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Development and Analysis of Milling Model Coupled Thermal-Mechanical

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Abstract

Milling simulation is involved many key technologies, which are less researched on the chip separation criteria and coupled thermal conduction model. Because of the limitations of geometry, physics chip separation standard, this paper presented a 3D milling chip separation criteria and developed a coupled thermal conduction model by considering the milling temperature and the interaction effects of milling force. The results using AdvantEdge FEM finite element software for milling simulation showed that the numerical simulation analysis of cutting force obtained a good agreement with experimental results which verify the reasonableness of the 3D milling model coupled thermal-mechanical and laid the foundation for CNC milling simulation system.

Keywords: *milling, coupled thermal-mechanical, chip separation criterion, simulation*

1. Introduction

Since the 1970s the finite element technology was applied in the simulation of metal cutting, a number of cutting finite element model [1] has been developed. A lot of researches are the simulation of 2D metal cutting, but the simulation of the 2D plane strain machining can only simulate the orthogonal cutting, and must ensure that the cutting width is more than five times the chip thickness. Almost all of the actual cutting is the 3D cutting, and pure 2D cutting is almost non-existent. Compared to the simulation of the 2D plane strain cutting, the 3D finite element simulation of cutting is much closer to the physical state and also has practical significance. This paper developed a 3D milling model coupled thermal-mechanical. For key technologies involved in the finite element simulation of milling, a 3D milling chip separation criteria and coupled thermal conduction model was developed to conduct the analysis of the 3D simulation of milling.

2. Establishment the Milling Thermal-Elastic-Plastic Finite Element Equation

In milling process, the workpiece cutting material occurred squeezing-elastic deformation-plastic deformation-fracture splitting under the action of the cutting edge. Cutting material near the cutting tool edge occur large plastic deformation, which is a typical thermal-elastic-plastic problem. Without considering the material creep case, based on the principle of virtual work, large deformation-large strain theory and using the modified Lagrangian equation (ULF) and Prandrl-Reuss [2] incremental theory, the thermal-elastic-plastic finite element equation under the large deformation can be given:

$$\left([K_{ep}] + [K_G] + [K_c] - [K_f]\right)\{\dot{u}\} = \int_v [B_\varepsilon][D^{\varepsilon p}]\{\dot{\varepsilon}^t\} dv - \int_v [B_\varepsilon]^T \{\dot{R}_{\bar{\varepsilon}T}\} dv + \{\dot{F}_0\} \quad (1)$$

$[K_{ep}]$ is the elastic-plastic stiffness matrix, $[K_G]$ is the geometric stiffness matrix, $[K_c]$ is the cutting load correction matrix, $[K_f]$ is the friction compensation matrix, $\{\dot{u}\}$

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is the node speed, $\{\dot{R}_{\tilde{\varepsilon}T}\}$ is a function of the yield surface the rate of change and $[\dot{F}_0]$ is the rate of change of the external load, including the actual load rate and the load rate caused by the change in shape of deformation.

3. Establish the 3D Milling Simulation Model Based on Coupled Thermal-Mechanical

3.1. Establish the 3D Milling Chip Separation Criteria–3D Stress Index

In metal milling process, with the movement of the tool and workpiece chips are separated and a new workpiece surface formed at the same time. After the separation, some of the chips can produce a continuous plastic deformation, and some chips generated jagged fracture. Determine the appropriate chip separation criteria, and automatic separation of the chip is a critical issue in cutting finite element simulation. So far, there are mainly two types of the chip separation criteria which have been proposed, namely, the geometric criteria and physical criteria. Geometric criteria are mainly based on the change in distance between tip and tip before unit nodes to determine separation. Physical criteria are mainly based on some established physical values to judge whether to reach a critical value.

Geometric criteria model is very simple, but the disadvantage is that it is not based on the physical condition of the chip separation. Therefore, it is difficult to find a common critical value using geometric criteria to suit the type of milling material and different processes. Using physical criteria would make the finite element simulation of metal cutting closer to the actual situation, but in the actual finite element simulation, when the tip reaches the node should be separate, physical values did not reach this point given physical standards. In other words, the chip is not be separated at this point. Based on the above analysis, this paper proposed a geometry-the stress of chip separation criteria-3D stress index.

3D stress index:

$$f = \sqrt{\left(\frac{\sigma_n}{\sigma_s}\right)^2 + \left(\frac{\tau_1}{\tau_{s1}}\right)^2 + \left(\frac{\tau_2}{\tau_{s2}}\right)^2} \tag{2}$$

σ_n is the normal stress at a specified distance from the front tip, σ_f is the failure stress under the pure tensile load conditions, τ_1、τ_2 is the shear stress at a specified distance from the front tip and τ_{f1}、τ_{f2} is the failure stress under the pure shear load conditions.

