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Research on Cutting Force Based on Thermal-Mechanical Coupling Precision Modeling

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Abstract

The accurate establishment of the constitutive model during the cutting simulation is very important. The improved finite element inverse method is used to establish an accurate material constitutive model, the optimal JC constitutive parameters are solved, and the thermal-mechanical coupling model constructed with ABAQUS is obtained. An accurate cutting simulation model. The output is based on the cutting force in the case of thermal-mechanical coupling, and it is compared with the experimental measurement values. The simulation values are basically consistent with the experimental values, which verifies the accuracy and feasibility of the model. It also provides reference and guidance for other accurate modeling of cutting simulation.

Keywords

Constitutive parameter; hermal- echanical Coupling; Cutting force; Cutting force coefficient.

1. Introduction

With the rapid development of manufacturing, production efficiency has always been the major problem discussed enterprise, the height of the milling process is a complicated nonlinear metal forming process, which includes the stress and strain, the strain energy of the flow stress, friction factor and heat flow distribution of complex problems, such as the finite element numerical simulation is a powerful tool to study of the above complex problems in cutting, in meet the requirements of the situation, to improve the efficiency and reduces the production cost, to drive the development of enterprises better.

In recent years, finite element numerical simulation has been rapidly developed and applied in various fields, and finite element cutting simulation has been favored by more and more people [1]. It is important to establish an effective and accurate model in the finite element simulation, which will directly affect the fit of the subsequent simulation process and the actual cutting process, the accuracy of the data, and whether it can guide the actual production process [2]. Establishing accurate cutting geometry model and constitutive model before simulation is a key step for accurately outputting important parameters such as cutting force and residual stress. In the study of dynamic constitutive model, Tang Qi [3] et al. Ke Yinglin et al. [4,5] proposed a finite element model combined with the calculation of the single factor flow stress formula for modeling and a thermal-mechanical coupling model based on the elastoplastic finite element equation. A dynamic constitutive model was established and the correctness of the model was verified; Wang Jingping [6] established the physical model of milling on the ABAQUS platform, compared the simulated cutting force with the software simulated cutting using Hopkinson bar impact experiments to obtain the material constitutive parameters. The effects of cutting parameters on cutting force and surface quality were observed. After optimizing the cutting parameters, the feasibility of the method was verified by experiments. In summary, many studies have shown that the finite element analysis method has certain accuracy and

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effectiveness, can reduce the experimental cost and time cost, and especially provides efficient and effective guidance for the study of cutting dynamics under the coupling of multiple factors. Forecasting is a time-saving and feasible method.

In this paper, through the finite element analysis software, an orthogonal cutting model based on thermal-mechanical coupling is established. At the same time, the optimal material JC constitutive parameters, damage model parameters, cutting friction model, and heat conduction model are selected using the finite element inverse solution. The cutting force value of thermal-mechanical coupling is compared with the experimental measurement value. The output data of the cutting model based on thermal-mechanical coupling is basically consistent with the experiment, which proves the effectiveness and accuracy of the method. Laying the foundation for cutting stability (SLD) prediction.

2. Cutting force model

Based on the dynamic model of orthogonal cutting of a spiral milling cutter, the model decomposes the instantaneous cutting force of the milling cutter into tangential and radial directions. According to the basic principles of elastic mechanics, the instantaneous tangential cutting force and radial cutting force are written as the linear microelement form is generalized from two-dimensional space to three-dimensional space, and its model expression can be written as [8]:

$$\begin{cases} dF_{t,mn} = g(\phi_{mn})\left(K_{tc}h(\phi_{mn}) + K_{te}\right)dz \\ dF_{r,mn} = g(\phi_{mn})\left(K_{rc}h(\phi_{mn}) + K_{re}\right)dz \\ dF_{a,mn} = g(\phi_{mn})\left(K_{ac}h(\phi_{mn}) + K_{ae}\right)dz \end{cases} \tag{1}$$

Where g(φmn) is a unit function, dFt,mn,dFr,mn,dFa,mn are tangential, radial, and axial cutting force microelements, and Ktc, Krc, and Kac are tangential and radial, respectively. Axial cutting force coefficients, Kte, Kre, Kae are tangential cutting edge, radial cutting edge, axial cutting edge force coefficient, and dz are cutting edge microelements.

$$\begin{cases} g(\phi_{mn}) = 1, & \phi_{st} \le \phi_{mn} \le \phi_{ex} \\ g(\phi_{mn}) = 0, & \phi_{mn} < \phi_{st} \text{或} \phi_{mn} > \phi_{ex} \end{cases} \tag{2}$$

In the formula, φst and φex are the cut-in angle and the cut-out angle, respectively.

