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Effect of grain wear on material removal behaviour of sapphire in ultra-precision grinding

Xingshi Gu[1], Qingliang Zhao[1], Bing Guo[1]

[1]School of Mechanical and Electrical Engineering, Harbin Institute of Technology, Harbin, Heilongjiang 150001, P.R. China

guxingshi@hit.edu.cn

Abstract
In sapphire grinding process, due to the great hardness of sapphire, the severe wear of diamond grinding wheel results in a lower consistency in surface roughness and higher grinding energy. This paper aims to reveal that how the fundamental characteristics, such as critical cutting depth for ductile-brittle transition (DBT), specific energy (Es), and material removal rate (MRR), are varied during grinding influenced by the wear of grinding wheel. To achieve this objective, single grit scratching tests have been conducted. Three grits with different degrees of wear, namely, no wear, micro-fracture, and wear flat, are employed in the scratching process. The critical cutting depth for DBT, Es, MRR and acoustic emission (AE) characterizations of each scratching test with various worn grits are analyzed quantitatively. The effect of grain wear on material removal mechanism of sapphire is discussed based on the experimental results. This work sheds lights on the effect of grain wear on ultra-precision grinding of sapphire which could contribute to the optimizations in views of ductile-regime grinding, energy-saving grinding and time-saving grinding.

Sapphire; Ultra-precision grinding; Grain wear; Single-grit scratching; Critical cutting depth

1. Introduction

In recent years, sapphire has been widely used in high-speed integrated-circuit chips, thin-film substrates, and infrared windows [1]. These applications demand for high quality surface finish, dimensional and form accuracy, which are commonly achieved by ultra-precision grinding. However, due to the great hardness of sapphire, the severe wear of diamond grinding wheel results in a lower consistency in surface roughness and higher grinding energy.

The wear of grains on the freshly dressed wheels starts right at the beginning of grinding process. As grains would be endured worn constantly as grinding proceeds, the material removal modes are varied dynamically during grinding. Thus, it is important to obtain insight into the characteristics of material removal behaviour with constantly changing grain wear during grinding.

This paper aims to reveal how the fundamental characteristics, such as critical cutting depth for ductile-brittle transition (DBT) d_c, specific energy (Es), material removal rate (MRR) and acoustic emission (AE) signals are varied during grinding influenced by the wear of grinding wheel. To achieve this objective, single grit scratching tests with ramp cutting depth have been conducted. Three grits with different degrees of wear, namely, no wear, micro-fracture, and wear flat, are employed in the scratching process. The critical cutting depth for DBT, Es, MRR and AE of each scratching test with various worn grits are analyzed quantitatively. The effect of grain wear on material removal mechanism of sapphire is discussed based on the experimental results.

2. Materials and methodology

Monocrystalline sapphire (α-Al2O3) was commercially acquired and its surface was polished to obtain the roughness (Ra) lower than 5 nm. The scratching tests were performed along the $[0\,1\,\bar{1}\,0]$ direction on C-plane. As shown in Figure 1, the single grit was clamped on a wheel holder which rotated at a speed of 60 rmp. Three controlled diamond grits with different wear degrees, namely, no wear, micro-fracture, and wear flat, were employed in the scratching tests. During scratching process, the scratching force and AE signal were measured.

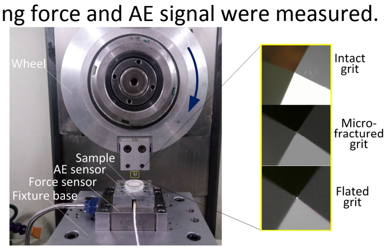

Figure 1. Experimental setup of single grit scratching tests

The critical cutting depth for DBT and groove topography are detected by a white light interferometer (WLI)and scanning electron microscopy (SEM), respectively. In this study, the characteristic parameters, MRR and Es, were calculated using the following equations,

$$\mathrm{MRR} = \frac{A - A_1 - A_2}{A} \tag{1}$$

$$\mathrm{Es} = \frac{F'}{A \cdot MRR} \tag{2}$$

where A is the cross sectional area of the scratched groove; A_1 and A_2 are the cross sectional areas of pile-ups, which are positive values in ductile regime and negative values in brittle regime, as shown in Figure 2; F' is the cutting force effective value, under which the consumed energy is equal to actual situation.

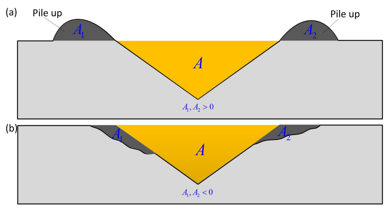

Figure 2 . The diagram of MRR

3. Results and discussion

3.1. Grooves topography and critical cutting depth for DBT

The scratched groove topography was investigated using SEM and WLI, as shown in Figure 3. It can be seen that each groove experienced three removal regimes, namely, ductile regime(DR), ductile brittle transition regime (DBTR) and brittle regime (BR), during sapphire scratching process. The cutting depth in DBTR was defined as d_c which characterizes the possibility of high quality of ground surface in grinding process [2]. The d_c values of differently wear grits were shown in Figure 3. It showed that the d_c was smaller as grain wear was more serious. What's more, once the grit was worn from micro-fracture to flat the d_c was dropped sharply. In addition, the scratch results indicated that the grain wear could result in more serious brittle fracture which agreed with MRR results (in Figure 3, the maximum cutting depth of (c) is less than that of (a) and (b) for measuring d_c exactly). These phenomena may attribute to the various removal mechanisms in cutting process with sharp and blunt cutting tool. This work implied that the wear flat of grain should be eliminated in order to obtain a high quality ground surface in ultraprecision grinding.

