Thermomechanical Modeling and Analysis of Workpiece in End Milling Process

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Abstract. In order to study the cutting force distribution of the workpiece during the process of vertical milling machining, the thermomechanical model of the steady oblique cutting is derived. The measuring system of cutting force is also established, and then the feasibility of theoretical model is verified. First, according to the steady oblique cutting of cutting force and cutting temperature characteristics, coupled thermomechanical model of the workpiece in the milling process is derived. Based on above, a dynamic solving approach for cutting force is proposed. Then, the dynamic measurement system of force is established by using artificial Kistler force measurement. Finally, the thermomechanical model and dynamic measurement system are used to analyze the cutting force of AISI1045 steel under specific conditions. Analysis results indicate that the maximum of Fx, Fy and Fz are 198 N, 40 N and 90 N respectively, the error between calculated and measured value are 2%, 20% and 10% respectively. It shows that the established method can be used to investigate the thermo-mechanics of workpiece accurately in milling process.

Introduction

Because existing complicated thermal, dynamical and couple effects, it is hard to establish accurate thermal-dynamic model. Hence, it should make some reasonable simplification to establish its thermal-dynamic model in milling process [1]. Then, fairly accurate analysis of the change of the real-time physical quantities such as temperature, stress and strain can be done.

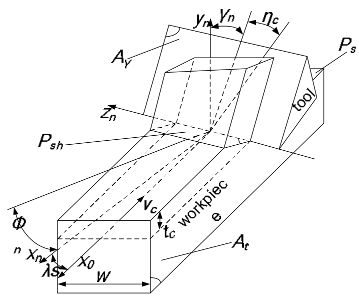
Thermal-dynamic modeling of oblique cutting is widely studied by scholars all over the world. Thermal-dynamic model of orthogonal cutting process is put forward by OXLEY[2], and rakecasting analysis is done under the assumption that cutting force is ignorant of oblique cutting angle and flow cutting angle. MOUFKI et.al[3]took fully account of thermal-dynamic couple effect which would affect cutting formation, and put forward calculation method of flow cutting angle. WU[4]gave theoretical formation of oblique cutting force by coordination transfer method. Research above was mainly on milling force and temperature of oblique milling respectively, but are not on relationship of each other. Present study can't build effective relation between milling force and temperature, thus can't reflect dynamic process of milling force versus rotation angle. Based on oblique milling force model, 3-D milling force calculation model of end milling process is built by micro element discretion in this paper. Moreover, the relation between milling force rakecast model and temperature rakecast model is build. Based on above, periodical varied condition of cutting force during milling process are analyzed, which provide accurate basis for high speed milling work analysis and optimization.

Cutting Force Model

Geometric Relationship. The Fig.1~2 show the geometric model of oblique cutting process[5].Where, x_n axis of plane $P_n$is vertical to the cutting edge and locates inside the cutting plane P_S. z_n axis is coincide with cutting edge, and y_n axis is vertical to plane P_n. x_0 axis of cutting plane P_S is opposite to cutting speed. z_0 axis is parallel to the radial cutting width w. y_0 axis is vertical to the cutting plane P_S, y_0 axis and z_0 axis formed the reference plane P_0. Other related cutting plane has shear plane P_{sh}, rakeface A_γ and equivalent plane P_e. The equivalent plane P_e is determined by the cutting speed v_c

and chip speed v_e. The cutting mechanism ofP_e can be regarded as the accumulation of 2-D cutting state.

In addition, angles about oblique cutting haveinclination angle λ_s, rake angle $\gamma_n$of planar P_n of c utting tool , the shear angle Φ_n in normalplane,chip flow angle$\eta_c$of rake faceA_γ and the shear flowan gle η_s in shear plane P_{sh} .



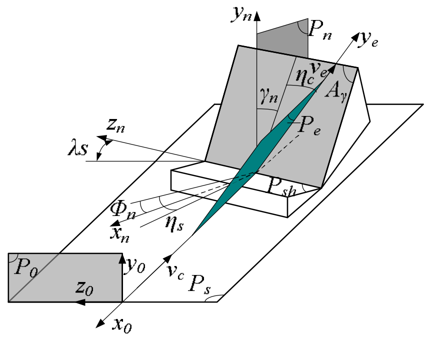


Fig. 1: Oblique Cutting Process Fig. 2: Geometric Relationships

Equivalent plane orientation is determine by the equivalent plane Angle η_e.

$$\tan\eta_e = \frac{\tan\eta_c\cos\eta_s + \sin(\Phi_n - \gamma_n)\sin\eta_s}{\cos(\Phi_n - \gamma_n)} \tag{1}$$

According to the geometrical relationship, the flow Angle of η_s can be express as below

$$\tan\eta_s = \frac{\tan\lambda_s\cos(\Phi_n - \gamma_n) - \tan\eta_c\sin\Phi_n}{\cos\gamma_n} \tag{2}$$

Where,η_c——chip flow Angle (rad), using Stabler's test rules, $\eta_c=\lambda_s$.