Assume that the milling cutter helix angle is oblique, and decompose the instantaneous cutting force into rectangular coordinates through coordinate transformation, that is:

$$\begin{cases} dF_{x,mn} = -dF_{t,mn}\cos\phi_{mn} - dF_{r,mn}\sin\phi_{mn} \\ dF_{y,mn} = dF_{t,mn}\sin\phi_{mn} - dF_{r,mn}\cos\phi_{mn} \\ dF_{z,mn} = dF_{a,mn} \end{cases} \tag{3}$$

By summing the axial cutting force micro-element and the cutter tooth integral, the total cutting force form in each direction is obtained:

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$$\begin{cases} F_x = \sum_{m=1}^{J}\sum_{n=1}^{L}\left[-dF_{t,mn}\cos\left(\phi_{mn}\right)-dF_{r,mn}\sin\left(\phi_{mn}\right)\ \right] \\ F_y = \sum_{m=1}^{J}\sum_{n=1}^{L}\left[dF_{t,mn}\sin\left(\phi_{mn}\right)-dF_{r,mn}\cos\left(\phi_{mn}\right)\ \right] \\ F_z = \sum_{m=1}^{J}\sum_{n=1}^{L}dF_{a,mn} \end{cases} \tag{4}$$

By integrating the above formula in the range of cutting angles, the average cutting force of each cutter tooth in a cycle is:

$$\begin{cases} \overline{F}_x = -\frac{Na}{4}K_{rc}f_z - \frac{Na}{\pi}K_{re} \\ \overline{F}_y = \frac{Na}{4}K_{tc}f_z + \frac{Na}{\pi}K_{te} \\ \overline{F}_z = \frac{Na}{\pi}K_{ac}f_z + \frac{Na}{2}K_{ae} \end{cases} \tag{5}$$

Using the average cutting force data obtained at different feed rates, the linear force regression of the above formula can be used to obtain the corresponding cutting force coefficients in each direction. During the cutting process of the workpiece material, because the workpiece material is deformed by plastic deformation of the cutting layer under the tool's extrusion, this process must follow the material yield criterion.

3. Finite element cutting simulation

This paper builds a three-dimensional orthogonal cutting simulation model based on ABQUS software. As shown in Figure 1, the simulation cutting tool is a solid carbide milling cutter. Its material is WC and the workpiece material is 45 steel. Due to the consideration of the dynamic change of heat during cutting, a thermal-mechanical coupling algorithm is used to calculate the cutting model. The workpiece imposes constraints in the three directions of x, y, and z to allow the tool to translate and rotate. The defined cutting parameters are shown in Table 1. It is assumed that the initial temperature of the cutting environment is 20 degrees at room temperature, and the tool and the workpiece are subdivided in local areas on the mesh to reduce the calculation time and improve the data accuracy. The grid type selects the four-node temperature-displacement coupling element for simplified integration.

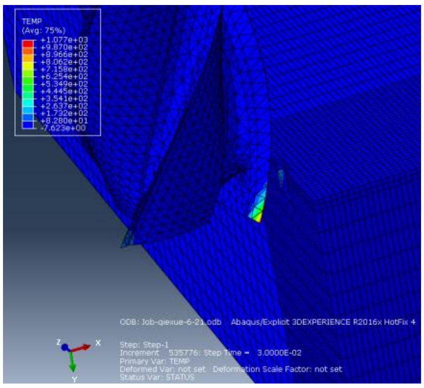

Fig 1. 3D orthogonal cutting model

Table 1. Cutting parameters

Numble	ft/mm	n/(r/min)	a/mm	V/(mm/min)
1	0.05	2000	1	400
2	0.07	2000	1	560
3	0.09	2000	1	720
4	0.11	2000	1	880
5	0.13	2000	1	1040
6	0.15	2000	1	1200

After the cutting model is established, the matching material plastic constitutive model, damage model, friction model, and heat transfer model are selected and simulated at the same time to obtain cutting deformation parameters, mechanical parameters, and cutting heat flow distribution. Then the iterative calculation of the constitutive model after heat conduction is performed, and finally the cutting force under the influence of thermal-mechanical coupling is output.

