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Three-dimensional modelling and simulation of vibration marks on surface generation in ultra-precision grinding

Shanshan Chen[a,b], Chi Fai Cheung[a,*], Fehu Zhang[b], Chenyang Zhao[a]

[a] *Partner State Key Laboratory of Ultraprecision Machining Technology, Department of Industrial and Systems Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, Hong Kong*

[b] *Harbin Institute of Technology, School of mechanical and electrical engineering, Harbin, China, China*

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ABSTRACT

Nowadays, most modelling work for ground surface topography is based on either abrasive kinematics (micro-level) or high-frequency vibration of the grinding wheel (macro-level) to predict surface quality or grinding performance, but there is a lack of a correlation model to relate these two levels together. In this research work, wheel shape with two radii and wheel synchronous vibration are modelled first for the interference of the tool edge in 3D space to reveal the evolution mechanism of surface waviness under different vibration conditions (phase shift from 0.0 to 1.0). Hence, a multi-scale model is established considering the diverse protrusion heights of the grits and incorporating the wheel shape and micro-vibration of the tool so as to explain the mechanism of the generation of the surface marks on the ground surface. The result shows that four principal residual marks are formed on the ground surface including spirals, tool feed marks, cumulative phase marks and abrasive grain scratches. The amount of surface waviness resulting from the tool unbalance is equal to the ratio of the rotating speed of the grinding wheel and the workpiece. The feed mark representing the tool locus and tool nose geometry is a spiral pattern from edge area to the machined center. The phase shift marks are caused by the phase accumulation effect. The grit scratches are related to the wheel geometry, kinematics and distribution of protrusion heights. In addition, the phase shift tends to increase the density of grinding marks, with a significant decrease when the phase shift is equal to 0.5. The surface generation model is further verified by a closed surface matching method, which shows the simulation results agree reasonably well with the grinding experiments.

1. Introduction

Ultra-precision grinding is widely applied to precision manufacture a wide range of materials and components with different geometries, which can achieve remarkable workpiece tolerance and accuracy. With the technological advancement of ultra-precision grinding machine with high stiffness and high accuracy, it is feasible to machine hard and brittle materials, such as silicon carbide (SiC), silicon nitride (Si_3N_4) and tungsten carbide (WC) without inducing fracture damage [1–3]. Ceramic materials are typically difficult-to-machine materials due to their extremely high hardness and fragility [4–7]. Due to the outstanding properties of chemical inertness and wear resistance of silicon carbide (SiC) for engineering ceramics as compared to traditional metallic materials [8,9], it has been applied not only to machine structural components but also precision optical parts in recent years [10–12]. Ultra-precision diamond grinding is more properly used to machine SiC due to its high material removal rate and is able to achieve favourable surface integrity [13]. Form accuracy and surface quality have become the key indicators to evaluate the preference of the grinding process. To achieve a mirror-finished surface without fracture damage, considerable research work has been devoted to studying the cutting mechanics and surface generation mechanisms in ultra-precision grinding.

However, ultra-precision grinding is a complex process, which is influenced by many factors, such as the workpiece material, wheel characteristics and grinding conditions. The modelling of the surface generation is more complicated than that of single point turning (SPDT) or multipoint milling [14]. In recent years, with the increasing demand for a high degree of accuracy and high-resolution optical systems, there is growing demand for high surface quality and integrity of machined workpieces. Improving the surface quality of optical components is a critical issue in ultra-precision grinding. To better understand the process of surface generation in ultra-precision grinding, a theoretical surface generation model is of great need to be developed to explain the interaction of grinding wheel and workpiece. There are two ways to establish a surface generation model, i.e. empirical approach and analytical approach. For the empirical approach, surface roughness prediction is performed based on a large number of machining experiments in order to calculate the coefficients in polynomials. The analytical

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[*] Corresponding author.

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approach is based on studying the geometrical relationships between the cutting edges and the workpiece so as to determine the surface topography. In comparison to empirical models, an analytical approach is preferable due to its better predictability and suitability under a wide range of cutting conditions [15]. A large number of analytical models have been developed, which are focused on studying the surface generation mechanisms so as to trace and track the optimal cutting parameters [16–19]. Tool characterization is a key aspect to model surface finish, mostly adopting statistical analysis to define a random distribution function of grits with different protrusion heights, and kinetical analysis is used to describe the cutting event so as to determine the surface roughness [20–23]. CHENG, et al. [24], proposed a geometrical model of surface roughness in the micro-grinding of soda-lime glass by considering different densities and protrusion heights of abrasive grains. In the model, the different densities for various protrusion heights are deterimined and the low surface roughness can be achieved with a fine feed rate and high speed for the grinding wheel. Liu, et al. [25] estabilished a theoretical model to predict the workpiece surface roughness by considering the different shapes of grains. In this research, sphere, truncated cone and cone abrasive grains combining the dressing condition are considered to predict the surface roughness and it was found that the dressing is the dominant factor deterimining the final surface roughness. McDonald, et al. [26] developed a kinematic model for surface generation and the undeformed chip thickness based on experimentally measuring the grinding wheel topography. In order to enhance the computational efficiency, a new peak-removal method is proposed to remove erroneous spikes. Aleksandrova [27], presented a model to optimize the dressing parameters in cylindrical grinding by a generalized unility function, which related the tool life, machininability, and grinding force to the dressing parameters. In considering both the wheel topography and relative vibration. Kuriyagawa, et al. [28], study the nano-topography generation in grinding of axisymmetric aspherical surface and analyse the relationship between workpiece and wheel revolution speeds and machining marks caused by the nano-topography. Yoshihara, et al. [29], developed a new model to describe the cross sectional profile of the ground surface resulted from the unbalanced vibration of grinding wheel in machining axisymmetric surface. In this model, the arc-shaped wheel is considered and spatial frequency analyse is conducted to uncover the changes of the amplitude of the cross sectional profile of the machined surface in the direction of grinding wheel feed. CAO, et al. [30], adopted the gaussian distribution function combined with the umblance vibration of the grinding wheel to drive the trajectory of each abrasive grain and simulate surface topography generation in cutting direction, in which the influence of grinding operation parameters, grit size and vibration amplitude of the wheel on the surface roughness and waviness was studied.

