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Finite Element Simulation Analysis of Three-Dimensional Cutting Process Based on AISI1045

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ABSTRACT*:* *Metal cutting process is a complicated process of plastic deformation and the finite element method is used to simulate the cutting process. Chip is an important product of the cutting process, it has important significance to analysis of it's formation process and influence factors in the research of material processing performance, cutting tool optimization, etc..In this paper, the three-dimensional orthogonal and oblique cutting models were established based on Johnson-Cook material constitutive models and damage laws. The formation process of chip was analyzed according to the metal simulation cutting process, the influence of cutting variables (Cutting depth, Cutting speed, Work piece thickness)on chip was analyzed based on the status of chip.*
Keywords - *Chip, Simulation, Three-dimensional cutting model*

I. Introduction

At present, three-dimensional computer aided design (CAD) has been widely used in the design of a variety of products.In Computer Aided Engineering (CAE) which is related to it, the method has been gradually expanded which related performance (e.g., thermal,conductivity, etc.) of the product were analytical researched in advance by using the geometry simulation and finite element method (FEM).The development of cutting process simulation technology mainly includes two aspects[1]: One is geometry simulation,it is mainly used to display the movement track of the cutter, determine whether the cutting tool, the knife clip and the workpiece and the fixture whether the interference; The other is to study the various physical phenomena in the process of cutting,Such as the processing of material due to the formation of plastic deformation and heat, producing smear metal which the material is removed by cutting tool rake face,the machining surface formation which by the cutting edge of the cutting tool to remove the material etc., and this series of cutting through computer simulation.

It is not only a long period, but also a high cost which the cutting mechanism is studied by using the traditional method of cutting experiments. With the rapid development of computer and finite element, the finite element simulation technology is used to study the cutting process[2].WANG Ming-hai etc. researched ultrasonic vibration milling of Ti6Al4V by three dimensional finite Element simulation[3];Murat Demiral etc. researched the influence of strain gradients by numerical modeling of micro-machining[4].Many problems in cutting process are studied by means of two dimensional orthogonal cutting model. Because it is easy to model and operate simple, but it is not suitable for complex tool and work piece model research. Metal cutting process is a complicated process of plastic deformation and the finite element method is used to simulate the cutting process. Chip is an important product of the cutting process, it has important significance to analysis of it's formation process and influence factors in the research of material processing performance, cutting tool optimization, etc..In this paper, the three-dimensional orthogonal and oblique cutting models were established based on Johnson-Cook material constitutive models and damage laws.The formation process of chip was analyzed according to the metal simulation cutting process, the influence of cutting variables (Cutting depth, Cutting speed, Work piece thickness)on chip was analyzed based on the status of chip.

This paper uses a unified international unit: Pa, m, s,K. Symbol description:(1)Vc is the cutting speed;(2)ap is the cutting depth;(3)This the work piece thickness.

II. Cutting Simulation Modeling

2.1 Material constitutive modelsand damage laws

2.1.1Material constitutive models

To a large extent the accuracy of the simulation is determined by the material constitutive models. The work piece material was often located in high temperature, high strain and high strain rate in the cutting process. At the same time, the strain rate and temperature of each part of the cutting layer were maldistribution and largely changed in gradient. So in the cutting simulation, it is very important to correctly select the constitutive model which can reflect the strain rate,the temperature field and the influence of the flow stress on the flow stress of the material.

Johnson-Cook constitutive equation is one of the constitutive models for high strain rate and high temperature deformation.Therefore,it has been widely used in the study of finite element simulation[5-9].The Johnson–Cook constitutive equation was represented by the following:

$$\bar{\sigma} = \underbrace{(A + B\bar{\varepsilon}^n)}_{(1)} \underbrace{[1 + C\ln(\frac{\dot{\bar{\varepsilon}}}{\dot{\varepsilon}_0})]}_{(2)} \underbrace{[1 - (\frac{T - T_{room}}{T_{melt} - T_{room}})^m]}_{(3)} \tag{1}$$

Where the first term in equation(1) corresponds to the hardening, A is the yield stress, B and n are the hardening parameters. The second term represents the effect of the strain rate as a function of the parameter C. The third term refers to the thermal softening where m is the temperature sensitivity. The determination of these five parameters requires quasi-static and dynamic tests at different strain rates and temperatures[10].A,B,C,n,m are the material parameters and given by Table 1[11]. $\bar{\sigma}$ is the equivalent flow stress, $\bar{\varepsilon}$ is the equivalent plastic strain, $\dot{\bar{\varepsilon}}$ the equivalent plastic strain rate, $\dot{\varepsilon}_0$ the reference strain rate which equals $1\,s^{-1}$,Tmelt is the melting temperature (1623K,in this paper) and Troom is the room temperature (298 K, in this paper).

