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Prediction of effect of helix angle on cutting force coefficients for design of new tools

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For accurate cutting force prediction in a milling process, material data for a given tool and workpiece, i.e. cutting force coefficients are required. Generally two methods, namely, orthogonal to oblique transformation or mechanistic method are used for calculation of cutting force coefficients. These methods have several drawbacks in designing of new milling tools. In order to help design of new tools, two methods are proposed to predict the effect of helix angle on cutting force coefficients. The methods were tested on five tools with different helix angles and predictions of the methods were compared with experiments.

1. Introduction

Competition is fierce in the machining industry. Order book of the machining companies, especially in aerospace sector is in an increasing trend. Hence, they are constantly looking for ways to minimize cycle time without sacrificing from quality. Moreover, new alloys are being developed to increase functional performance of the products. This may generally have a negative effect on productivity of the machining process with existing tooling. For these reasons, cutting tool companies are continuously developing new cutting tools that can achieve higher productivity for both new and existing materials.

Coating and geometry of a cutting tool have considerable effect on the tool performance. Tooling geometry includes cutting edge geometry, namely rake angle, clearance angle and hone radius, and oblique angle. Oblique angle corresponds to helix angle for milling tools.

This paper focuses on effect of helix angle. In tool design, it is used on the milling tools to distribute the force on a longer time frame and decrease instantaneous increase of cutting forces. Moreover, cutting forces are directed through the axial direction with higher helix angle [1], and hence radial forces responsible for form errors are minimized. On the other hand, high helix angles can result in high axial forces which may cause tool pull-out from the tool holder. For those reasons, helix angle is an important design parameter in design of the milling tools.

Process models [2–4] can be employed to understand the effect of helix angle on cutting forces during the design stage. Material data for the cutting tool and workpiece material is required for accurate prediction of cutting forces. Two well established methods are generally used for identification of material data in practice. The first one is the mechanistic identification and the second one is orthogonal to oblique transformation.

Mechanistic identification method [5,6] identifies cutting force coefficients by performing cutting tests with a specific milling tool. Milling tests are performed on a range of cutting speeds and feed rates. Milling forces are measured for each test and cutting and edge force coefficients are calculated specific to the milling tool for each cutting speed. Any change on the tool geometry requires repetition of the whole experimental process in the mechanistic method. For example, if the mechanistic identification was performed on a 30° helix angle and if new design requires a 15° helix tool, the experimental work needs to be repeated for the new tool.

The second method, which is orthogonal to oblique transformation [6,7] is more flexible. If there is a change in helix angle, it allows calculation of cutting force coefficients for the new tool without making additional experiments. In this method, orthogonal turning tests are performed for a range of cutting speeds and feed rates. The turning tools need to have the same material, coating and same edge geometry, i.e. rake angle, clearance angle and hone radius, with the milling tool. Turning forces and cut chip thickness are measured for each cutting test. Orthogonal database, i.e. shear stress, shear angle and friction angle and edge force coefficients are identified from these measurements. Then using the orthogonal to oblique transformation method, cutting force coefficients for milling tools, that have the same tool material, coating, rake angle, clearance angle and hone radius, are calculated.

On the other hand, finding a turning tool with the same tool material, coating and edge geometry with the milling tool may be challenging. Moreover, the tool needs to be an orthogonal turning tool. Hence, special turning tools may need to be manufactured. Besides, workpiece material for milling may not be available in cylindrical shape for turning tests. It will require further processing of the material. For example, this is a challenge for milling of additively manufactured components and composite parts. Even if the cylindrical shape is available, the primary process to produce a cylindrical geometry may be different than a process to produce rectangular prism geometry. Hence, material properties may be different in each case.

Measurement of cut chip thickness is another challenge. Some processes such as ceramic and composite turning produce chips like dust. Hence it is not possible to measure thickness of cut chips.

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As orthogonal to oblique transformation method is more flexible, it is more suitable for the task of designing of new milling tools. However, due to the reasons explained above, there is a need to have a flexible method which uses milling for cutting force coefficient identification process while designing new milling tools.