In this paper, the Johnson-Cook constitutive model [1] is used, as shown in equation (6). At the same time, because of the influence of temperature on the model, temperature parameters are added. The 45-steel material deformation criterion uses the J-C damage model [9], as shown in equation (7).

$$\bar{\sigma}=(A+B\varepsilon^{n})\left[1+CIn\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right]\left[1-\left(\frac{T-T_{room}}{T_{melt}-T_{room}}\right)^{m}\right] \tag{6}$$

Where is equivalent stress, is equivalent elastic strain, is equivalent elastic strain rate, is reference equivalent elastic strain rate, T, Troom and Tmelt are deformation temperature, room temperature and melting temperature of the workpiece in turn. A is the yield stress, B is the hardening modulus, and C, m and n are the material's characteristic factor, thermal softening factor and work hardening index. The above parameters are selected as the optimal constitutive parameters reversely solved by the improved finite element method [3], as shown in table 2. The thermal conduction model and friction model of cutting materials refer to the literature [10, 11].

Table 2. Johnson-Cook constitutive model parameters

A/MPa	B/MPa	C	n	m	Tmelt
507	320	0.0785	0.28	1.564	1538

The J-C damage model element damage value of the material can be expressed by the following formula:

$$D=\sum\frac{\Delta\varepsilon^{-p}}{\varepsilon^{-pf}} \tag{7}$$

In the formula: Δ εp is the equivalent plastic strain increment at the material integration point, and εpf is the failure strain value of the material. When D> 1, a failure occurs in the material element at the integration point, the material failure strain can be written as:

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$$\varepsilon^{-pf} = (D_1 + D_2 \exp D_3\sigma^*)\left[1+D_4 In\frac{\dot{\varepsilon}^{-p}}{\dot{\bar{\varepsilon}}}\right]\left[1-D_5\left(\frac{T-T_0}{T_{melt}-T_0}\right)\right] \quad (8)$$

In the formula: D1, D2, D3, D4, D5 are the damage parameters of 45 steel materials, as shown in Table 3.

Table 3. J-C damage model parameters

D1	D2	D3	D4	D5
0.10	0.76	1.57	0.005	-0.84

According to the six sets of simulated cutting parameters provided in Table 1, input them into the established cutting model, and then output the cutting force in consideration of the three directions of x, y, and z corresponding to the thermal coupling, as shown in Figure 2. The data was analyzed and processed to obtain the average cutting force values in each direction, as shown in Table 4. Then the data is substituted into equation (4), and the linear regression fitting is performed, as shown in FIG. 3, and the six cutting force coefficients finally calculated are shown in Table 5.