Φ_n——normal shear Angle (rad), applying model given by Armarego, $\Phi_n = \pi/4-(\beta_n-\gamma_n)$.

β_n——normal friction Angle (rad).

r_c is a ratio between the cutting thickness of t_c and chip thickness t_{ch}, obtained generally by the test data.

$$r_c = \frac{\sin\Phi_n}{\cos(\Phi_n - \gamma_n)} = \frac{t_{ch}}{t_c} \tag{3}$$

Velocity Relationship. Shear line vector*p in e*quivalent plane can be got by unit normal vector m of the shear plane$P_{sh}$and the unit normal vector *n* of equivalent planar P_e. According to the equation(4), it can be obtained. Where, the unit quantity *m* can be got by clock wisely revolving around the z axis Φ_n. A unit vector *n* can be got by clock wisely revolving around the *x* axis η_c. So the relation of the shear Angle Φ_e ofthe equivalent plane can be obtained assinΦ_e=sin$\Phi_n$cosη_c; The relationship about shear length L_e of the equivalent plane is$L_e=t_c/\sin\Phi_n\cos\eta_c$.

$$p = m\times n = \begin{pmatrix} \cos\Phi_n\cos\eta_c \\ \sin\Phi_n\cos\eta_c \\ \sin\Phi_n\sin\eta_c \end{pmatrix} \tag{4}$$

Chip velocity component in upward thickness direction of the shear zone is constant value[6]. After taking into the boundary conditions, the shear velocityv_s , chip velocity v_e, and shear plane area A_{sh} of equivalent plane can be express as equation (5), (6) and (7).

$$v_e = v_c\frac{\cos\lambda_s\sin\Phi_n}{\cos\eta_c\cos(\Phi_n - \gamma_n)} \tag{5}$$

$$v_s = v_c\frac{\cos\lambda_s\cos\gamma_n}{\cos\eta_s\cos(\Phi_n - \gamma_n)} \tag{6}$$

$$A_{sh} = \frac{wt_c}{\cos\lambda_s\sin\Phi_n} \tag{7}$$

Force Relationship. According to the relation of cutting force in oblique cutting process, the mechanics model of oblique cuttingis more complex than the model of orthogonal cutting, but the mechanics model of cutting plane is wholly same with the situation of orthogonal cutting. The relationship of cutting force in normal plane can be obtain as equation 8~10.

$$F_{tn}=t_s w t_c \frac{\cos h_s \cos(b_n - g_n)}{\sin f_n \cos l_s \cos(f_n + b_n - g_n)} \tag{8}$$

$$F_{an}=t_s w t_c \frac{\cos h_s \sin(b_n - g_n)}{\sin f_n \cos l_s \cos(f_n + b_n - g_n)} \tag{9}$$

$$F_{rn}=F_s \sin h_s = t_s w t_c \frac{\sin h_s}{\sin f_n \cos l_s} \tag{10}$$

Considering the influence of inclination angle λs, the cutting force of main plane can be get after coordination transformation.

$$\begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} = \begin{bmatrix} \cos l_s & 0 & \sin l_s \\ 0 & 1 & 0 \\ -\sin l_s & 0 & \cos l_s \end{bmatrix} \begin{bmatrix} F_{tn} \\ F_{an} \\ F_{rn} \end{bmatrix} \tag{11}$$

Material Constitutive Model

Cutting process is a thermal process with a high strain rate, high shear rate and the high rising temperature. Whether thethermal-mechanical characteristic equation of workpiece material is correct or not will directly affect the accuracy of cutting parameter prediction. In this article, the workpiece material as a viscous plastic solid isotropic material, its thermal properties can be describedby Johnson-Cook model. Introducing it into primary shear zone boundary conditions, simplified constitutive model can be obtained as shown as equation 12[8].

$$t = r\left(v_c \cos l_s \sin f_n\right)^2 g + t_0 \tag{12}$$

Where, ρ——material density (kg.m^{-3}).

