1 Experimental Conditions |
|---------------------------------|
| **Title**                  | **Specification**                                         | **Title**                  | **Specification**                                         |
| Grinding Machine            | CNC cylindrical grinding machine MGKS1332/H                | Depth of cut               | 1-20 \(\mu m\)                                            |
| Grinding wheel              | Vitrified Diamond Wheel D91 V+ 2046 J1SC-23 C150 E        | Coolant                    | Water-based emulsion 5\% (10 L/min)                       |
| Mode                        | Up grinding                                              | Wheel spindle balancing system | SBS Model SB-4500 Below 0.03 \(\mu m\)                   |
| Wheel speed                 | 20-150 m/s                                               | Materials                  | Reaction Sintered SiC                                     |
| Workpiece speed             | 300-1200 mm/min                                          |                             |                                                           |
The columnar workpiece of reaction-sintered silicon carbide ceramics, with a width of 20mm and diameter of 60mm, was used in this work. The material has a hardness of 23GPa, elastic modulus 23GPa, Poisson’s ratio 0.16 and fracture toughness 3.5 MPa.m1/2. Before each set of test, the grinding wheel was balanced below 0.03μm with a dynamic balancing system (SBS Model SB-4500).

3.2 Grid calculation for the ductile removal percentage

In this paper, the ground surface topography was detected through a Scanning Electron Microscope (SEM) Quanta 250 from Czech. Before the observation, the workpiece materials were cleaned with acetone in the ultrasonic bath for 20 min. In order to quantitatively evaluate the ground surface topography, a grid calculation method was used to determine the surface ductile removal percentage, as shown in Fig.4. This method is on the basis of a C# programmed calculation method. Firstly, the SEM picture is imported into the software and divided by different lateral and radial units, like 20×20 in this figure; then, the brittle fracture surface will be selected based on the surface topography; finally, the brittle surface percentage can be achieved by calculating the grids, thus the ductile surface percentage could be complementary to 1. As is shown in Fig.4, the brittle surface percentage is 24.25%, then the ductile surface area accounts for 75.75%.

![Fig.4 Surface ductile removal percentage determination-Grid calculation method](image)

The grid calculation method is depicted in Fig.4. In this figure, the classification of ductile mode in blue color and brittle mode in red color is manual click selection, which could be a little subjective. Therefore, based on the Bifano et al.(1991), the judge criteria could be defined by the following rules:

1. The brittle zone is mainly reflected by fracture concave surface damages, which is generally white bright zone as shown in Fig.4.
2. The ductile zone is generally reflected by almost integral surface without surface crack removal, just some plastic upheaved rag and stripes.
3. For grid calculation balance, some of the grids with a mix of ductile and brittle zone could be selected as brittle, while some would not.
4. The last line of black area will be proportionally selected to match the real situation.

4 Model Validation

Based on the grid calculation method, the Ductile Surface Area (DSA) can be examined quantitatively to show the predicted error of different models. In order to validate the proposed chip thickness model, a series of experiments were conducted in Table 2. In this table, the Rayleigh predicted DSA in formula (12) and Gaussian predicted DSA in formula (18) are separately calculated to compare with the experimental DSA measured through the grid calculation method. The results show that the Gaussian predicted model has an average error of 11.74% compared with a 3.25% of Rayleigh predicted chip thickness model, which means that the Rayleigh chip thickness model is more close to the real
chip thickness model. Fig. 5 is the histogram of the model predicted DSA data compared with the experimental results, from which a better match of Rayleigh chip thickness model can be directly found. On the other hand, the predicted error from two different models is depicted in Fig. 6, from which a much lower error of Rayleigh model can be found compared with much higher error of Gaussian chip thickness model.

Table 2 DSA Error for Gaussian and Rayleigh chip thickness

| No. | $V_s$ (m/s) | $V_w$ (m/s) | $a_e$ (μm) | Exp. DSA | Guas. Error | Rayl. Error |
|-----|-------------|-------------|------------|----------|-------------|-------------|
| 1   | 140         | 0.3         | 15.9       | 37%      | 48.40%      | 30.30%      |
| 2   | 20          | 0.075       | 5          | 48%      | 28.77%      | 52.50%      |
| 3   | 20          | 0.025       | 3          | 62%      | 50.90%      | 58.60%      |
| 4   | 140         | 0.175       | 3          | 74%      | 89.90%      | 76.40%      |
| 5   | 140         | 0.1         | 1          | 91%      | 99.90%      | 92.50%      |
| 6   | 140         | 0.05        | 1          | 96%      | 99.9%       | 95.00%      |
| AVG |             |             |            |          | 11.74%      | 3.25%       |