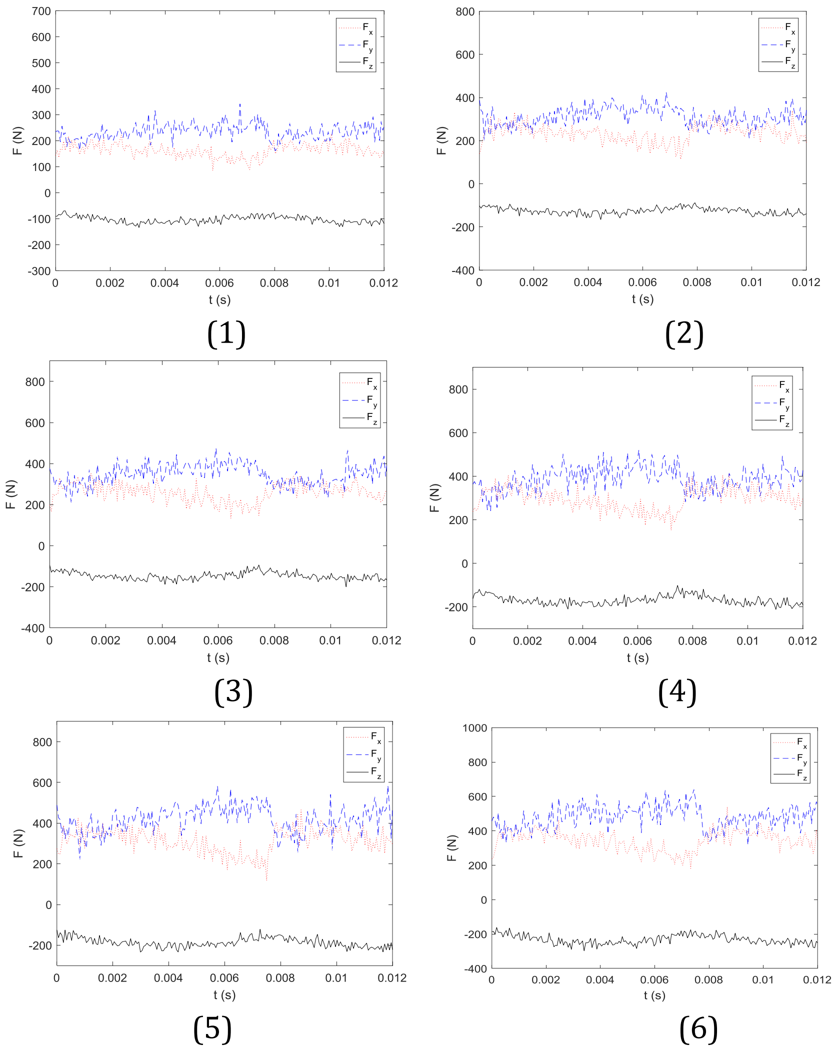

Fig 2. Cutting force simulation of each group of cutting parameters

Table 4. Simulation average cutting force (N)

Numble	Fx	Fy	Fz
1	220	-151.3	-78
2	280.2	-217.4	-105.6
3	320.2	-232.3	-120.7
4	385.5	-265.6	-160.4
5	436.8	-305.4	-188.5
6	485.1	-325.3	-225

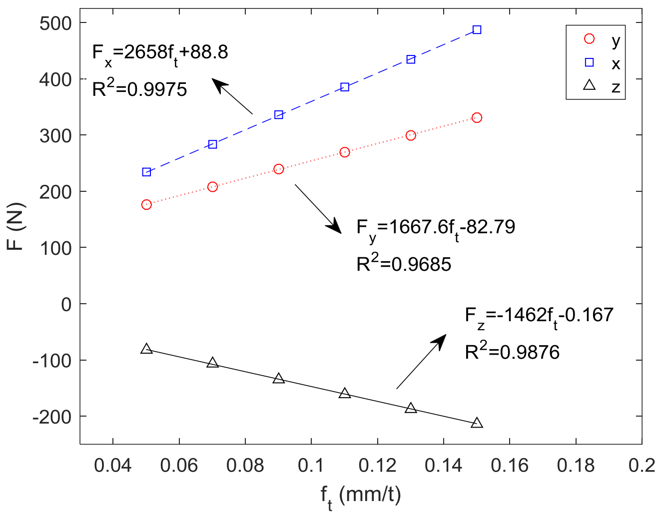

Fig 3. Simulation linear regression fitting

Table 5. Cutting force coefficient (N / mm2)

Material	Ktc	Krc	Kac	Kte	Kre	Kae
45	2658	1667.6	1148.3	69.7	65	8.3

4. Summary

Aiming at the difficulty in obtaining experimental cutting force data and studying the complex dynamic behavior of workpiece material deformation during metal cutting, this paper uses ABAQUS finite element analysis software to establish a precise three-dimensional orthogonal cutting model based on thermal and mechanical coupling. The stress and temperature generated during the cutting process are effectively predicted.

Through the analysis of the simulation cutting force data, it is found that the average cutting force value output by using the cutting model considering thermal and mechanical coupling is more reasonable, which indicates that the cutting model has certain validity and accuracy, and can be used as a simplified model for later cutting force experiments. , Greatly reducing time and economic costs.

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