In this paper, a hybrid method that combines the mechanistic identification and orthogonal to oblique transformation and an alternative method that uses Taylor series expansion are proposed to predict the effect of helix angle on cutting force coefficients. The next two sections detail the methods. Section 4 explains the experimental work performed. Section 5 presents the results comparing the calculations with experiments. Then the following chapter discusses the results. Finally, conclusions are listed in Section 7.

2. Hybrid method

The hybrid method and alternative model in the next section work with linear edge force model [6,7] coefficients. Cutting forces in radial, tangential and axial directions can be represented by the following equation in this model:

$$F_q = K_{qc}cd + K_{qe}d \quad q = r, t, a \tag{1}$$

where K_{qc} and K_{qe} are cutting and edge force coefficients, respectively in radial (r), tangential (t) or axial direction (a), c is the chip thickness and d is the cutting depth. As noted in [6,7], K_{qc} can be represented by Eq. (2) in radial, tangential and axial direction respectively in terms of shear stress (τ_s), normal shear angle (ϕ_n), normal friction angle (β_n), normal rake angle (α_n) and oblique angle (i).

$$\begin{aligned}
K_{rc}(i) &= \frac{\tau_s}{\sin(\phi_n)\cos(i)}\frac{\sin(\beta_n-\alpha_n)}{\sqrt{\cos^2(\phi_n+\beta_n-\alpha_n)+\tan^2(i)\sin^2(\beta_n)}}\\
K_{tc}(i) &= \frac{\tau_s}{\sin(\phi_n)}\frac{\cos(\beta_n-\alpha_n)+\tan^2(i)\sin(\beta_n)}{\sqrt{\cos^2(\phi_n+\beta_n-\alpha_n)+\tan^2(i)\sin^2(\beta_n)}}\\
K_{ac}(i) &= \frac{\tau_s}{\sin(\phi_n)}\frac{(\cos(\beta_n-\alpha_n)-\sin(\beta_n))\tan(i)}{\sqrt{\cos^2(\phi_n+\beta_n-\alpha_n)+\tan^2(i)\sin^2(\beta_n)}}
\end{aligned} \tag{2}$$

As oblique angle corresponds to helix angle in milling, helix angle i_o (Fig. 1) is equal to i. Note that Stabler's rule [8] was applied on these equations which assume chip flow angle is equal to oblique angle i. The proposed hybrid method is summarized by the following steps:

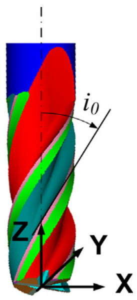

Fig. 1. Helix angle (i_o) on a milling tool.

1. Using mechanistic identification method, identify cutting and edge force coefficients on a milling tool with an arbitrary helix angle
2. Calculate normal friction angle (β_n)
3. Calculate normal shear angle (ϕ_n), using either
   a. Minimum Energy Principle (MEP)
   b. Maximum Shear Stress Principle (MSS)
   c. Empirical Method (EMP)
4. Calculate shear stress (τ_s)
5. Calculate the cutting force coefficients for the new tool which has a different helix angle using Eq. (2).

Firstly, using the mechanistic identification, the constant cutting force coefficients ($\tilde{K}_{tc}, \tilde{K}_{rc}, \tilde{K}_{ac}$) for an initial arbitrary helix angle i_{int} are obtained experimentally. These values can be expressed using the following equations.

$$\begin{aligned}
\tilde{K}_{rc} &= \frac{\tau_s}{\sin(\tilde{\phi}_n)\cos(i_{\text{int}})}\frac{\sin(\tilde{\beta}_n-\tilde{\alpha}_n)}{\sqrt{\cos^2(\tilde{\phi}_n+\tilde{\beta}_n-\tilde{\alpha}_n)+\tan^2(i_{\text{int}})\sin^2(\tilde{\beta}_n)}}\\
\tilde{K}_{tc} &= \frac{\tau_s}{\sin(\tilde{\phi}_n)}\frac{\cos(\tilde{\beta}_n-\tilde{\alpha}_n)+\tan^2(i_{\text{int}})\sin(\tilde{\beta}_n)}{\sqrt{\cos^2(\phi_n+\tilde{\beta}_n-\tilde{\alpha}_n)+\tan^2(i_{\text{int}})\sin^2(\tilde{\beta}_n)}}\\
\tilde{K}_{ac} &= \frac{\tau_s}{\sin(\tilde{\phi}_n)}\frac{(\cos(\tilde{\phi}_n-\tilde{\alpha}_n)-\sin(\tilde{\beta}_n))\tan(i_{\text{int}})}{\sqrt{\cos^2(\phi_n+\tilde{\beta}_n-\tilde{\alpha}_n)+\tan^2(i_{\text{int}})\sin^2(\tilde{\beta}_n)}}
\end{aligned} \tag{3}$$

