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Surface plastic deformation and surface topography prediction in peripheral milling with variable pitch end mill

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ABSTRACT

Peripheral milling with variable pitch end mills is available to improve the surface integrity during final machining. Among the indicators of surface integrity, surface plastic deformation and surface topography are the foremost characteristics. In this paper, two main aspects are included. On the one hand, a unique generic technique in terms of depth of plastic deformation, plastic strains distribution for analyzing the plastic deformations on the work piece is presented. The presented technique applies the problem of the Flamant–Boussinesq in the plastic deformation problem. Through experimental verification, the analytical results have a higher accuracy. On the other hand, the surface generation mechanism in peripheral milling with variable pitch end mills is studied. Corresponding surface generation model, which is used to predict the generated surface topography with incorporating the cutting process parameters and several sources of machining error such as tilting, run-out, deflection of the tool and work piece displacement, is proposed. Through a set of cutting tests, it is confirmed that the presented model predicts the surface texture and roughness parameters precisely. By the sensitivity analysis, Helix angle and feed rate have significant influences on surface topography, while the effects of cutting speed on surface topography can be neglected when the effects of the machining error sources on the behavior and performance of the model are not considered. Among the sources of machining errors, the deflection of the tool has the most significant impact on the surface profile. The sequence is the displacement of the work piece and the run-out of the tool.

1. Introduction

Peripheral milling plays an extremely important role in manufacturing a large variety of components which are used in aircraft, automobiles, ships, railroads, medical equipment, space vehicles, power generation and process equipment, etc. The application environment of peripheral milling puts forward higher requirement of machining quality. Among the indicators of machining quality, surface plastic deformation and surface topography are the foremost characteristics [1]. Using of the variable pitch end mills has been proved to be available to improve the machining quality of peripheral milling in practice. As a consequence, a specific study of surface plastic deformation and surface generation mechanism in peripheral milling with variable pitch end mills is needed to optimize milling conditions.

In the aspect of surface plastic deformation, analytical method is essential to study the plastic deformations on the work piece besides of experimental method. Barash and Schoech [2] predicted the plastic deformation on the work piece using a simple slip-line field model. In this model, the depth of plastic deformation is simplified to be the function of the shear angle and the depth of cutting. Park and Cohen [3] supposed that there is a linear relation between plastic strain and the depth of plastic deformation. Reviewing previous work on the mechanics of metal cutting and the surface integrity in machining reveals that there is no comprehensive analysis on the mechanisms responsible for plastic deformation in the machined surface, and lack of analytical models to assess the plastic damage due to machining in terms of depth of plastic deformation, plastic strains distribution on surface and subsurface plastic deformation.

With rapidly increasing computational capabilities and emerging new analytical modeling techniques, there is a growing worldwide interest in developing analytical and numerical techniques for predicting machining Surface topography. Li [4] proposed a kinematical–geometrical based model. The model includes tool diameter, number of cutting flutes, radial depth, axial

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depth, feed rate and run-out which were identified as important quantities in the surface generation process. The major problem associated with this model is that it was short of considering the influence of the milling force. Koenigsberger and Sabberwal [5] developed a mechanistic model that enables the determination of the cutting forces depending on the uncut chip thickness and cutting coefficients. The model only considered the effects of static deflection of the tool on the instantaneous chip thickness. Ismail [6] took the effect of dynamics into consideration. Several mechanical models were developed later on with different techniques. They differ in the way that whether the tool or the work piece is regarded as rigid. However, few models considered the combined effects of tool parameters, machine parameters and machine error sources such as the tool tilting, run-out, tool deflection, workpiece displacement on the surface topography simultaneously.

The main study includes two aspects in this paper. On the one hand, a unique generic technique for analyzing the plastic deformations on the work piece is presented. The presented technique is based on the problem of the Flamant–Boussinesq and the assumption that the depth of plastic deformation is a function of the stress–strain characteristics of the work piece material. The analytical results are verified through experiment. On the other hand, the surface generation mechanism in peripheral milling with variable pitch end mills is studied. Corresponding surface generation model, which is used to predict the generated surface topography with incorporating the cutting process parameters and several sources of machining error such as tilting, run-out, deflection of the tool and work piece displacement, is proposed. Milling experiments are carried out to verify the accuracy of the model. The measured and simulated surfaces are compared to test the accuracy of the proposed model. The characterization parameter S_q of the surface topography and the errors relative to the measured value are investigated. The model is then verified for its sensitivity to different helix angles and cutting process parameters. In the end, the effects of the sources of error on the behavior and performance of the model are analyzed.