Table 1 Johnson–Cook model constants for IASI 1045

A(MPa)	B(MPa)	C	n	m
507	320	0.064	0.28	1.06

2.1.2 Material damage laws

The equation (1) describes the flow stress in the cutting process, which is only related to the plastic deformation and elastic deformation stage of the material in the process. The smear metal and the machined surface were generated on account of the failure of the element in cutting finite element, therefore it is necessary that the failure criterion of the element should be defined. In view of the fact that the physical separation criterion is more close to the material failure conditions compared with geometric separation criterion, therefore the physical separation criterion was used in the model. Johnson-Cook shear failure criterion[12-13] belongs to the physical separation criterion. It is based on the equivalent plastic strain value of the element integral point, the elements failure were generated when the failure parameter $D > 1$:

$$D = \sum (\frac{\Delta\dot{\bar{\varepsilon}}^P}{\dot{\bar{\varepsilon}}^{Pf}}) \tag{2}$$

Where $\Delta\dot{\bar{\varepsilon}}^P$ is the equivalent plastic strain increment, $\dot{\bar{\varepsilon}}^{Pf}$ is the effect variable value when failure.

$$\dot{\bar{\varepsilon}}^{Pf} = (D_1 + D_2 e^{D_3 \frac{p}{q}})[1 + D_4 \ln(\frac{\dot{\bar{\varepsilon}}^{pl}}{\dot{\varepsilon}_0})][1 + D_5(\frac{T - T_0}{T_{melt} - T_0})^m] \tag{3}$$

Where D_1, D_2, D_3, D_4, D_5 are the material parameters and given by Table 2[14],p is the compression stress,q is the mises stress.

Table 2 Johnson–Cook shear failure criterion constants for IASI 1045

D_1	D_2	D_3	D_4	D_5
0.10	0.76	1.57	0.005	-0.84

2.1.3 Material properties for the workpiece and tool

The accuracy of the material parameters will directly affect the correctness of the results in the cutting simulation.

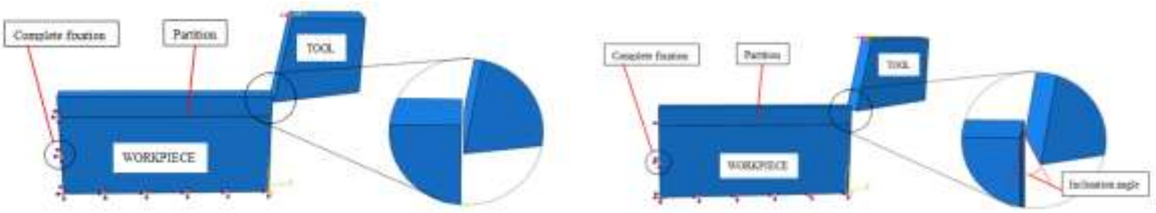
Material parameters are shown in Table 3[15].

Table 3 Material properties for the workpiece and tool

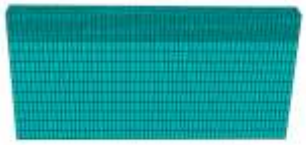
Material properties	Workpiece	Tool
Material properties	AISI 1045	CBN
Young's modulus (GPa)	210	587
Poisson's ratio	0.3	0.13
Conductivity ($Wm^{-1}\,{}^0C^{-1}$)	53.9	44
Specific heat ($Jkg^{-1}\,{}^0C^{-1}$)	420	750
Thermal expansion coefficient (${}^0C^{-1}$)	1.2×10^{-6}	4.7×10^{-6}

The hardness of the tool is much greater than that of the workpiece in the process of metal cutting, so the elastic deformation of the tool can be neglected, thus the cutting tool is assumed as a rigid body.

2.2 Geometric Model



(a)Orthogonal cutting model (b)Oblique cutting model



(c)Grid workpiece

Fig.1 Geometric model

Fig. 1 shows the basic geometry and boundary condition of the numerical model of the metal cutting process. The geometric model includes the orthogonal cutting model(as shown in the fig.1(a)) and the oblique cutting model(as shown in the fig.1(b)).The tool is fixed and cutting speed is applied to the workpiece to obtain the velocity field of the workpiece material, the rake angle is 100and the clearance angle is 70.The tool is a simplified model which the thickness is 0.0025m and the workpiece is a rectangular body which the length is 0.02m, the width is 0.01m and the thickness is 0.0015m as shown in Fig.1.The purpose of partitioning the workpiece is to separate the chip from the workpiece body,the chip area can be refined in this way when the workpiece is divided into grid as shown in the fig.1(c).

