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Development of a reference cutting force model for rough milling feedrate scheduling using FEM analysis

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Abstract

Recently developed feedrate scheduling systems regulate cutting forces at the desired level by changing the feedrate to reduce the machining time and to avoid undesirable situations. For effective scheduling, an optimized criterion is required to adjust the feedrate. In this study, a method to obtain the most appropriate reference cutting force for rough milling was developed. The reference cutting force was determined by considering the transverse rupture strength of the tool material and the area of the rupture surface. A finite element method analysis was performed to accurately calculate the area of the rupture surface. Using the analyzed results, the effect of various cutting parameters on the chipping phenomenon was determined. The calculation method for the reference cutting force considered the area of the rupture surface, the effect of the rake angle, and the axial depth of the cut. The reference cutting force calculated using the developed model was applied to feedrate scheduling for pocket machining. The experimental results clearly show that the reference cutting force obtained from the proposed method met the desired constraints that guarantee higher productivity without tool failure.

Keywords: Reference cutting force; Feedrate scheduling; FEM analysis; Transverse rupture strength; Rupture surface

1. Introduction

The manufacturing paradigm has changed from mass production to mass customization. To adapt to this transition, many industries require new technologies that can increase their production rate and decrease their production costs. The cutting process accounts for a large portion of the development and manufacturing of most products. Thus, by reducing the time required for the cutting process, higher productivity and shorter development periods for new products can be achieved. For this purpose, feedrate scheduling systems that regulate the material removal rate [1–3] or cutting force [4–10,12] to the desired level have been developed. These systems change the feedrate to reduce the machining time.

In rough milling, machining time is the most important factor that affects productivity. In this case, feedrate scheduling is focused on reducing the machining time. However, there is a trade–off between the machining time and cutting stability. The faster the feedrate, the larger the cutting force; an increased cutting force introduces various problems, such as machining chatter, tool wear, and breakage. In finish milling, on the other hand, dimensional tolerance is the dominant factor that affects productivity. There is a similar trade-off between the machining time and the machined surface error. A slower feedrate causes a longer machining time while it can introduce small tool deflections, which are the main source of machined surface errors. Thus, selecting the most appropriate reference cutting force is very important for effective feedrate scheduling.

Previous research has focused on designing a feedrate scheduling model to regulate the cutting force. To improve the cutting performance, Tarng et al. [4] applied a geometric modeling system to an in-process simulation of the cutting geometry for pocket machining. The area of the cut chip was identified; then the corresponding cutting performance was evaluated and optimized. Lim and Menq [5] created an integrated planner for machining complex

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surfaces that optimized the cutting path and feedrate. Bae et al. [8] proposed an automatic feed adjustment method that calculated the adjusted feedrate using a simplified cutting force model. This model obtained the cutting force from a non-parametric Bezier surface that was constructed from experimental cutting data. In their work on feedrate scheduling, Guzel and Lazoglu [9] adjusted the feedrate during ball-end milling to decrease the cycle time for sculpture surface machining. However, a reference or constraint for their cutting force was selected by experimental methods. Some researchers have used arbitrary values for the reference cutting force [5,8,9]; others have applied maximum values of measured cutting forces in non-scheduled machining [4]. Fussell et al. [6] developed a feedrate process planner for complex sculptured end milling cuts from mechanistic and geometric end milling models. A cantilever beam model of the tool was used to relate the vector force to the allowable tool deflection or tool bending stress. Thus, they set the desired constraint force of 133 N to a maximum 0.25 mm tool deflection.

Ko and Cho [10] presented an analytical model of off-line feedrate scheduling for three-dimensional ball-end milling based on a cutting force model that used cutting-condition-independent coefficients. They also defined the transverse rupture strength (TRS) of the tool to determine the reference cutting force that must be considered to avoid breakage of the tool shank and edge. The reference cutting force was calculated by several equations determined from cutter geometry and rupture surface position. The rupture surface position, however, has to be defined by the user, which can be considered as a very difficult task by itself. Therefore, a new method that calculates the exact area of rupture surface in various cutting conditions is required.

In our earlier work [7], a feedrate scheduling system was proposed, based on an improved cutting force model that could predict the cutting force accurately for general end milling situations. However, the cutting force was regulated at a safe level, which was the maximum allowable value for non-scheduled cutting. To increase the efficiency of the feedrate scheduling, a reference cutting force model was developed in this study. The reference cutting force was determined considering the TRS of the tool material proposed by Ko and Cho [10]. To predict the exact point at which tool breakage and chipping would occur, the area of the rupture surface and other effects were calculated using a finite element model (FEM) and the results from a mathematical analysis. The developed reference cutting force model makes it possible to determine the maximum level of force that a cutter can resist.

2. FEM analysis

The reference cutting force was derived considering the TRS of the tool material. The TRS is the stress required to break a specimen and is calculated from the flexure formula [11]. It has been used by tool makers to determine the strength of tool material. Using the TRS, the reference cutting force can be determined as follows [10]:

$$\begin{aligned} \mathrm{RF_b} &= \mathrm{TRS} \cdot S_\mathrm{b}, \\ \mathrm{RF_c} &= \mathrm{TRS} \cdot S_\mathrm{c}, \end{aligned} \tag{1}$$

where $\mathrm{RF_b}$ and $\mathrm{RF_c}$ represent the reference cutting forces that mark the onset of tool breakage and chipping, respectively, and S_b and S_c are the cross-sectional areas of the tool shank and edge. The reference cutting force is a minimum value between $\mathrm{RF_b}$ and $\mathrm{RF_c}$. S_b can be easily calculated from the tool geometric data. However, the chipping mechanism must be understood to determine S_c because most chipping occurs at the end of a tooth and the area of the rupture surface cannot be calculated using only the tool geometry. Therefore, FEM analysis was performed to understand the tool chipping mechanism and calculate the area of the rupture surface. Using the analyzed results, various cutting parameters, such as the cutting conditions and tool geometry, were considered to calculate the reference cutting force.

2.1. FEM analysis

When a cutting force is inflicted on a rake surface, the internal stress is concentrated into an arbitrary region. If the concentrated stress is above a critical level, then chipping occurs in this region. This region was defined as the rupture surface. To calculate the area of the rupture surface, the distribution of the internal stress of the tool was computed using ANSYS.

The following assumptions were made in the analysis.

(1) The chipping occurs due to the normal pressure cutting force on the rake surface of the tool. The frictional cutting force is negligible in the chipping mechanism.
(2) The normal pressure cutting force is distributed regularly on the engaged rake surface.
(3) The width of the engaged rake surface is equal to the uncut chip thickness, and it is a fixed value regardless of the axial position.

In general, the TRS is determined by subjecting the specimen to a uniformly increasing transverse load. The inflicted load, which provokes the rupture of the specimen, is applied parallel to the specimen cross-section or the rupture surface. During the cutting process, the frictional cutting force is perpendicular to the rupture surface. Thus, only the normal pressure cutting force was used in this analysis, as described by the first assumption and illustrated in Fig. 1. From the second assumption, an arbitrary pressure was inflicted on the engaged rake surface instead of a force. Inflicting a force on limited points can produce incorrect analytical results because the cutting force is distributed over the entire engaged rake surface. As illustrated in Fig. 1, a constant value was used for the width of the engaged rake surface. Because of the helix angle, the uncut chip thickness varied with the axial position. From