Fig. 5 Model predicted DSA compared with the experiments

Fig. 6 Gaussian and Rayleigh Model Prediction Error
5 Temperature-based Rayleigh distribution of contact arc length

The grinding contact arc length $l_g$ is a parameter which could reflect the wheel-workpiece contact status. It can be defined as (Wu et al., 2016):

$$l_g = (1 + \frac{V_w}{V_s})\sqrt{a_e d_e}$$  \hspace{1cm} (20)

From this formula, it can be found that the contact arc length $l_g$ is only dependent to the process parameters. For a certain contact arc length, the active grits scratch into the workpiece with different chip thicknesses. Therefore, the contact arc length could reflect the real active grits’ status and related chip thickness of different grits. Fig.7 give the grinding temperature signal in a certain contact arc length detected through a thermocouple testing system. Fig.7(a) is the original temperature signal in both with and without coolant. Fig.7(b) is the predicted temperature based on the Rayleigh heat flux distribution. It can be found from the Fig. 7 that the grinding temperature signal in the certain contact arc length matches well with the Rayleigh distribution, which could further validate the Rayleigh chip thickness model for Silicon Carbide ceramics. In this Figure, the contact position at peak temperature value in Fig.7 (a) and (b) differs greatly, which is caused by the real grinding process. Temperature curve in Fig.7 (a) is the detected grinding temperature, which is easier to reach the peak value than Fig.7 (b) of predicted value. In grinding of brittle materials, rubbing and early ploughing at a low indentation depth produce very small thermal energy, which makes the low contact position reaches peak temperature value earlier than the theoretical predicted temperature curve.

6 Ductile-based grinding topography with Rayleigh chip thickness model

In order to reveal the relationship between the ground surface quality and ductile removal percentage, the surface roughness and related topography are given in Fig.8. In Fig.8, it can be found that the surface roughness decrease from 0.541μm with a 30.3% DSA to 0.445μm with a 52.5% DSA, and then drop all the way to 0.155μm with a 95.0% DSA. The surface roughness data correlates almost linearly with the DSA percentage, which means that more grits scratch the workpiece in a ductile regime, the surface will be more smooth and less damage will be produced in the ground surface. Thus, a lower surface roughness value and better surface finish could be expected when the DSA data is high enough.

Fig.9 is the SEM pictures of ground surface, $\delta_e$ represents the experimental DSA. This figure reflect the surface SEM topography under different experimental DSA. It can be found that the ductile grinding removal increases with the increase of DSA percentage, while the brittle removal surface decreases substantially. Moreover, when the DSA is low at 37%, the upheaved rag is the main damage together with fracture crack. While with the increase of DSA, the upheaved rag becomes less and vanishes at a experimental DSA of 96%.
Fig. 8 Surface roughness and topography with the variation of DSA (a) $\delta_r = 30.3\%$; (b) $\delta_r = 52.5\%$; (c) $\delta_r = 58.6\%$; (d) $\delta_r = 77.5\%$; (e) $\delta_r = 92.5\%$; (f) $\delta_r = 95.0\%$

Fig. 9 Surface SEM topography under different experimental DSA $\delta_e$. (a) $\delta_e = 37\%$; (b) $\delta_e = 48\%$; (c) $\delta_e = 62\%$; (d) $\delta_e = 74\%$; (e) $\delta_e = 91\%$; (f) $\delta_e = 96\%$. (X10000) A represents the ductile grinding; B the brittle grinding with damages; C the upheaved rag.

Conclusions

In this paper, the real chip thickness model for brittle materials has been modeled based on the stochastic distribution of grits' chip thickness. As the typical co-existence feature of ductile and brittle removal of brittle materials, the validation of chip thickness model cannot be what the metallic materials does to examine the real chip size. A grid calculation method was used to validate the proposed Rayleigh and Gaussian chip thickness model. The results show that the chip thickness for Silicon Carbide ceramics is more close to the Rayleigh model with a lower average error of 3.25% compared with a higher 11.74% error of Gaussian model. Moreover, the grinding temperature signal in a single contact arc length also prove that the Rayleigh chip thickness model is more close to the real model. Finally, grinding experiments were conducted to reveal the grinding surface roughness and topography. It was found that ductile-oriented
ground surface with a higher surface roughness was increased with the enhancement of the DSA and a substantial suppression of surface crack, upheaved rag and damage generation could be obtained.

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