Using the above relationships, an expression for the unknown normal friction angle ($\tilde{\beta}_n$) in terms of the known constants $\tilde{K}_{tc}$, $\tilde{K}_{rc}$, $\tilde{K}_{ac}$ and i_{int} can be found as presented in Eq. (4). Please note that if the helix angle on the tool (i_{int}) is equal to zero, the Eq. (4) needs to be replaced with a simpler one which can be easily obtained by Eq. (2)

$$\tan\tilde{\beta}_n = \frac{\sin\tilde{\alpha}_n}{\cos(\tilde{\alpha}_n)-\frac{\tilde{K}_{rc}\tan i_{\text{int}}}{\tilde{K}_{tc}\sin i_{\text{int}}-\tilde{K}_{ac}\cos(i_{\text{int}})}} \tag{4}$$

Normal rake angle $\tilde{\alpha}_n$ needs to be calculated before normal shear angle calculation ($\tilde{\beta}_n$) using Eq. (5) [9]

$$\tilde{\alpha}_n = \tan^{-1}(\tan(\alpha_r)\cos(i_{\text{int}})) \tag{5}$$

where α_r is the radial rake angle of the tool. Similarly, orthogonal friction angle β_a can be calculated using the Eq. (6).

$$\beta_a = \tan^{-1}\left(\frac{\tan\tilde{\beta}_n}{\cos(i_{\text{int}})}\right) \tag{6}$$

For calculation of the normal shear angle (ϕ_n) there are three alternative methods, namely the maximum shear stress principle (MSS), the minimum energy principle (MEP) and the empirical approach (EMP) of Armarego and Whitfield [10]. Each method is represented in Eq. (7), respectively.

$$\begin{aligned}
\text{MSS}: &\quad \phi_n = \frac{\pi}{4}-(\beta_a-\alpha_n)\\
\text{MEP}: &\quad \phi_n = \frac{\pi}{4}-\frac{\beta_a-\alpha_n}{2}\\
\text{EMP}: &\quad \phi_n = \tan^{-1}\left(\frac{\cos(\alpha_n)}{1-\sin(\alpha_n)}\right)-\beta_n
\end{aligned} \tag{7}$$

After calculation of normal friction angle ($\tilde{\beta}_n$) and normal shear angle (ϕ_n), shear stress (τ_s) is calculated using $\tilde{K}_{tc}$ formulation in Eq. (3). As assumed in orthogonal to oblique transformation, orthogonal shear angle (ϕ) is assumed to be equal to the normal shear angle (ϕ_n). Hence, orthogonal database that consist of shear stress, orthogonal friction angle and shear angle is obtained. Finally, cutting force coefficients for the new tool can be calculated using Eqs. (2), (5) and (6).

3. Taylor series method

An alternative method that does not require using an additional equation for shear angle is also developed. It uses Taylor series expansion and hence it is called Taylor series method. It predicts the cutting force coefficients for varying helix angle $i = i_{\text{int}} + \delta$. Firstly, Eq. (2) is divided by Eq. (3) to get a relationship between the cutting force coefficient functions and their constant experimental counterparts as shown in Eq. (8).

A good approximation for λ is found by taking the first term from the Taylor series (with respect to δ) of the square root in Eq. (9) and assuming $\phi_n \approx \tilde{\phi}_n$, $\beta_n \approx \tilde{\beta}_n$, $\alpha_n \approx \tilde{\alpha}_n$, i.e. setting $\lambda = 1$. Then, new cutting force coefficients for a new helix angle can be calculated by Eq. (8) together with normal friction angle