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A model for predicting surface roughness in single-point diamond turning

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ABSTRACT

The relative tool-work vibration is not generalized enough to represent the actual displacement between tool and workpiece in previous prediction models. This is due to the fact that the vibration was assumed as a steady simple harmonic motion and was only measured before turning process. In this study, an improved method is presented to evaluate the actual relative tool-work vibration. By using this method the vibration information obtained is more credible, as it contains the components caused by machine tool error, cutting force, material property and changing of cutting parameters. Moreover, the swelling effect is analyzed using a new evaluating method and taken into account for predicting surface roughness. On the basis of analyzing both the relative vibration and the swelling effect, a model is proposed for predicting surface roughness R_a in single point diamond turning. Prediction results prove that this model is a closer approximation of the actual turning process as compared to the previous models and shows a higher predicting accuracy of surface roughness.

1. Introduction

Single point diamond turning (SPDT) is a promising tool based machining technology, which can be used for manufacturing optical components and precision molds. The main feature of SPDT is its ability to produce high-quality surface finish on the order of nanometers while meeting tight form tolerances on the order of micrometers [1]. For products, surface roughness is an important index of product quality and technical requirement [2]. In some cases, the surface roughness is required to be kept within a certain range rather than the possible lowest value, especially in the case of precision mold inserts of optical parts used for injection molding process. On the other hand, SPDT is a complicated process influenced easily by the material swelling effect because of a fine feed rate and high spindle speed [3]. Consequently, the investigation on prediction of surface roughness in SPDT is significant and necessary in order to control the desired surface roughness of product in a fast and effective manner.

Many researchers are interested in the prediction of surface roughness and research in this field has yielded some useful findings along with successful experience through the use of approaches based on machining theory, experimental investigation and artificial intelligence [2,4–8]. Each approach possesses its own unique advantages and disadvantages. However, machining theory based approach together with the experimental investigation approach appears to be the most promising approach. Combining the two approaches allows the accurate prediction of surface roughness along with this approach aiding with the evaluation and improvement of machine tool performance.

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In machining theory based approach, a model based on the theory of machining is used to simulate the creation of the machined surface profile and visualize the surface topography along with assessing surface roughness [2]. The surface roughness profile is generated with the repetition of the tool tip profile at intervals of feed per revolution (ideal surface roughness profile) plus a relative displacement between the tool and workpiece. Sata et al. [9] found that the roughness profile was composed of tool feed component, swelling of workpiece, spindle rotation error and chatter vibration error using spectrum analysis method. Takasu et al. [10] estimated the surface roughness profile as a function of both the ratio of vibration amplitude to geometrical roughness and the phase shift of the vibration to work rotation. He established a theoretical model for creation of roughness profile and also indicated that, due to the tool interference, surface roughness in the tool feed direction can be made much finer than the sum of whole vibration amplitude and geometrical roughness. On the basis of the model created by Takasu et al., Cheung et al. [11] established a three-dimensional surface topography simulation model, which takes into account the tool geography, the machining condition as well as the relative tool-work vibration in the kinematics of diamond turning process. The surface topography was generated by a linear mapping of the predicted surface roughness profiles on the surface elements of a cross lattice. Lee et al. [12] presented a dynamic surface topography model for the prediction of nano-surface generation in which an additional displacement caused by material induced vibration was introduced into the model as compared to the previous model.

2. Previous theoretical models

The basic idea for the theoretical models mentioned above is the fact that the actual surface roughness profile is formed by an ideal surface roughness profile plus a relative displacement between the tool and workpiece, which is achieved by theoretic calculation. Ideal surface roughness profile is determined by cutting conditions, while a relative displacement between tool and workpiece was considered as the relative tool-work vibration. In the case of the primary models, materials were assumed as homogeneous and isotropic and the relative vibration was assumed as a steady simple harmonic motion. For anisotropy of crystalline materials, an enhanced model, which adds material induced vibration to the primary model, was used. Although, they are able to predict surface roughness with low error, there are two major issues impacting prediction accuracy in previous theoretical models. First, the relative tool-work vibration was assumed as invariable, and it was measured before turning process. The second is related to the material swelling effect, which was ignored in previous models.

In the cutting process, the actual relative tool-work vibration was caused by machine tool error, cutting force, material property and change in cutting parameters. Some scholars have tried to analyze the relative vibration using the spectrum method or by measuring the force in cutting process [9,13–15]. However, no research work has been reported which takes the actual relative tool-work vibration into account when establishing a model. On the other hand, according to the results of roughness profile based on the spectrum analysis, it can be concluded that the material swelling is an important part contributing to the surface roughness profile [9,13]. Additionally, empirical data suggests and supports that material swelling obviously changes the surface roughness profile [3]. However, no report predicts surface roughness while considering the effect of material swelling.

In the present study, a prediction model is presented to predict the surface roughness in the SPDT process, which takes both actual tool-work vibration and material swelling into account. It is almost impossible to measure the actual tool-work vibration directly in cutting process. To overcome this challenge, a concept of equivalent amplitude was proposed to aid with the evaluation of the actual tool-work vibration with the assistance of experiments. Furthermore, the swelling proportion of every material was defined to quantify the swelling effect, and the relation between the swelling effect and cutting parameters was investigated by means of experiments.

3. Experimental setup

A series of face cutting tests were conducted on a four-axis CNC ultra-precision machine tool (made by Nachi-Fujikoshi Corp., Japan) shown in Fig. 1 (left). A diamond tool used in tests is shown in Fig. 1 (right), with a rake angle of 0°, a front clearance angle of 6° and a tool-nose radius of 0.5 mm.

The tests were carried out on three kinds of materials including copper (Cu), aluminum alloy (Al7075-T6) and electroless-nickel (NiP) during studying relative tool-work vibration and the swelling effect. Aluminum alloy and copper were available in market, while samples of NiP were prepared on an aluminum alloy rod (7075-T6). In order to achieve both the required hardness and good machinability, the compounding of coating solution was optimized to generate medium-phosphorus NiP, which possesses a coating depth of more than 50 μm and a hardness of 50HRC. Table 1 tabulates the cutting conditions in the tests studying relative tool-work vibration and the swelling effect.

The surface profile was measured about 10 mm in length by contact probe profilometer, Form Talysurf PGI 1240 (Taylor Hobson Ltd.) in 2D, while the surface topography was measured by a non-contact type surface measurement system, White Light Interferometer Veeco NT1100 (WLI, Veeco Metrology Group) in 3D for each sample. The measurement data was then processed with MATLAB software. The diamond tool wear was observed by a scanning electronic microscope (SEM, Hitachi S-4700) and an optical measuring microscope (STM6, Olympus, Japan).

4. The relative tool-work vibration

4.1. Evaluating the relative tool-work vibration

Relative vibration may be caused by machine tool error, cutting force, material properties and change in cutting