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Modification of tool influence function of bonnet polishing based on interfacial friction coefficient

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ABSTRACT

Aimed to improve the modeling accuracy of tool influence function (TIF) of bonnet polishing, a theoretical and experimental study is presented. This paper starts with the affecting mechanism of key parameters on the material removal of workpiece. It is indicated that the interfacial friction coefficient between tool and workpiece is changed with the variety of the tool rotational speed, which impacts the TIF but has not been taken into account in most current TIF models. Consequently, modification of TIF model based on the interfacial friction coefficient is proposed and then experimentally validated. The results show that, for the experimental groups in which the spot size is 15 mm, the difference between the maximum removal depth of the TIF predicted with the pre-modified model and that of the experimental TIF is −0.204 to 1.244λ (λ = 632.8 nm), which is obviously larger than that between the TIF predicted with the modified model and the experimental TIF −0.187 to 0.168λ. Moreover, for the experimental groups in which the spot size is 20 mm, the difference between the maximum removal depth of the TIF predicted with the pre-modified model and that of the experimental TIF is −0.135 to 2.235λ, while that between the TIF predicted with the modified model and the experimental TIF is −0.046 to 0.571λ. The experimental results indicated that the TIF predicted by the modified model is much closer to the experimental TIF, which proves the effectiveness and correctness of the modification.

1. Introduction

Computer controlled polishing is usually applied as the last procedure of the machining of hard brittle materials, such as glasses, ceramics, etc. During polishing process, the tool influence function (TIF) is the base to compute the dwell time and predict the removal depth of workpiece, therefore its accuracy directly affects the degree of certainty of material removal, which determines the precision and efficiency of the polishing process. Consequently, the modeling of TIF is concerned in the studies of most polishing technologies [1–4].

For most modeling processes of TIF, the theoretical foundation is the Preston's law, which expresses the TIF as

$$RR = k \cdot P \cdot V \cdot t \tag{1}$$

where *RR*(i.e., TIF) denotes the removed material from workpiece by polishing tool in certain time *t*. *k* denotes the Preston coefficient, *P* and *V* denote the pressure and relative velocity distribution on the contacting area, respectively. Since *k* is usually supposed to be unchanged during polishing process, the modeling of TIF is actually the calculation of *P* and *V*.

Regarding to bonnet polishing, researches on the TIF have also been reported. Walker et al. [5] firstly proposed the bonnet polishing technology, and obtained the TIF from experiment, however, they did not model it mathematically. Kim et al. [6] calculated the pressure distribution and the velocity distribution based on the Gaussian theory and the analysis on the tool kinematics, respectively. After that, according to Preston's law, the tool influence function (TIF) was presented and validated. Zhang et al. [7] also established the TIF model in the light of Preston's law and the study on the pressure distribution and velocity distribution. But different to the Kim et al., they achieved the pressure distribution according to the Hertz contact theory. Finally, the

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experimental results demonstrated good coincidence between the measured and simulated TIF. Cheung et al. [8] established a predicted model for the TIF with the assumption of modified Gaussian distribution of the contact pressure in bonnet polishing. Wang et al. [9] mathematically modeled and experimentally validated three kinds of the tool influence functions (TIFs) of bonnet polishing. In that work, the remarkable contribution is confirming the pressure distribution on the contact area by finite element analysis (FEA) technology. Cao et al. [10] presented a multi-scale theoretical model for the prediction and simulation of the TIF in the computer controlled bonnet polishing, based on the study on contact mechanics, kinematics theory and wear mechanisms. After that, a series of spot polishing tests and simulation experiments by the theoretical model were conducted. The predicted results agreed well with the experimental data. Feng et al. [11] proposed the removal function (i.e., TIF) of bonnet polisher based on the distribution of velocity and pressure, which were calculated from the geometry of the process tool-motion and Hertzian contact theory, respectively. Subsequently, a finite element analysis (FEA) model was constructed to optimize process parameters. At last, detailed experimental studies were carried out to verify the optimal parameters.

According to the above literatures, most studies paid attentions to the calculation of the pressure and velocity distribution, but the determination of the Preston coefficient k (in Eq. (1)) is mentioned a little, due to the non-fully understanding on the material removal mechanism during bonnet polishing process. Normally, k is obtained from experiment and supposed to be unchanged. However, according to our latest work, the interfacial friction state between tool and workpiece contained in k varies apparently with the change of the tool rotational speed, which means k should be changed as well. From this perspective, if k is set to be constant as most current TIF models, the accuracy of TIF would be affected. A similar view was expressed by L Téllezarriagaet al. [12], their work put forward that it was necessary to propose a new model, in which the friction coefficient has certain dependence with relative speed. Therefore, they suggested that the Preston equation has to be modified, in order to take the friction coefficient into account as a function of the relative speed.

