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An analytical approach for machining thin-walled workpieces

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Abstract

An analytical approach is developed to predict the dynamic chip thickness variation in ending milling of thin-walled workpieces. The proposed model considers the mechanism of calculating the stiffness of removed material by the end- mill from the overall stiffness of the workpiece to work out the changing stiffness of the workpiece which in turn is used to determine the displacement occurring. The displacement of the workpiece influences the radial depth of cut and thus yields a dynamic variation. The generalized model of the volume of removed material is computed by considering the discrete axial depth of cut, the radial depth of cut and the circumferential section of the tool radius contact for each tool step taken. The features of this model cater for the helical tool geometry used. The stiffness of removed material is updated by subtraction from the overall stiffness of workpiece. The overall stiffness of the wall is updated by considering the removed material at each time step. The feedback of the displacement amplitude is linked with a cutting forces model to address the influence of the dynamic displacement of the workpiece from the acting chip load. The cutting forces is modeled based on the Oxley variable flow stress machining theory. The predictive capabilities of the proposed model are verified with the experimental results. The comparison of the results is encouraging and reasonable correlation is achieved.

*Keywords:*dynamic chip thickness; milling process; stiffness; thin-walled; variable flow stress

1. Introduction

Thin-walled components are widely used in aerospace and automobile industries as well as in turbines. The feature of a thin wall workpiece is to change the workpiece dynamic structure due to the change in its geometrical shape. The challenge is in the creation of these thin-walled sections. During the machining process, the workpiece undergoes deflection due to the application of external forces by the helical end mill. Due to the milling cutting forces the wall deflects and produces varying chip thicknesses resulting in dimensional surface errors that are considered as challenges in machining thin-walled parts. It is worthwhile to understand the mechanism of the wall deflection under the cutting forces during the machining process when machining thin walls. Various research efforts are being made to study the deformation of thin-walled sections. Kline *et al.*[1] proposed a model to predict the milling process of a thin-walled plate. The workpiece was considered to be a clamped-clamped-clamped-free rectangular plate. The workpiece is modeled based on Finite Element Analysis (FEA). The work material is Aluminium 7075-T6 alloy with the end mill cutter considered to be flexible. The workpiece displacement has not been taken into account in their proposed model. Budak and Altintas [2] proposed an analytical model to predict cutting forces and dimensional surface errors. The workpiece geometry is updated by using FEA Analysis. The workpiece is considered to be a clamped- free-free-free flexible plate. The model considers the variation in the immersion angle due to deflection of the workpiece. The results indicate that the cutting force and static surface error cannot be predicted accurately unless the changes in the tool-workpiece interface are considered in the model. Elbestawi and Seghrian [3,4] established a model to predict the thin wall deflection taking into account the workpiece geometry changes during the milling process. The workpiece is modeled as a 3-dimensional

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Nomenclature

D_c	cutter diameter
E	Elastic Modulus
f_t	feed rate (mm/tooth)
Fy	cutting force
H	thin-wall height
K_y	total stiffness for the workpiece
r_d	radial depth of cut
Δr_d	discrete radial depth of cut
SK	stiffness for each removed chip segment
SKF	total stiffness of removed material
t_1	undeformed chip thickness
T_H	wall thickness
u	workpiece displacement
W_T	width of wall
Δz	discrete axial depth of cut
$\Delta\theta R$	circumferential section of the tool

FEA model. The calculation of the workpiece displacement is composed of four routines; acting dynamic forces, finite element, automatic mesh and dynamic response data generation routines. Their study concluded that the depth of cut, the radial depth of cut and the number of teeth of the tool have significant effect on the workpiece displacement. An increase in these variables will result in the error of the workpiece surface increasing. Additionally, the spindle speed has varying impact on the finished surface. It is also found that the finished surface is overcut in case of up milling process, while in case of down milling the finished surface is undercut.

Ratchevet *et al.*[5-7] present a numerical model to simulate material removal using FEA. The proposed model focused on the study of the impact of cutting forces on the thin-walled workpiece displacement. Wang *et al.*[8]performed an analysis to predict vibration in thin-walled workpiece. The workpiece was assumed to follow the Kirchhoff-Love theory of plates. The cutting force and vibration are only considered in the radial direction. Eksioglu and Altintas [9] proposed a new general formulation to predict stability of thin walls, based on the time discretised model. This model is useful for different tool geometries, low radial immersion and high axial depth of cut. Both cutter and workpiece are discretised into equal number of segments with each element of cutting configuration having a unique dynamic characteristic.

Gonzalo *et al.*[10] proposed a model to predict thin-walled workpiece deflection. The cutting force has been modeled in the time domain based on a mechanistic model. FEA is used to model the dynamic structural performance at several machining stages.

This short review shows that the dynamic characteristics of the thin-wall change, as the cutter rotates to remove a layer of material. There is an opportunity to perform research on the milling process on a thin-walled workpiece based on the variable flow stress machining theory. The cutting forces can be obtained using the Oxley Machining Theory[11]. The thin-walled workpiece will be discrtesied based on the cutter geometry by considering the helix angle and the tool radius. This is presented in the next Section.

2. Modeling Methodology

The proposed model considers the dynamic changes occurring with the workpiece during the end milling process. In addition, the influence of the dynamic displacement of the chip during the machining load is also taken into account. The following describes the procedure for the modeling approach used to predict thin-walled workpiece displacement:

2.1. Step 1

In this research, the workpiece is modeled as a flexible plate and has a Clamped-Free-Free-Free (CFFF) boundary condition as shown in Fig. 1. The milling cutter is modeled as a rigid body.

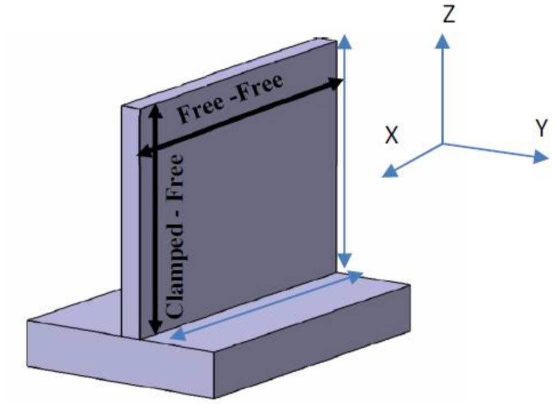

Fig. 1. Thin-walled workpiece (Free-Free in x direction, Clamped-Free in z direction).

2.2. Step 2

The total stiffness for the workpiece is determined before performing the machining process. The three dimensional structural geometry of the workpiece including the thickness, width and height of the wall are used as parameters to identify the stiffness of the workpiece shown in Fig. 2. The total stiffness can be computed as given in Eq.1[12] where E is the Elastic Modulus of the workpiece, T_H is the wall thickness, H is the wall height and W_t is the wall width.

$$K_y = \frac{E\left(W_t^{\,3}\right)T_H}{4H^3} \qquad (1)$$

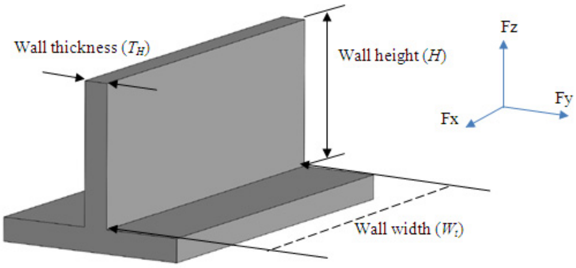

Fig. 2. Geometrical structure of a thin walled workpiece.