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Study on wear of the grinding wheel with an abrasive phyllotactic pattern

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ABSTRACT

An investigation was conducted on the wear of abrasive particles on two differently designed grinding wheels. One wheel had a random distribution of grains, but the other kind of wheels was engineered to explore the concept of using a bio-inspired phyllotactic pattern having the same grain density as the former wheel. Wear areas of grains on both grinding wheels were compared using a computer-aided imaging system after being used for grinding under same conditions. Results showed that the standard deviation and the mathematical expectation of grains' wear areas on the wheel with the phyllotactic pattern were less than those of the reference wheels. To understand this phenomenon, cutting fluid flow in grinding zone was studied based on numerical simulations with a computational fluid finite element technique. Additionally, the average force load on grain was investigated. Finally, through analyzing the influence of the phyllotactic coefficient on the worn areas of grains, based on experiment and theory analysis, the following behavioral changes were observed: the mathematical expectation of worn areas of grains increases firstly and then decreases with the increasing of phyllotactic coefficient, and there is positive correlation between the standard deviation of worn areas and the phyllotactic coefficient.

1. Introduction

Grinding occupies certain proportion of the expenditures in all machining processes [1], stock and installation of machine tools [2]. So it is necessary to assess the lifetime of grinding wheels [3]. The wear of grinding wheel is an important indicator to assess the lifetime of grinding wheel, because high wear may lead to thermal damage or other unexpected defects of workpiece [4]. However, it is more difficult to accurately predict and control the wear of grinding wheel than other tools because the grains for the cutting operation are randomly shaped, oriented, and positioned on a grinding wheel. Some advanced researches have been conducted to predict the wear of grinding wheel. Nakaia [5] proposed an intelligent system composed of four types of neural networks to estimate the wear during the grinding of advanced ceramics. A model of wear process was built by Yu [6] based on grit pullout mechanism and associated state of damage percolation. Simulations of grinding wear using finite element method were applied to study the wear of brazed CBN grits during grinding [7,8]. The predictions can help us understand the mechanism of wear and make better use of grinding wheels. But what is more important is to reduce and resist the wear of grinding wheels after knowing the mechanism. A novel grain of ultrahard polycrystalline diamond was produced, which its wear resistances performed better than normal polycrystalline diamond [9]. A new grinding method of EUAG (Elliptical Ultrasonic Assisted Grinding) could reduce wear flats of grains by producing more micro-fracture and cleavage of abrasive grains [10]. The wear tests showed that orientated diamond grains manufactured by the technology of laser ablation and CVD could be minimized by employing micro-arrays with crystallites of particular orientation (i.e. CVD-MCC-110) [11]. Wear areas of grinding wheels could also be effectively reduced by applying techniques of cutting fluid applied in grinding, such as minimum quantity lubrication (MQL) and nanofluids [12,13].

At present, engineered grinding wheels are attracting more researchers because of their better performance in the aspects of heat dissipation and grinding force [14,15]. Most of the engineered wheels are manufactured using the technology of electroplate and brazing with grains of CBN or diamond [16–19]. So the grains on most engineered grinding wheels are monolayer. The CBN or diamond is remarkable for the superior wear resistance. But the monolayer grinding wheel is more sensitive to wear due to the transient nature of its grinding performance [20], which is attributed to its impossibility of dressing and sharpening [21].

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Consequently, it raises the significance to study the wear of engineered grinding wheels.

In this study, comparison of wear tests has been conducted under the same grinding conditions among the bionic grinding wheels, other two engineered grinding wheels, and a grinding wheel with a random distribution of grains. Wear areas of grains on grinding wheels after grinding have been detected and calculated by the computer-aided imaging system which is mainly composed of a charge-coupled device (CCD), microscope and the processing program of images. Finally, the wear characteristics of different engineered grinding wheels and the bio-inspired grinding wheels with different values of phyllotactic coefficient have been obtained through analyzing the wear areas of grains.

2. The grinding wheel with an abrasive phyllotactic pattern

2.1. Phyllotaxis theory

Phyllotaxis is a kind of arrangement, which many biological structures conform to. The cylindrical phyllotaxis pattern of plant's leaves is described by Fig. 1

The Eq. (1) is deduced from the biological researches based on the theory of statistics [22–24]:

$$\begin{cases} \rho = R_0 \\ \phi = n \cdot \alpha \\ H = n \cdot h \end{cases} \tag{1}$$

R_0 and h are constants for a particular cylindrical model, h is phyllotactic coefficient; α is the divergence angle put forward by Fibonacci between these two sequential elements, the golden angle of 137.508° is chosen for α as the result of natural selection [25].

