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Finite element simulation of surface roughness in diamond turning of spherical surfaces

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ABSTRACT

In this paper, a 3D finite element (FE) model is proposed for the diamond turning of spherical surfaces, and the movement control subroutine in the software is developed to describe the actual movement of diamond tool. In the simulation ns, the surface roughness is evaluated by collecting and calculating the coordinates of the nodes on the topmost machined surface, and the influences of tool nose radius, depth of cut and feed rate on surface roughness are investigated. A series of experiments with the same values of tool geometry and cutting condition parameters used in FE simulations are carried out, and the experimental results agree well with the simulation results. Besides, according to the results, the influence of tool nose radius on the surface roughness is greatest followed by feed rate, and the influence of depth of cut is smallest.

1. Introduction

Surface quality greatly affects the mechanical properties of machined parts, such as fatigue strength, tribological properties and corrosion resistance [1]. The surface roughness is widely used to evaluate the surface quality in the machining process, and it is also used as the technical requirement of products generally [2].

In diamond turning, especially in ultra-precision diamond turning, the surface roughness of the machined component is quite small and the form accuracy is in sub-micrometer range [3]. Tiny changes in surface roughness may significantly affect the performance of components. Hence, it is important and necessary to investigate the generation of surface roughness in diamond turning. Many studies focusing on surface topography prediction and simulation in diamond turning have been done. Li et al. [4] investigated the influences of different machining parameters on the optical effects of machined surfaces. The first order diffraction and specular reflectivity were selected to evaluate the surface quality. Finally, a mathematic model was established to optimize the machining process parameters, and in this mathematic model only the first order diffraction was considered. Cheung and Lee [5] developed a model to simulate the surface topography generated in ultra-precision diamond turning process. In the model, the kinematics of the turning process, the tool geometry and the relative motion between the tool and the workpiece were all taken into consideration. Besides, the equi-contour mapping technique was used to describe the topography of the machined surface. Huang and Liang [6] proposed a model to study the surface roughness generated in diamond turning. In their study, the relative tool-work vibration in infeed direction was considered additionally. The model can be used to describe the generation of surface roughness in machining of the flat and cylindrical surfaces but no verification for more complex surfaces. Chen and Zhao [7] proposed an improved method to evaluate the actual relative vibration between tool and workpiece. Then a model based on the relative tool-work vibration and swelling effect was established to predict the surface roughness. All these studies mentioned above are based on machining theory or experimental investigation, in some cases designed experiments method and artificial intelligence method were also employed. For machining theory based approach, most studies simulate the cutting process with the consideration of kinematics and cutting tool parameters, some additional parameters such as relative tool-workpiece vibration are also included in the studies to achieve more accurate results. The drawback of these approaches is that many other factors affecting the surface roughness formation are not considered, for example tool wear and thermal phenomena. For experimental investigation based approach, many experiments are required which means much more money and time, and sometimes the experiments produce the unexpected results.

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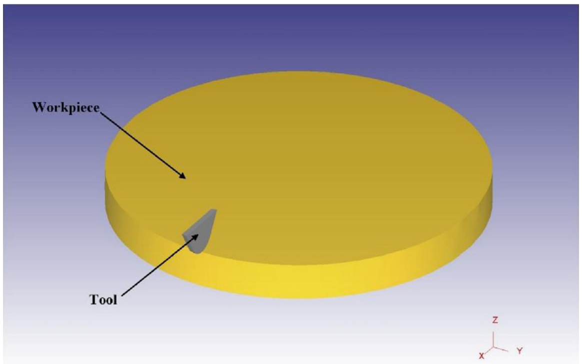

Fig. 1. Geometric model of workpiece and tool.

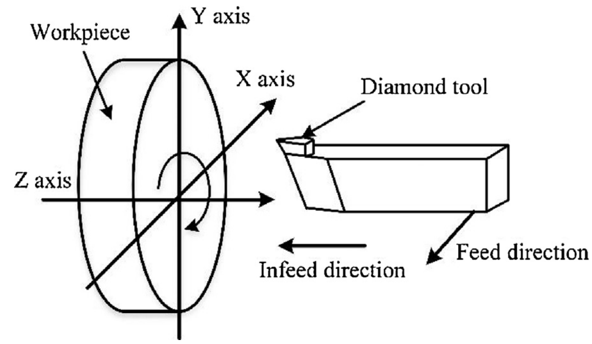

Fig. 2. Schematic diagram of the diamond turning process.

Table 1
Physical properties of Al6061 and PCD.

