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Multi-scale modeling and simulation of material removal characteristics in computer-controlled bonnet polishing

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ABSTRACT

Computer-controlled Bonnet Polishing (CCBP) is an enabling technology which is capable of fabricating ultra-precision freeform surfaces with sub-micrometer form accuracy and surface roughness in the nanometer range, especially for difficult-to-machine and ferrous materials. However, the material removal mechanism of computer controlled bonnet polishing (CCBP) usually exhibits multidisciplinary and multi-scale complexity and hence our understanding of the material removal characteristics is still far from complete. As a result, this paper presents a multi-scale theoretical model for the prediction and simulation of the material removal characteristics in the CCBP process. The model is established based on the study of contact mechanics, kinematics theory and wear mechanisms. A series of spot polishing tests as well as simulation experiments by the theoretical model were conducted. The predicted results agree well with the experimental data. The successful development of the theoretical model helps to make the CCBP process more predictive, and so that optimizing the manufacturing process, and forms the theoretical basis for explaining some material removal mechanisms in CCUP, such as the critical polishing depth for minimizing pad scratching.

1. Introduction

Free-form surfaces with high form accuracy and good surface finish have become increasingly required for example in the field of precision optical applications [1,2]. However, the geometrical complexity and high quality requirement of freeform surfaces bring considerable challenges for the fabrication of these surfaces [3]. Computer-controlled Bonnet Polishing (CCBP) is an enabling technology that actively controls the position and orientation of a spinning, inflated, membrane tool (the 'bonnet') as it sweeps through the polished surfaces [4,5]. CCBP has the advantage of high polishing efficiency, mathematically tractable influence function, and flexibly controllable spot size with variable tool hardness [6]. Therefore, CCBP is one of the promising ultra-precision polishing technology which shows a great potential with regard to the application value in the fabrication of freeform surfaces with sub-micrometer form accuracy and nanometric surface finish. It is well known that the surface generation of the polishing process can be regarded as the convolution of the influence function and the dwell time map along the pre-specific tool path. Hence a predictable and stable tool influence function and an optimized path generator are of paramount importance for the success of the freeform polishing process. Moreover, polishing of freeform surfaces with submicrometre form accuracy and surface finish in the nanaometric range is complex and multi-scale in nature. As a result, knowledge of the removal mechanisms and factors affecting material removal characteristics are vital to determine the surface quality and form control in the polishing process.

During the past few decades, much research has been performed on the modeling of the material removal characteristics based on the Preston's equation [7–10]. Cheung et al. [11] established a predicted model for the material removal characteristics with the assumption of modified Gaussian distribution of the contact pressure in bonnet polishing. Li et al. [12,13] and Wang et al. [14] calculated the pressure distribution in the contact area by the axisymmetric elastic solid model with finite element analysis (FEA). However, in their model, the pressure on the polished surface is only related to the elastic deformation of the polishing tool. Bouvier [15] and Zeng et al. [16] developed the material removal model using modified Preston equation and Hertz contact mechanics theory. But the pressure distribution and surface deformation predicted by Hertz's equations must be modified, when comes to that a slurry film is present and the polishing pad slides over the surface in the actual polishing process. Moreover, the material removal characteristics in bonnet polishing is affected

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by various parameters (tool radius, *precess* angle, polishing depth, head speed, tool pressure, polishing time, polishing cloth, slurry concentration, particle size and type etc.), while the predicted model based on the Preston's equation is only concerned with the velocity of polishing tool relative to the workpiece and the contact pressure between the polishing tool and the workpiece.

Besides the mechanical model based on the Preston's equation, many researchers have developed comprehensive material removal models in order to reveal insights into the contact behavior and wear mechanism in the similar chemical-mechanical polishing (CMP) process. Luo and Dornfeld [17] developed an indentation-sliding model for predicting the material removal rate with the fully plastic deformation assumption over the wafer–abrasive interface. In their model, the periodic roughness of the pad surface was used to calculate the real contact area while the normal distribution of abrasive particle size was assumed to predict the number of active abrasives. To further take into account the effect of the pad surface roughness and the variation of asperity height on the material removal rate, Greenwood and Williamson's elastic contact model was commonly used to model the contact stress and the real area of pad/wafer contact in CMP [18,19]. Bozkaya and Muftu [20] analyzed the contact interactions due to the two-body (pad-wafer) contact and the three-body (pad-particles-wafer) contact using contact mechanics and finite element (FE) modeling, and modeled the material removal rate by considering adhesive and abrasive wear mechanisms for CMP. Furthermore, Kim et al. [21,22] developed the theoretical model based on contact mechanics and abrasive wear models to correlate pad surface topography and the material removal rate in CMP. According to the difference among processing conditions and the mechanisms between the CMP and CCBP, these models for CMP cannot be directly used for predicting the material removal rate in CCBP.

Despite intense theoretical and experimental research on bonnet polishing [23–25], there is still serous lack of fundamental understanding of extensive physical mechanisms in this process. As a result, the present paper presents a theoretical and experimental investigation of material removal characteristics in order to better understand and optimize the polishing process. A multi-scale model is built based on the study of contact mechanics, kinematics theory and wear mechanisms. Hence, a series of experiments have been undertaken to reassuringly validate the theoretical and simulated predictions.