In fracture analysis, when the stress index f reached 1.0, the material was considered failure which means the material occurred fracture at this point and the unit was separated. Before the simulation, 'trial cut' of the workpiece was conducted. Under the given the geometric conditions and calculates the front tool nose given node stress σ_n、τ_1、τ_2 (generally preferably 2 or 3 units, located between a length of about 70-100μm, before the tip paper is taken from the two units long.) distance, simulated workpiece before "trial cut." According to Mises flow rule so that $\tau_s = \sigma_s / \sqrt{3}$,into the formula (2) calculate the failure stress of the material σ_s、τ_{s1}、τ_{s2}.

As the stress node failure criterion chip separation, when it formally machining simulation. With the cutting tool along a predefined path forward, to keep the nose before a specified distance and stress into equation (2) is calculated. Materials are considered invalid when f value reaches 1, the chip to achieve separation. The standard is based on the geometric standards, through a "test cut" in the finite element software, has been pre-specified point to the cutting edge of normal stress and shear stress, and then use plastic mechanics Mises flow rule to calculate the fracture stress values. Finally, the chip separation is judged based on stress criteria. The method is the integrated use of the advantages of standard geometric and physical standards. Based on the above analysis, we propose a geometry-stress of chip separation criteria.

3.2. Analysis of Tool-Chip Friction Type

In metal milling process, there is the tool - chip friction at the rake face, which affects the chip formation, cutting force, the temperature of the cutting, tool wear and the formation of scales thorn and BUE, thereby affects machined surface quality. Establish the correct friction model between the rake face and the chip is one of the key factors for simulation success. For the convenience of finite element simulation, the complex nonlinear problems between the general tools and chips were simplified into two friction area of different mechanisms [3]. In the slide area, the normal stress is relatively small, barely dry friction.In the bond area, the normal stress is high, similar to a constant friction stress.tool-chip interface friction model is usually based on Coulomb friction model in metal cutting finite element model has been established which is defined in the equation:

$$\tau = \mu p \text{ As } \mu p < \tau^*{}_s \text{ (Sliding friction region)} \quad (3)$$

$$\tau = \tau^*{}_s \text{ As } \mu p \geq \tau^*{}_s \text{ (Adhesive friction region)} \quad (4)$$

$\tau^*{}_s$ is the ultimate shear flow stress of the workpiece material; μ is the coefficient of friction; p is tool-chip interface pressure. Depending on the size of tool-chip interface friction stress can determine the sliding friction or viscous friction.

3.3. Development of 3D Coupled Thermal Conduction Model

When the elastic body by an external force and the thermal load change occurs, if from a stable state to another stable state over the course of the elastic body is considered equilibrium state, therefore neglect the effect of temperature change and the acceleration term and thermal conduction equation and the equations of motion independently, there is no coupling between the two. But with temperatures dramatic changes and deformation in metal milling process, is an unsteady temperature field problems, not only the temperature field changes with time, the elastic deformation also change over time. At the same time because of the deformation and thermal conversion, the temperature field distribution elastomer, not only with heat absorption, but also with deformation related. Therefore, metal milling process is a strongly coupled [4-5] or fully coupled process. Metal plastic deformation temperature field is a problem with the heat source heat unstable, so this paper coupled heat conduction model.

According to the theory of Helmholtz free energy and unit volume inner energy, we have:

$$dQ \bullet d\tau + \dot{q} = C_\varepsilon \frac{\partial T}{\partial \tau} d\tau + T\beta \frac{\partial \varepsilon_{ij} \delta_{ij}}{\partial \tau} d\tau \quad (5)$$

According to the balance between the three-dimensional infinitesimal flow in to and out of the heat, we have:

$$dQ = \lambda \nabla^2 T \quad (6)$$

The above equation into(8), to obtain coupled heat conduction equation:

$$\lambda \nabla^2 T + \dot{q} = C_\varepsilon \frac{\partial T}{\partial t} + T\beta \frac{\partial e}{\partial t} \quad (7)$$

e is the volume strain, T is the temperature, ρ is the density, t is the time, β is the coefficient of thermal stress, λ is the thermal conductivity, $C_\varepsilon = \rho c_v$ is the constant volume specific heat elastomers, $\dot{q}$ is the volumetric heat generation rate, and $\nabla^2 T = \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}$ is Laplace operator.

3.4 Wear Model of Tool

Tool wear is an inevitable phenomenon in the milling process, the factors cannot be ignored. Because of the complex stress and a relatively high temperature region in the milling action, followed by the extension of time to grind slowly oxide layer surface of the tool. Since the tool-chip and tool-there is a high positive pressure working between the plastic deformation layer attendant milling, resulting in the friction and frictional heat becomes large without breaking. Wear model also consider many factors, such as complex structure of knives and plastic deformation of the the workpiece material. In the case of the contact point movement to make the milling process to produce inconsistent, leading to the bonding region and the slide area are mixed in a knife-between workers-crumbs. So you want a true description the frictional relationship of knife-chips and knife-workpiece is very difficult. AdvantEdge FEM finite element software provides three prediction models, the standard model of wear, custom wear model and Usui (Usui Eiji) wear model. In high-speed milling, worn main performance under milling force and milling temperature combined effect of abrasive wear, abrasion and chemical bonding wear. Therefore, we use a custom wear model:

$$\dot{W} = K \bullet e^{\left(-\frac{Alpha}{T+273.15}\right)} \bullet V \tag{8}$$

K and $Alpha$ is a material constant,determined experimentally and provide; $\dot{w}$ are wear rate (volume loss per unit time per unit volume within); T are the milling stage cutting temperature of stable milling stage, V is the milling speed.