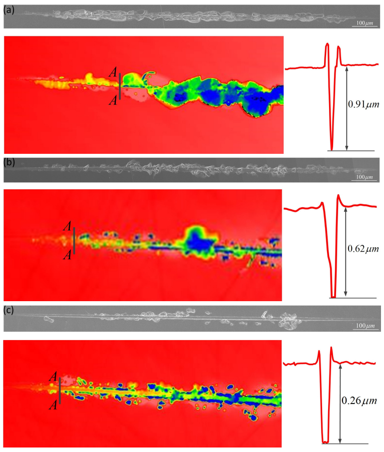

Figure 3. The topography and d_c of groove scratched by intact (a), micro-fractured (b) and truncated flat grit (c).

3.2. MRR and Es

The MRR and Es were seriously affected by grit wear. As shown in Figure 4, the MRR was increased with the increase of grit wear degree in slight brittle removal regime (cutting depth was less than 1 μm). However, in severe brittle removal regime, the intact grit could contribute to much larger MRR compared to micro-fractured and flat grit as cutting depth increased. This may because that blunt grit would generate cone-crack systems, yet sharp grit contributes to radial-median crack systems [3]. Besides, as for Es, the different tendency with MRR was found. In grinding process, the micro-fractured grit may consume more energy, followed by flat grit and intact grit in order. Compared with flat grit, the smaller MRR of micro-fractured grit was the main factor that resulted in larger Es. Additionally, the larger Es generated by micro-fractured and flat grit was mainly resulted from the greater friction during scratching process probably.

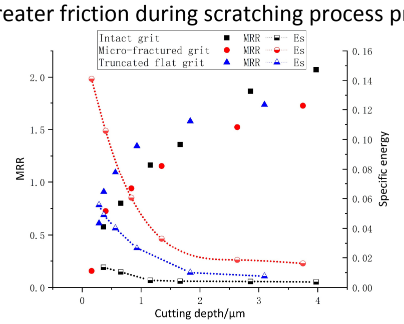

Figure 4． The influence of grit wear evolution on MRR and Es

The above results enlightened that in terms of time saving grinding micro-fractured and flat grain may be preferred, but for energy saving grinding, intact grain has the priority. However, the wear flat grain is advantageous taking account of time and energy saving in grinding.

3.3. AE signals

AE has been widely applied to monitor MRR or even roughness during grinding process [4]. However, the impact of grain wear was also involved in the total AE signals. This part would reveal the effect of grain wear on AE characterizations by frequency analyzing. From the frequency characteristic in Figure 5, it can be understood that the grain wear would cause fewer high frequency AE signals in material removal process. With the effect of grain wear, the proportion of AE signals in 0-50kHz was increased. What's more, the occurrence of wear could eliminate AE signals in about 250kHz, and with the wear degree increasing, AE intensity in 130-150kHz was reduced continuously. Thus, in grinding process, the frequency analysing can be employed to characterize the grinding wheel wear degree.

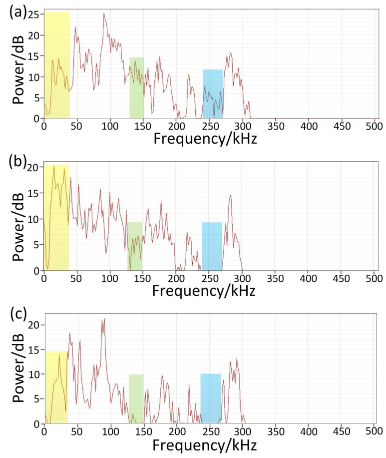

Figure 5. The power spectrum of AE signals in different scratching tests by intact (a), micro-fractured (b) and truncated flat grit (c).

4. Conclusions

In present work, the effect of grain wear on material removal behaviors in terms of d_c, MRR, Es and AE in sapphire grinding process were studied. The following conclusions were obtained:

(1) Ductile removal regime could be obtained despite the varied degrees of grain wear. Truncated flat grain resulted in sharp decrease of d_c.

(2) MRR in slight brittle removal regime and Es in whole removal regime would increase as grain wear evolved in scratches, and wear flat grain was superior in time and energy saving grinding.

(3) In grinding, the occurrence of wear could eliminate AE signals in about 250kHz, and with the wear degree increasing, AE intensity in 130-150kHz was reduced continuously.

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References

[1] Dobrovinskaya E R, Litvinov L A and Pischik V 2009 Sapphire: Material, Manufacturing, Application *Springer Science and Business Media* (Berlin) 6-31

[2] Wang H, Riemer O, Rickens K and Brinksmeier E 2016 *Scripta Materialia*. **114** 21-26

[3] André D, Jebahi M, Iordanoff I, Charles J, luc and Néauport J Ô 2013 *Meth. Appl. Mech. Eng.* **265** 136–147

[4] Kim H Y, Kim S R, Ahn J H and Kim S H 2001 *J. Mater. Process. Technol.* **111** 273–278