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Effect of tool inclination angle on the elastic deformation of thin-walled parts in multi-axis ball-end milling

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Abstract

Thin-walled freeform surface parts are widely used in many fields, such as aerospace, automotive, etc. However, it is difficult to produce high quality thin-walled freeform parts in Numerical Controlled(NC) machining due to bending and twisting deformations induced by cutting forces. To overcome this problem, key issues are focused on twofold. First, the relationship between the milling force and the tool inclination angle in ball-end milling was established by using the theoretical and experimental methods. Second, the influence of tool inclination angle on the elastic deformation of thin-walled parts was analyzed by the finite element method. Finally, verification experiment was carried out in a 4-axis CNC machine tool, and the deformation values of the stainless steel test workpieces were measured by a coordinate measurement machine(CMM). The results show that when the tool inclination angles are 15° or 45°,both the milling force and the deformation of the test workpieces are the smallest.

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Keywords: Ball-end milling;tool orientation;thin-walled parts;elastic deformation

1. Introduction

Thin-walled freeform surface parts are used in a variety of areas., such as aerospace, automotive, etc. Because thin-walled parts are easy to distort due to its weak stiffness, it is quite difficult to control the machining accuracy, often resulting in the high processing costs[1]. As an important cutting parameters, tool orientation has a significant effect on machining accuracy in multi-axis CNC machining. Hence, it is meaningful to study the relationship between tool orientation and the deformation of thin-walled parts.

To save machining time, improve workpiece surface quality and tool life, Toh[2] identified and reviewed three main areas of literature studies namely analytical analysis on plane milling, entrance and exit effected of the cutter motion and inclined milling effects. Ko[3] attempted to reduce tool wear by controlling the machining inclination angle between the tool and the workpiece. The simulation results showed that a machining inclination angle of 15° was good enough from the point view of machinability, and this value was verified by a cutting experiment using high-speed ball end milling. Han [4]researched the influence of tool inclination angle on surface integrity, especially surface topography/roughness and residual stress in high-speed milling of P20 die steel by means of milling experiments including 8 cases of ball-end milling of freeform surface. Finally, the optimal tool inclination angles including lead angle and tilt angle and milling method were obtained for 5-axis ball-end milling.

Chen[5] described the development of a simulation model for ball end milling with inclination angle based on a finite element method. In another paper, a dynamical model is established to predict the deformation in multilayer machining a thin-walled part. It is considered that the machining deformation of the previous layer will influence the nominal cutting depth of the current layer[6]. Cheng[7] focused on the thin-walled parts of titanium alloy, the mathematical model of

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milling force of the ball-end milling cutter was established. And the deformation regularity and cutting force variations were analyzed with the finite element simulation method.

In this paper, To reduce the deformation caused by cutting force in ball end milling, the effect of tool inclination angle on cutting forces is analyzed firstly, and a simulation model for ball end milling with inclination angle is presented by using the FEM.

2. Effect of tool inclination angle on cutting forces

2.1. Geometric model

As shown in Fig.1, There are two coordinate systems are established to decompose the cutting force for the FEM model. The XYZ coordinate system is the tool coordinate system. The Z axis is along the cutter orientation. The X axis is perpendicular to the Z axis and along the feed direction. The Y axis is determined by the right-hand law of Cartesian coordinates. The local coordinate system was established as X'Y'Z'. The X' axis is along the feed direction. The Z' is along the face normal. Both the origin of the tool coordinate system and the local coordinate system is located at the center of the ball-end cutter.

Generally, two angles are defined in 5-axis CNC machining, heeling angle and inclination angle. When the tool rotate an angle about the direction perpendicular to the feed direction, the angle is defined as the heeling angle α. When the tool rotate an angle about the feed direction, the angle is defined as the tool inclination angle β. The paper only talk about the tool inclination angle perpendicular to the feed direction. Due to the tool inclination, the local coordinate system and the tool coordinate system do not coincide with each other. The mathematical model of thin-walled parts with the multi-axis machining is shown in Fig.1[8].

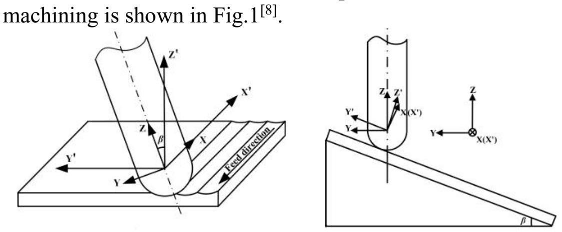

Fig.1 Coordinate systems and tool inclination angles

2.2. Cutting force analysis with the tool orientation

The workpiece used in this paper is a thin-walled plate as shown in Fig.2. The deformation caused by the cutting forces is bending deformation.

As shown in Fig.1, the machining coordinate system is parallel to the tool coordinate system. the cutting force at any cutting position should be decomposed to F_x, F_y and F_z, respectively in order to apply them in the FEM model. When the tool inclination angle is β, $F_{x'}$,$F_{y'}$ and $F_{z'}$ can be obtained by Eq(1).

$$\begin{bmatrix} F_{x'} \\ F_{y'} \\ F_{z'} \\ 1 \end{bmatrix} = A \begin{bmatrix} F_x \\ F_y \\ F_z \\ 1 \end{bmatrix} \tag{1}$$

Where

$$A = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\beta & -\sin\beta & 0 \\ 0 & \sin\beta & \cos\beta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

As a consequence, the cutting force in the normal direction of any cutting position can be obtained by the Eq.(3) as follow:

$$F = F_{z'} = F_z \cos\beta + F_y \sin\beta \tag{3}$$

It can be concluded from the Eq.(3) that the force in the normal direction of the thin-walled part is closely correlated to F_y, F_z and β, The level of the deformation can be reflected by the magnitude of F, that is to say, lower F leads to less deformation.

3. Prediction of elastic deformation

3.1. FEM model

Because the tool is considerably harder than the thin-walled parts, to simplify the simulation process, the tool is simplified to be a rigid body and the deformation of the tool can be ignored. Only the static elastic deformation of the thin-walled plate under ball-end milling forces in the finish milling process is considered in this paper.

The thin-walled plate is a simplified model of a thin-walled blade used in an aeroengine. The material of the workpiece is the stainless steel 1Cr11Ni2W2MoV. The dimensions of the plate are shown in Fig.2. Three cross-sections are chosen to calculate the deformations of the plate along the X direction: section A, section B and section C, and eight nodes on each section are chosen to calculate the deformations, as shown in Fig.3.

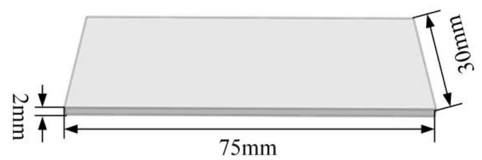

Fig.2 Dimensions of thin-walled plate

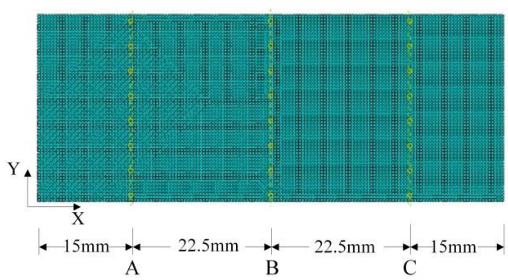

Fig.3 Illustration of cross-sections and nodes