τ_0——shear stress when just coming into the shear zone (Pa).

γ—— strain rate [9], can be approximated as $g = \frac{\cot f_n + \tan(f_n - g_n)}{\cos h_s}$.

Experimental Study

Experimental Principle. Measuring principle of milling force and temperature is shown in Fig.3 [10-11], the coordinate origin in the system is located in the position of lines in the top right the artifacts. x, z axis is shown in the figure, y axis is determined by the right-hand rule. Kistler 9257B dynamometer is used to measure the three-dimensional cutting force in milling process. The dynamometer is connected with artifacts through the four bolts, and recycling splint is fixed on the machine tooling platform to ensure smooth dynamometer in the cutting process.

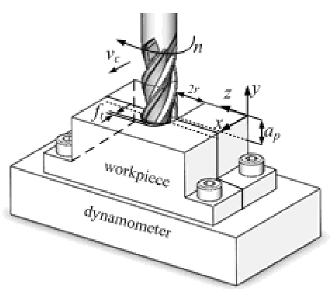


Fig. 3:Cutting Test Principle

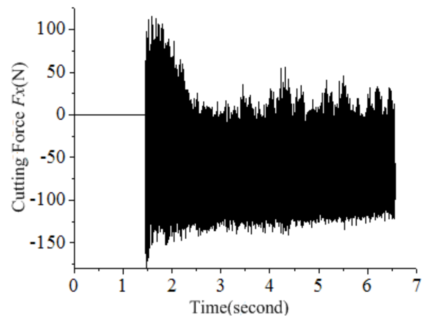


Fig.4: Measurement Curve of F_x

Experimental System. Machine tool is vertical milling machining center MCV850, the highest spindle speed is 50 ~8 000 rpm. Material of workpiece is AISI1045 steel; Specimen size is 80×80×30 mm; carbide four blade milling cutter model is HPL10.0 M, diameter is 10 mm, the nominal spiral Angle i = 30 °, radial rake angle γ_n= 0 °, tool clearance angle α_0 = 20 °, tooth wedge angle δ= 70 °. Experimental system consist of thedynamometer, multi-channel signal analyzer and computer. The model of multi-channel signal analyzer used in the test is DH5922N. The application of MFC AppWizard is based on dialog box data acquisition interface, which has a sampling frequency of 1 000 Hz. Cutting speed v_c is 100 m/min, the spindle speed is 3200 r/min, the axial cutting depth a_p is 0.5 mm, each tooth feeding f_t is 0.025 mm, the radial cutting width a_e is 10 mm; Dry down slot milling is taken.

Experimental Result. Signal figure collected is shown in Figure 4. It can be seen from the graph that the maximum of F_x is around 160 N; Cutting force fluctuation change, after removal not ideal signal curve, the minimum basic cutting force appears near the 0 N, accords with the basic change law of milling forces.

Thermalmechanical Analysis

Method of Thermomechanical Analysis. The 3-D calculating model of cutting force in milling is established through the micro discrete method. The instantaneous chip thickness of micro element can be obtained by the geometric relations.

$$h_i = f_t \sin j_{ki} \Gamma_{ki} \quad (13)$$

Where, φ_{ki}——the case of infinitesimal rotation angle i as shown in expression (14) .

Γ_{ki}——judgment coefficient, as shown in expression (15).

$$j_{ki} = q(t) - \frac{y_i}{R_i}\tan h_s + (k-1)\frac{2p}{N} \quad (14)$$

Where, k—— the k_{th} blade.

N——the number of blades.

R_i——rotation radius of the i_{th} element.

$\Gamma_{ki} = 1$ (when the i_{th} element of k_{th} blade contacts workpiece) (15)

Tangential, radial and axial cutting force of micro element of cutting blade can be respectively expressed by formulations (16-18)[12].

$$dF_{t,j_{ki}} = (K_{tc}h_i + K_{te})dy_i \quad (16)$$

$$dF_{r,j_{ki}} = (K_{rc}h_i + K_{re})dy_i \quad (17)$$

$$dF_{a,j_{ki}} = (K_{ac}h_i + K_{ae})dy_i \quad (18)$$

Where, K_{tc}、K_{rc}、K_{ac}—— cutting force coefficient of tangential, radial and instantaneous axial respectively, can obtained by expressions 8~ 10 considering Φ_n and material flow stress variation.

K_{te}、K_{re}、K_{ae}——tangential, radial and axial force coefficient on the edge, when the h_i equals zero, obtained by reverse cutting force test curve.