2. Plastic deformation of the workpiece

Plastic deformation of the work piece is assessed in terms of depth of plastic deformation and plastic strains distribution. To achieve the objectives, the stress distribution of the work piece should be modeled from a physics based approach focusing on cutting force, work piece temperature, and contact stress. The cutting forces are predicted from the uncut chip thickness. Temperature rise are proposed with the moving heat resource method. Outputs from these modeling areas are then used to predict the thermo-mechanical loading experienced by the work piece and form the stress field.

2.1. *Stress distribution of the workpiece in milling*

2.1.1. *Force modeling*

The approach of Kline [7] is followed in breaking the helical tool up into a finite number of Δz thick disk elements. For each tooth of each disk, the elementary cutting forces are modeled by a single-point orthogonal cutting model. The entire milling forces are determined by carrying out a summation over all the disk elements and all the cutting teeth. The elementary cutting force, ΔF, acting on the work piece is expressed by its radial and tangential components ΔF_t and ΔF_r:

$$\Delta F_t = K_s \Delta z h^m \tag{1}$$

$$\Delta F_r = K_r \Delta z \Delta F_t \tag{2}$$

where K_s, K_r and m are cutting force coefficients depending on the work piece material and the tool geometry, and h is the exact uncut chip thickness computed in the radial direction. As the system is expected to be infinitely rigid in the tool axis direction, the axial cutting forces are not computed. Furthermore, the plowing forces are not considered in this model.

2.1.2. *Thermal modeling*

The thermal effects due to the cutting process can have a significant effect on the surface deformation produced. Extensions of Jaeger's [8] solution to moving heat sources have been widely used in the literature to determine the temperature rise due to cutting. In modeling the work piece temperatures, two heat sources are assumed to exist. The first is the primary heat source generated from the shear zone. The second heat source is a result of rubbing between the tool and the work piece. The temperature rise modeling techniques developed by Richardson [9] are used in this research. The proposed model for peripheral milling is expressed by Eq. (3).

$$\theta_m = \frac{1}{\pi\kappa} \int_0^{\omega_c} q_m \frac{\sin\omega}{\cos\omega_c} e^{-v(y-R\sin\omega)/2\alpha} K_0\left[\frac{v}{2\alpha}\sqrt{(y-R\sin\omega)^2+(x+R(1-\cos\omega))^2}\right] R\cos\omega \, d\omega \tag{3}$$

where θ_m is the temperature rise at point m, κ is the thermal conductivity, ω_c is the angle of contact between cutting tool and work piece, ω is the integration variable, q_m is the maximum heat flux, v is the velocity of moving heat source, R is the radius of the tool, K_0 is the modified Bessel function of the second kind of order zero, α is the thermal diffusivity, and x and y are the coordinates of the point m.

2.1.3. *Stress calculation*

The following section is dedicated to calculating stresses within the material due to both mechanical and thermal loading.

In order to calculate the mechanical stress, The Flamant–Boussinesq problem (shown in Fig. 1), which is considered as the most celebrated problem in the classical elastic theory, is applied. In this problem, a half-space under plane-strain condition is acted upon by a concentrated line force on its surface. The concentrated line force is equal to the sum of stresses acted on the circle with center at o. Consequently, stress components at each point of the work piece are represented by Eq. (4).

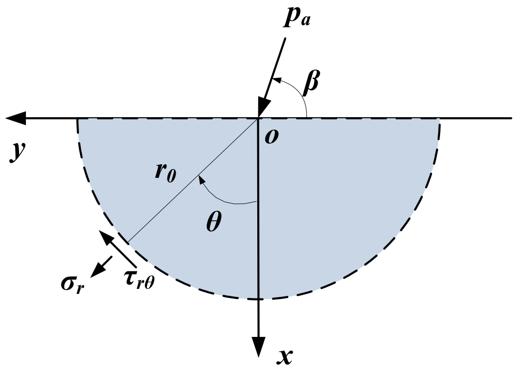

Fig. 1. Schematic illustration of a foundation subjected to concentrated force at the surface.