2. Multi-scale theoretical modeling of material removal characteristics for computer controlled bonnet polishing

The material removal mechanism in CCBP involves multi-scale interaction between the pad, abrasive particles and the workpiece. Fig. 1 shows the flowchart of the theoretical modeling. The pressure and velocity distributions are determined based on the kinematics theory and contact mechanics at the macro-scale, and the pad topography which affects the contact ratio and hence the material removal rate at the micro-scale, and the micro- or nano-sized abrasive particles scratch the surface at the nano scale. In the coming section, the material removal characteristics is modeled step by step with the following assumptions: (1) The polishing bonnet is assumed to be a perfect sphere and much softer than the polished flat surface, hence, the polishing bonnet is elastically deformed while the polished surface remains flat in the contact area; (2) The polishing bonnet pressures the target flat surface is assumed to be a viscous sphere on a hard plane regardless of the contribution of slurry hydrodynamic pressure, pad asperities, contact-surface instability and pad-abrasive-workpiece contact; (3) Material removal occurred in CCBP is assumed to be only

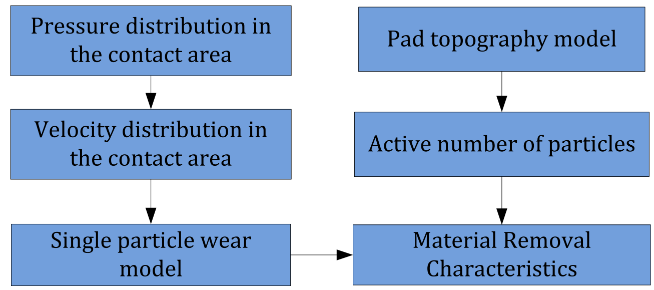

Fig. 1. Flowchart of multi-scale theoretical modeling process for CCBP.

related to the removal of material by plastic deformation caused by abrasive particles.

2.1. Modeling of surface velocity distribution

Fig. 2 shows the graphical illustration and detailed geometry in the polishing area by the polishing bonnet on flat surface. Where ω is angular velocity in rad/min, $\overrightarrow{\omega}=\frac{\pi S}{30}\{0,-\sin(\varphi),\cos(\varphi)\}$; φ is the inclination angle; S is angular velocity in rpm; O_b is the center of the bonnet; L is the axis of rotation of the bonnet; O_w is the center of polishing spot; d is the polishing depth in mm; R_b is the radius of the bonnet in mm; O_r is the swing center of point P and can be expressed as $(0, y_0, -y_0\cot\varphi)$; P is any point in polishing contact area and can be expressed as $((R_b-d)\tan\alpha\sin\theta, (R_b-d)\tan\alpha\cos\theta, -(R_b-d))$, $0\le\alpha\le\arccos\left(\frac{(R_b-d)}{R_b}\right)$, $0\le\theta\le 2\pi$. Hence, the vector of $\overrightarrow{O_bO_r}$ and $\overrightarrow{O_rp}$ can be represented as

$$\overrightarrow{O_bO_r}=\{0,y_0,-y_0\cot\varphi\} \tag{1}$$

$$\overrightarrow{O_rp}=\{(R_b-d)\tan\alpha\sin\theta,(R_b-d)\tan\alpha\cos\theta-y_0,\\ -(R_b-d)+y_0\cot\varphi\} \tag{2}$$

Since $\overrightarrow{O_bO_r}\perp\overrightarrow{O_rp}$, the solution of y_0 can be expressed as

$$y_0=\frac{(R_b-d)(\tan\alpha\cos\theta+\cot\varphi)}{1+(\cot\varphi)^2} \tag{3}$$

Therefore, the vector of $\overrightarrow{O_rp}$ can be written as

$$\overrightarrow{O_rp}=\{U,V,W\} \tag{4}$$

where $U=(R_b-d)\tan\alpha\sin\theta$;
$V=(R_b-d)\tan\alpha\cos\theta-\frac{(R_b-d)(\tan\alpha\cos\theta+\cot\varphi)}{1+(\cot\varphi)^2}$;
$W=-(R_b-d)+\frac{(R_b-d)(\tan\alpha\cos\theta+\cot\varphi)}{1+(\cot\varphi)^2}\cot\varphi$.

The velocity vector $\overrightarrow{v_p}$ at point P can be obtained by using vector operation (cross product):

$$\overrightarrow{v_p}=\overrightarrow{\omega}\times\overrightarrow{O_rp}=\frac{\pi S}{30}\left[-(V\cos\varphi+W\sin\varphi)\overrightarrow{i}+U\cos\varphi\overrightarrow{j}+U\sin\varphi\overrightarrow{k}\right] \tag{5}$$

Therefore, for polishing a flat surface, the relative velocity V_r at the point P is

$$V_r=\frac{\pi S}{30}\sqrt{(V\cos\varphi+W\sin\varphi)^2+U^2(\cos\varphi)^2} \tag{6}$$

2.2. Modeling of pressure distribution

Since the plasticity index for a soft polymer has only about one tenth of the value for metal, the contact between a polymer and a metal is almost completely elastic, except against very rough