A Multi-Parameter Fusion Turning Force Prediction Method Considering the Arc Radius of the Tool Tip

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Abstract. According to the force analysis of turning, the principle of oblique cutting is applied. A new multi-parameter fusion turning force prediction method considering the radius of cutter tip arc is proposed. The mathematical model of new turning force prediction is established. The influence of cutting parameters, cutting parameters and machining conditions on the cutting force is considered in this method. By using the method of cutting force coefficient of the front cutting face, three cutting force coefficients on the front cutting face can be solved by one turning experiment, and the turning force prediction can be realized under the conditions of different cutting tool geometry parameters and different cutting parameters. Finally, the feasibility of the method is verified by TC4 turning test of titanium alloy. And it has high prediction accuracy.

Keywords: Prediction method of turning force, Cutting force coefficient, Influence of cutting force.

1. Introduction

In the process of cutting, cutting force is the most direct factor that reflects the state of machining. The change of cutting force directly affects the generation of cutting heat, the surface quality of workpiece, the condition of tool wear and the vibration of machine tool [1]. At the same time, it is also an important basis for determining the power and efficiency of machine tools. Therefore, cutting force modeling can not only optimize cutting parameters and control machining accuracy, but also can be used for fixture design. Tool wear provides important reference, which is of great significance to the rational design of machine tool and process system.

Turning force is the basis of other cutting forces. Many scholars at home and abroad have done a lot of research on it. Based on a large number of experimental cutting data, the empirical formula between cutting force and cutting parameters was established by using the exponential curve fitting method in literature [2]. Literature [3] established material constitutive model of materials under high temperature and high strain environment through cutting mechanism and material constitutive relationship through a large number of experiments. In literature [4], the cutting force model per unit area was calculated by using the main cutting force and cutting area measured by experiment. In literature [5], a large number...
of typical cutting experiments were used to provide enough training samples to establish the cutting force prediction model of artificial neural network. To sum up, the current turning force prediction methods need to be based on a large number of cutting experiments.

Considering the influence of cutting parameters and cutting tool angle parameters on turning force, a new turning force prediction model considering the arc of the tool tip is established in this paper, and the accurate prediction of the turning force is realized. The validity of this method is verified by the titanium alloy TC4 turning test.

2.  A cutting Force Prediction Model considering the Radius of the Arc of the tool Tip

2.1. Turning tool cutting edge discretization

In turning, the existence of cutter tip arc will influence the cutting process, and make the modeling process more complicated than the traditional oblique cutting with single cutting edge. Therefore, in this paper, the cutting edge arc is discretized into many straight cutting edge microelements. For each discrete element, the expressions of local principal deflection angle, normal antecedent angle and edge dip angle are derived by coordinate transformation and geometric relations.

On the base plane Pr, First of all, the cutting edge can be discretized into K+2 section straight cutting edge unit. Uses to identify (0≤s≤K+1). The main cutting edge with the same chip thickness can be regarded as a single integral unit (For example, the s=0 section in Figure 1). For the tool arc edge with varying chip thickness, it is discretized into K+1 straight cutting edge microelements (as shown in Figure 1, s=1, 2, K, K+1 part). In the actual cutting process, the cutting tip arc edge of the workpiece is divided into two parts, which are measured by Φσ and Φα, respectively. Φσ and Φα are the cut-in and cut-out angles of the first part, as shown in figure 1. The first part (for interval angle øσ) is divided into K cutting edge elements, which identify 1≤s≤K and take ∆Ø as the increment angle. According to the geometric relationship, the following Angle expression can be obtained:

\[ Φ_{ex} = \frac{π}{2} - sin^{-1}(0.5f_{r}/r_n) \]  
\[ Φ_s = Φ_{ex} - Φ_{st} \]  
\[ ΔØ = Φ_s/K \]  
\[ Φ_a = 2sin^{-1}(0.5f_{r}/r_n) \]

The local cutting parameters of each discrete element s (1≤s≤k) in the tip arc edge can be calculated with the following formula.

\[ Φ^s = Φ_{st} + (s - 1)ΔØ \]  
\[ k^s_r = \frac{π}{2} - Φ^s - ΔØ/2 \]  
\[ φ^s = \frac{π}{2} - k^s_r \]  
\[ θ^s_r = k_r - k^s_r = Φ^s - \frac{π}{2} + k^s_r + ΔØ/2 \]  
\[ a^s_w = 2r_n sin(ΔØ/2) \]
\[ t^s = f_r \sin(k_r^s) \]  

(11)

Where \( \theta^s, k_r^s, \phi^s, \theta_r^s, a_{\omega^s}, t^s \) respectively represents the position angle of the S th discrete cutting unit, Local main deflection Angle, residual deflection Angle, cutting width and thickness.