However, this modelling work for ground surface generation is mainly based on either the abrasive kinematics (micro-level) or high-frequency vibration of the wheel (macro-level) to predict surface generation or evaluate the performance of the grinding process. There is a lack of a compressive model to study surface generation in detail. In grinding operation, imbalance of the grinding wheel is not uncommon and results in changes of abrasive grain trajectories, in turn impacting on the machined surface, especially the phase shift which has a remarkable influence on the evolution of surface generation. In this paper, a theoretical model is established to study the influence of phase shift on surface waviness and grain trace on the surface quality of the ground workpiece so as to reveal the fundamental mechanism of grinding mark generation on ground surfaces.

2. Modelling of vibration marks in ultra-precision grinding

In this study, contour grinding operation for flat surface was considered. Grinding is a complex machining process with a large number of parameters which affect the surface generation in the grinding process. It is almost impossible to conduct kinematics analysis by considering all the factors. As a result, it is necessary to make some simplifications in the modelling. Some assumptions were made as follows:

(i) Wheel wear effect and the movement errors of the workpiece spindle were ignored;
(ii) The vibration amplitude of the grinding wheel was kept stable at all rotational speeds (39000 RPM-40500 RPM);
(iii) The deformations of the wheel and workpiece were not considered; only the geometrical removal of material was considered without ploughing and rubbing phenomena.

2.1. Modelling of grinding wheel geometry

In ultra-precision grinding, a rotary part feeds over a spinning wheel with a constant feed rate to remove the materials from the workpiece, as shown in Fig. 1. The grinding wheel has a small tool nose radius r) on the wheel edge and a large wheel radius R), which can be approximated to a three-dimensional ellipsoid, as shown in Fig. 1. In general, the tool nose radius is significantly larger than the depth of cut, the former measured at millimetre scale with the latter characterized in the micrometre range. As a result, the tool nose profile at the cutting edge determines the surface topography of the ground workpiece. The radius of curvature of the ellipse arc and the contact area of the tool nose radius at the lowest contact point can be considered to be equivalent due to the super small contact region between the wheel and the workpiece.

$$\frac{x^2}{R^2} + \frac{y^2}{b^2} + \frac{z^2}{R^2} = 1 \tag{1}$$

However, the minor axis of the ellipsoid b) is unknown, so to calculate b, the instantaneous curvature radius r') in z-y section is derived as below:

$$r' = \frac{1}{\rho} = \frac{\left[1 + \left(\frac{\partial z}{\partial y}\right)^2\right]^{\frac{3}{2}}}{\left|\frac{\partial^2 z}{\partial y^2}\right|} \tag{2}$$

In the z-y coordinate system, an ellipse is shown in Eq. (3):

$$\frac{y^2}{b^2} + \frac{z^2}{R^2} = 1 \tag{3}$$

where:

$$z = \pm\sqrt{R^2(1 - \frac{y^2}{b^2})} \tag{4}$$

$$\frac{dz}{dy} = \mp\frac{yR}{b^2}\left(1 - \frac{y^2}{b^2}\right)^{-\frac{1}{2}} \tag{5}$$

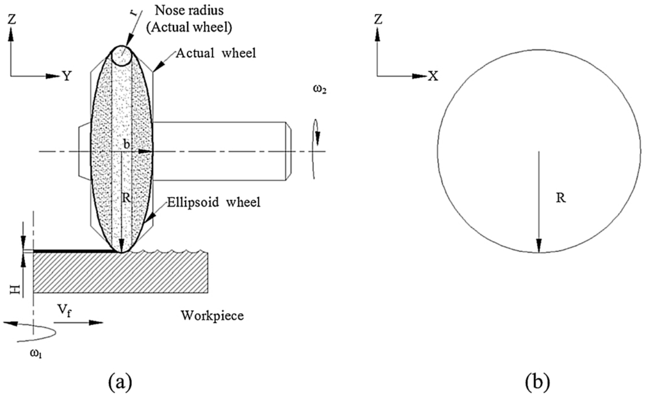

Fig. 1. Illustration of the ellipsoid model for the grinding wheel: wheel geometry (a) in the Z-Y plane, (b) in the Z-X plane The ellipsoid is expressed by Eq. (1) and its center is set at the origin.