Properties	Al6061	PCD
Density(Kg/m^3), ρ	2700	4100
Poisson's ratio, ν	0.33	0.1
Young's modulus(Gpa), E	68.9	800
Thermal conductivity(J/Kg/°C), k	167	500
Specific heat(W/m/°C), C	896	435
Thermal expansion coefficient(10^{-6}/°C), λ	23.6	4.0

With the rapid development of computer technologies, numerical simulation, especially finite element methods (FEM) is widely used in scientific study. The earliest work where FEM model was used to simulate the diamond turning process was done by Carroll and Strenkowski [8]. Up to now, finite element (FE) simulation is used to study different problems involved in diamond turning process, such as chip formation, residual stresses, cutting temperature and cutting force, et. Woon et al. [9] investigated the effect of tool edge radius on chip formation mechanism, the distribution of stress and effective rake angle in micromachining of AISI 4340 steel. Kim et al. [10] developed a finite element model based on thermos-viscoplastic theory to study the distribution of cutting temperature and its influence on cutting forces. Lee et al. [11] studied the influence of material anisotropy on shear angle and cutting force variation by using crystal plasticity finite element models (CPFEM). Zong et al. [12,13] developed a model to analyse the diamond turning process with consideration of tool loading and unloading procedures. According to the simulation results, the relationship between residual stress and different parameters varies with cutting edge radius, cutting speed, rake angle and clearance angle were revealed by two regression equations.

Although a large amount of studies with use of FE simulation related in diamond turning process had been presented, the 3D FE simulations are rarely presented, the studies mentioned above mainly carried out based on the 2D model. Besides, previous researches were mainly concentrated on plane analysis so little attention was paid on the generation of spherical surface or more complex surfaces.

Therefore, in this paper, a 3D FE model is constructed to simulate the diamond turning of spherical surfaces. The actual movement of diamond tool is realized by modifying the original movement control subroutine, then the generation of spherical surface can be simulated. The surface roughness is evaluated by collecting and calculating the coordinates of the nodes on the newly machined surface. The influences of tool nose radius, feed rate and depth of cut on the achieved surface roughness are also investigated by simulations and experiments.

2. Finite element model

In this work, the geometrical model of workpiece and diamond tool is firstly built in Pro/E software. Then the 3D geometrical model is imported into DEFORM-3D software, which is used to simulate the turning procedure, as shown in Fig. 1. Fig. 2 is the diagram of the diamond turning process, as shown in the figure, the workpiece rotates around the Z-axis, the diamond tool moves along the X and Z directions, then the spherical surface can be machined. The material of workpiece is aluminium alloy 6061 (Al6061), and the tool is made up of polycrystalline diamond (PCD), the physical properties of Al6061 and PCD are listed in Table 1 [14,15]. The workpiece is assumed to be plastic and deformable with thermo-mechanical coupled analysis, on the contrast, the diamond tool is modeled as perfect rigid and only heat transfer analysis is considered. All nodes on the bottom surface of workpiece are fixed, as a result, the workpiece is unmovable in all directions. The movement of diamond tool is controlled by modified movement control subroutine.

Meshing is a very important step in the process of FE simulation whose quality directly affects the accuracy of numerical calculation, so it should be conducted reasonably according to the actual situation. The element type of workpiece and tool is four nodes tetrahedral element. In order to improve the calculation accuracy, the local refinement method is used to mesh the contact area of workpiece and tool. It is likely that the element distortion would occur during simulation due to the large deformation in turning process, so the global remeshing method is used for both workpiece and tool.

There are several commonly used material constitutive models [16]. In this work, the Johnson-Cook's model is used to represent the actual changes of the material's physical properties during the cutting process, which can be described as [17]:

$$\sigma = \left[A + B\varepsilon^n\right]\left[1 + c\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right]\left[1 - \left(\frac{T - T_r}{T_m - T_r}\right)^m\right] \quad (1)$$

where σ is the flow stress, ε is the equivalent total strain, $\dot{\varepsilon}$ is the equivalent total strain rate, $\dot{\varepsilon}_0$ is the initial strain rate, and A, B, c, n, and m are constant factors in the equation. T is the transient temperature, T_m is the molten temperature of Al6061 and T_r is the room temperature. The values of parameters in the Johnson-Cook equation are shown in Table 2 [12].

In metal cutting, friction between tool and workpiece will produce cutting heat. The heat will affect the stress, strain and the distribution of temperature, etc., which will bring the variations of machining accuracy and machined surface quality. Hence, an accurate representation of the interaction between the tool and chip is important for obtaining reliable simulation results. In this work, Zorev's model [18], which also can be called as the extended Coulomb friction model, is used to describe the sliding and stick-