Based on the analysis above, non-fully understanding of the material removal mechanism during bonnet polishing affects the modeling of TIF. Therefore, aimed to improve the accuracy of TIF, a theoretical and experimental study is presented. Firstly, in Section 2, through conducting a series of experiments, the material removal mechanism during the bonnet polishing process is enriched, and the limitation of the existing TIF models is pointed out. Subsequently, in Section 3, theoretical modification and experimental validation of the modified TIF model is presented, followed by the discussion. At last, the conclusions of this paper are revealed in Section 4.

2. Experimental study

In this section, by investigating the effect of key parameters on the material removal of workpiece, the current material removal mechanism is enriched, and thereby the disadvantage of the current TIF calculation model is indicated.

2.1. Determination of key parameters

Fig. 1 depicts the classic bonnet polishing process: a bonnet filled with gas is used as polishing tool, the workpiece is fixed on the worktable and polished by the rotating bonnet tool, whose surface is attached with polyurethane pad. During polishing, slight slurry containing fine abrasive particles is released onto the pad surface. Based on Fig. 1, the involved parameters during the polishing process are the inner pressure (i.e., the pressure of the gas inside the bonnet) of the bonnet P_b, the precession angle ρ, the diameter of the contacting area S_c and the tool rotational speed n. According to our latest work, S_c and n have much more effect on the material removal of workpiece than other parameters. As a result,

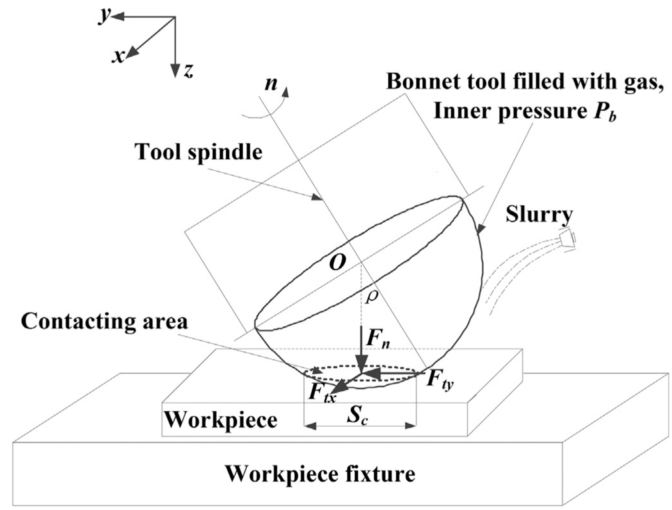

Fig. 1. Classic bonnet polishing process.

those two are defined as key parameters, while others are kept constant in this study. It should be noted that, in our study, S_c is determined by the z-offset of the machine tool, which was obtained with the assistance of the static stress sensor before polishing, as described in our previous study [13].

2.2. Experimental design and setup

After the determination of key parameters, to study the effect on the material removal of workpiece, orthogonal experimental groups were designed and conducted. The details are listed as below:

(1) Orthogonal experimental groups were designed, which are shown in Table 1.
(2) For the parameters of each group in Table 1, static pressure distribution on the contacting area is collected before polishing, using the static pressure sensor (model I-Scan, made by Tekscan), the principle of which is revealed in Fig. 2.
(3) The workpiece was polished with the motion shown in Fig. 1, with the conditions listed in Table 1. During polishing process, the polishing forces (see Fig. 1) were collected with the dynamometer (model 9257B, made by Kistler) shown in Fig. 3, the details for collecting the polishing forces have been introduced in our previous work [13].
(4) After polishing, with the assistance of the sub-aperture interferometer (model SSI, made by QED), the experimental TIF (corresponding to material removal) was obtained.

In this experiment, the workpieces are square BK7 glasses, whose dimension are 100 mm *100 mm *10 mm. The powder of the polishing liquid is CeO_2, the size and concentration of which are ~1 μm and ~1%, respectively. Note that, for each experimental group in Table 1, three tests were repeated and the average polishing forces and TIFs were obtained.

With the above steps, the correlation of key parameters, polishing forces and TIFs was established, thus the affecting mechanism of key parameters on material removal was revealed and discussed in the following section.

2.3. Experimental results

As stated in the Preston's law (Eq. (1)), the material removal of workpiece during polishing process can be calculated by the Preston elements i.e., k, P and V. Consequently, the affecting mechanism of key