Thermomechanicalcalculation steps of vertical milling processing are shown as follows.

(1) determine the point of integral step length $\Delta\theta$,integration stepΔa_p of the blade in axial, and the cutting out angle Φ_{ex} (Φ_{st}=acos(a_e/r-1)， Φ_{ex}=π).

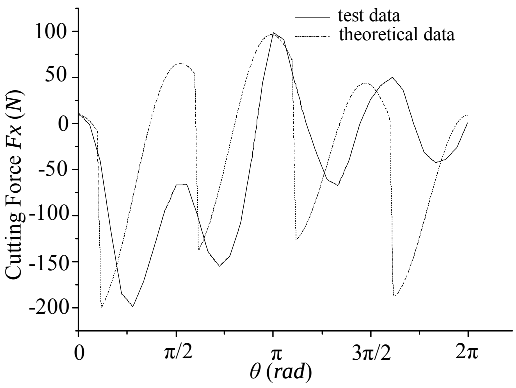
(2) when the milling cutter rotation to arbitrary Angle θ(t), calculate the cutting forcedistribution.

(3) composite θ(t), Φ_{st} and Φ_{en}geometric relations, it can ensure the angle θ(t)in the k_{th}blade, then calculate the cutting force for integral processing in their respective axial cutting depth. After this step,it can obtain the total cutting force of the k_{th}blade.

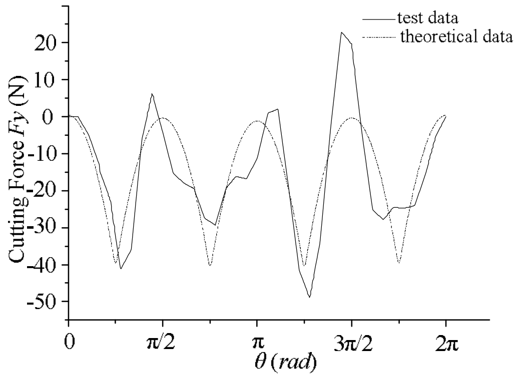
(4) change θ(t), repeat step 2and 3, it can get the cutting force changes when the blades rotating.

Analysis Results. For the study of thermalmechanical changes in end milling process, above thermomechanical calculation method is used. The same conditions and scheme as the experimental study is accepted. During Calculation, $\Delta\theta$=5°,Δa_p=0.025mm, the number of discrete points between shear line and the tool-chip contact line is 10.

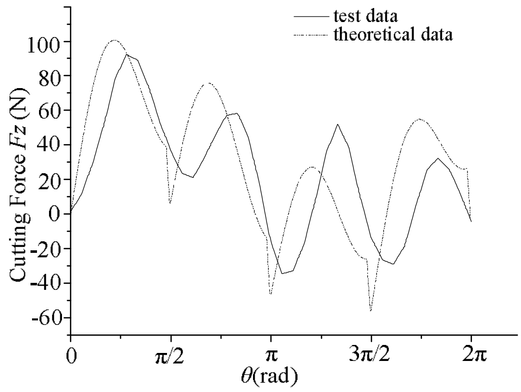
As the Fig.5shown,the change curve of cutting force with blade rotation within 1circle is obtained. From theresults of theFig.5a~5c can be seen that the cutting force F_x, F_y and $F_z$in the main cutting plane show obvious periodic (π/2) variation. With the comparing of experimental and theoretical results, it hasa little phase lag (because of the response lag in the force transducer).The maximum F_x of theoretical analysis is about 198N, the maximum F_y is about 40N, the maximum F_z is about 90N, which all appeared when the rotation angle equal to π/4.The error between calculated and measured value of maximum F_x, F_y and F_z are 2%, 20% and 10% respectively, but the trend was consistent.



(a) Cutting Force F_x



(b) Cutting Force F_y



(c) Cutting ForceF_z

Fig.5: Comparing of Results

Summary

(1) The steady-state oblique cutting thermal model is established; based on the above,the dynamical solving method of cutting force in the helical gear vertical milling processing was developed, the cutting force changes of AISI1045 steelunder specific conditions was studied, and the feasibility of the method is validated through the milling test.

(2) The proposed method not only takes the thermal effect of material flow stress change into account, but also the chip thickness influence on cutting force and cutting temperature.

(3) For whole cutting process, the maximum cutting force F_x, F_y and F_z are 198 N,40 N and 90 N respectively, the error between the test data are 2%, 20% and 10% respectively, basically meet the requirements of thermal error of problem solving.

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