2.2. Phyllotactic grinding wheel

Structures abstracted from natural systems have been applied to engineering and technological design in many researches [26–28]. In particular, the biomimetic surface structures have also been used in the filed of abrasive antiwear [29,30]. The phyllotactic pattern has been applied to the engineered grinding wheel due to its natural quality in this paper. The leaves of plants are required to absorb adequate sunlight so as to carry out photosynthesis in nature. So the phyllotactic pattern must ensure the contact area of leaves' exposure to sunlight maximum. Meanwhile, this arrangement could help plants stay standing in the wind easier by decreasing aerodynamic drag. Absorbing sunlight needs "high-density" of leaves and decreasing aerodynamic drag needs "low density" of leaves. The nature found the phyllotactic pattern after the evolution of hundreds of millions years to perfectly resolve this conflict. In grinding technology, more active grains and more cutting fluid in grinding zone are all expected. However, more grains would narrow the gaps between grains to block cutting fluid flow in the grinding zone, which would increase undesirable wear of a grinding wheel. The phyllotactic pattern is introduced into the fabrication of the engineered grinding wheel to resolve this conflict in grinding technology. To validate the inference, the wear performance of grinding wheel with an abrasive phyllotactic pattern has been studied. The masking technology was used [31] in order to create the pattern of grains on the grinding wheel as shown in Fig. 1. The process of fabrication of the biomimetic grinding wheel is shown in Fig. 2.

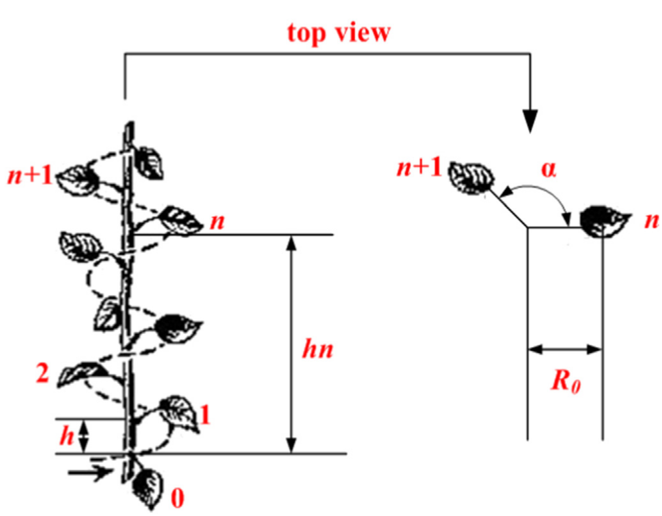

Fig. 1. The sketch of the phyllotaxis pattern.

3. Material and method

3.1. The measuring system

Imprint method is an easy way to measure wear of grinding wheels, but it is time-consuming and tedious to measure wear areas of grains from the prints. There are many other advanced devices to measure the wear of grinding wheel, such as scanning electron microscope (SEM), fiber optic digital microscope (VHS), white light interferometer (WLI), and confocal laser scanning microscope (CLSM). But these devices are relatively expensive and they require extremely rigid mounting for accurate measurement, and sophisticated positioning systems to scan over the grinding wheel surface [32]. As a result, a convenient and effective method is proposed to detect wear areas of grains.

There are two types of grains' wears in grinding process for an engineered grinding wheel: fracture wear and abrasive wear. Fracture wear is relatively positive due to the generation of new cutting edges or enhancing grain sharpness. However, abrasive wear occurring on the grain–workpiece contact interface might expand wear area of grains, which could increase grinding force and heat to shorten the service life span of a grinding wheel. Therefore, it is a primary task to measure the abrasive wear. For this purpose, a measuring system was built based on different levels of light reflection of grains' different parts. The measure devices are shown in Fig. 3.

In Fig. 3, the camera and lens are placed perpendicular to the grinding wheel's surface. The parallel light produced by the fiber optic illuminator ensures that the light hits the worn flats of grains normally. So the light can be reflected directly back to the camera, by which the worn flats can be seen clearly. In order to remain the same magnification of each picture of wear flat, the distance (l) between the grinding wheel's surface and the lens as seen in Fig. 3 must keep constant. The grinding wheel rotates around the axis and the charge-coupled device (CCD) camera can move up and down freely. Therefore, every worn flat of grain on the grinding wheel's surface can be observed.

The picture of each worn grain can be read and stored based on Fig. 3. An image processing procedure must be done to get the size of worn area. This processing is illustrated in Fig. 4.

In Fig. 4, the photo ① is exported from the CCD camera directly, the black circle around the grain in ① is the imprint left of mask hole with a diameter of 400 μm as seen in Fig. 2. In order to reduce calculating time and help computer recognize the grain, some