4. Analysis and Validation based on 3D Milling Simulation Coupled Thermal-Mechanical

According to the literature [6] provided the milling conditions, the use of finite element software AdvantEdge FEM aluminum alloy 7050-T7451 simulation, with non-thermal-mechanical coupled simulation and experimental results were compared, in order to validate that the three-dimensional milling simulation model based on coupled thermal-mechanical established. The tool tip is assumed to be absolute sharp rigid in the simulation and through the elastic modulus of the tool material is set to a very large value （E=2.15x1015MPa，Pr v=0.22）to achieve. The thermal conductivity of the tool is k = 120W / m • K and the friction coefficient of the tool-chip is 0.4. Carbide The tool is a ball end mill carbide material, the initial temperature of the tool and workpiece at room temperature(20 ℃) and the tool-chip of heat transfer coefficient is 11N / s • mm • ℃.

Orthogonal parameter table and milling test analog values as shown in Table (1). Application software AdvantEdge FEM simulated and analyzed, three-dimensional milling simulation model shown in Figure 1. Based on three-dimensional thermal-mechanical coupled milling simulation of transient milling force FX, Fy, Fz and non-thermal-mechanical simulation results and experimental results were compared in Figure 2.

Table 1. Milling Test Simulation Value

序号	Cutting speed *n* /(r/min)	Feed rate *f* /(mm/min)	Cutting depth *a* /(mm)	F_x	F_y	F_z
1	475	100	1	0.32785	-8.76972	24.03391
2	600	140	1	2.21182	-22.88017	-1.05453
3	300	160	1	8.27807	-6.20325	14.3729
4	600	100	2	5.81218	-14.81865	1.95748
5	300	140	2	21.73669	22.02159	39.85806
6	475	160	2	13.1146	4.65316	19.08834
7	300	100	3	57.20571	96.01825	96.60411
8	475	140	3	32.01912	62.26081	57.45139
9	600	160	3	29.52182	56.26563	54.64165

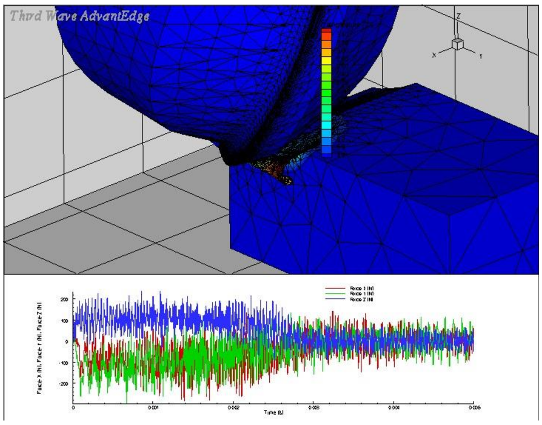

Figure 1. Three-Dimensional Simulation Model of Milling

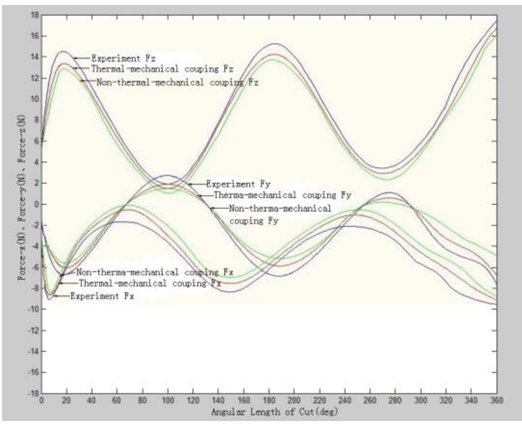

Figure 2. Transient Milling Force Fx, Fy, Fz Compare

5. Conclusion

In this study, a standard of chip separation was established and a coupled thermal conduction model was developed based on key technologies involved in the milling simulation. 7050-T7452 aluminum alloy materials were used to conduct the high-speed milling simulation. From Figure 2, the results of simulation milling force Fx, Fy and Fz based on 3D coupled thermal-mechanical simulation is much closer to the experimental results compared to the results of non-thermal-mechanical coupled. The simulation results using this model are more accurate which meet the needs of the qualitative analysis. This study has a high reference value on development and optimization of tool and provides a theoretical basis for guiding practice.

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