The effective cutting area of the S \((0 \leq s \leq k)\) th discrete cutting element in the \(P_r\) plane is calculated by the formula.

\[ S^s = a_{\omega^s} t^s \]  

(12)

**Figure 1.** Projection of discrete cutting edge on base plane.

2.2. New turning Force Prediction Model

After the tool tip and edge are discretized, the cutting force on each discrete unit's local front face is calculated by using the three-way turning force coefficient on the tool's front face obtained through the following formula.

\[
\begin{bmatrix}
F_1^s \\
F_2^s \\
F_3^s
\end{bmatrix} = S^s \begin{bmatrix}
K_{\omega^s} \\
K_{\theta^s} \\
K_{t^s}
\end{bmatrix}
\]  

(13)

Where \(F_1^s, F_2^s, F_3^s\) represents the cutting force of the S discrete cutting unit on Local front tool surface. The \(S^s\) is the effective cutting area of the S discrete cutting micro element on the local front tool surface.

Secondly, the cutting force of the S discrete cutting element on the local front cutting face is obtained. The method of coordinate transformation is converted to XYZ coordinate system.

\[
\begin{bmatrix}
F_1^s \\
F_2^s \\
F_3^s
\end{bmatrix} = T^s \begin{bmatrix}
F_1^s \\
F_2^s \\
F_3^s
\end{bmatrix}
\]  

(14)

Where \(T^s\) is the coordinate transformation matrix when the cutting force in the XYZ coordinate system is converted to the triaxial cutting force on the front cutter surface. That is,

\[ T^s = T_1^s T_2^s T_3^s \]  

(15)

The \(T_1^s\) is a transformation matrix of the angle of \((90^\circ - K_1^s)\) around the Y axis in the XYZ coordinate system. The \(T_2^s\) is a transformation matrix of the angle of \(\lambda_1^s\) around the \(X_1\) axis; The \(T_3^s\) is a transformation matrix of the angle of \(\gamma_1^s\) around the \(Z_2\) axis.
\[
T^*_1 = \begin{bmatrix}
\sin(K^*_y) & 0 & -\cos(K^*_y) \\
0 & 1 & 0 \\
\cos(K^*_y) & 0 & \sin(K^*_y)
\end{bmatrix}
\]

(16)

\[
T^*_2 = \begin{bmatrix}
1 & 0 & 0 \\
0 & \cos(\lambda^*_y) & \sin(\lambda^*_y) \\
0 & -\sin(\lambda^*_y) & \cos(\lambda^*_y)
\end{bmatrix}
\]

(17)

\[
T^*_3 = \begin{bmatrix}
\cos(\gamma^*_y) & \sin(\gamma^*_y) & 0 \\
-\sin(\gamma^*_y) & \cos(\gamma^*_y) & 0 \\
0 & 0 & 1
\end{bmatrix}
\]

(18)

By summing up the upper formula, the triaxial cutting force can be obtained.

\[
\begin{bmatrix}
F_x \\
F_y \\
F_z
\end{bmatrix} = \sum_{i=1}^{3} \begin{bmatrix}
F'_x \\
F'_y \\
F'_z
\end{bmatrix}
\]

(19)

3. Experimental verification of turning force prediction method

3.1. Cutting experiment condition

In order to verify the validity of the prediction model of turning force established in this paper. The cutting force test platform was set up by using CK6143, Kistler9257B dynamometer and industrial control computer, and the relevant cutting experiments were carried out. The experimental material is TC4, and the cutting tool material is KC5510. The specific parameters are shown in table 1. Normal temperature dry cutting, cutting parameters are shown in table 2.

| Tool | K_r | K_y | \( \gamma_0 \) | a_0 | \( \lambda_s \) | r_e (mm) |
|------|-----|-----|----------------|-----|--------------|---------|
| T01  | 93° | 7°  | 7°            | 5°  | -8°          | 0.4     |
| T02  | 75° | 6°  | 12°           | 13° | 6°           | 0.8     |

3.2. Cutting experiment scheme

1) First of all, T01 was selected to carry out the turning test by using the cutting parameters numbered 0 in Table 2. The three cutting force coefficients \( K_x, K_y, K_z \) are 173.89, 702.21 and 1013.18 respectively by measuring \( F_x, F_y, F_z \).

Then, according to the experimental parameters in Table 2, the cutting parameters of T01 are changed to obtain the predicted and measured turning force under different cutting parameters as shown in Figure 2. The maximum relative error of \( F_x, F_y, F_z \) is 4.39%, 4.31% and 4.32% respectively.

2) Changing T02, according to the cutting coefficient obtained from T01, according to the cutting parameters of Table 3, the predicted value and the measured value are shown in Figure 3. The maximum error of \( F_x, F_y, F_z \) triaxial force prediction is 6.03%, 6.0% and 5.98% respectively.
Figure 2. T01 cutting force predicted and measured.

Figure 3. T02 cutting force predicted and measured.

4. Conclusions
1) Through the idea that the cutting force of three directions is converted to the front face of the cutting tool, the expression of cutting force of different angle turning tool is unified, and the turning force prediction under different cutting angle is realized.

2) The cutting force can be described by cutting coefficient method, and the influence of cutter material, workpiece material, and heat treatment, cutting fluid and other factors on cutting force can be considered, and it can be applied to the prediction of turning force under different cutting parameters.

3) The prediction of cutting force with less cutting force is realized, and it has good generalization.

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