III. Results

3.1 Chip Formation Process

(1)Experiment and Simulation Chip

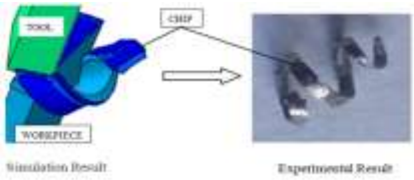


Fig.2 Experiment and simulation chip

The simulation results show that the spiral chip is generated in the oblique cutting process as in Fig.2 is shown on the left.The experimental condition of cutting simulation is : Vc is equal to 20m/s, ap is equal to $7\times10^{-4}m/rev$,and Th is equal to $1.5\times10^{-3}m$ .The chip is produced in the process of cutting on the CA6140 lathe under the same cutting conditions as in Fig.2 on the right.The chip has the same bending trend by comparing the simulation and experimental results.Thus the cutting simulation model was adopted in this paper with the intent of saving cost and time,and effectively avoiding other complicated factors in cutting process.

(2)Chip formation process

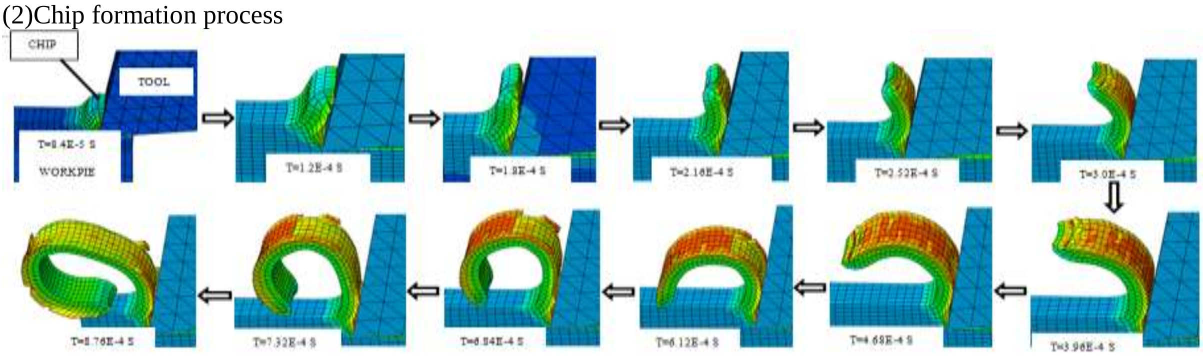


Fig.3 Chip formation process

Fig.3 shows the cutting status and the temperature of the node at each point of time.Simulation cutting variables are Vc=20m/s,ap=7.0E-4m and Th=1.5E-3m.The cutting process started when the tool cutting into the workpiece as the state of T=8.4e-5s,chip was slide along the rake face of the cutting tool(T=1.2E-4S),the separation of the tip of chip and cutting tool rake face when T=1.8E-4S,the chip continued to move upward and was gradually bent (T=2.16,2.52,3.0E-4S),lateral bending of chip was produced when T=3.96E-4S,the lateral bending of chip was continuing and gradually bending downward when T=4.68E-4S,the tip of chip was sustained bent downward until touching the undressed surface of workpiece when T=6.12E-4S,the inside curved chip was gradually generated as the cutting process continues to carry on and the friction between the tip of chip and the undressed surface of the workpiece when T=7.32E-4S,curled chip was formed when T=8.76E-4S.

(3)Node temperature and plastic energy dissipation

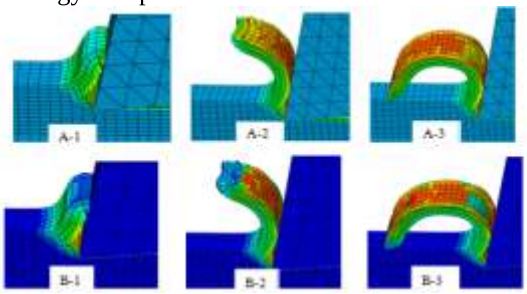


Fig.4 Node temperature and plastic energy dissipation

In Fig. 4, the A series is represented by nodes temperature distribution diagram of the cutting model at a certain time, while the B series is expressed as the total plastic dissipation energy of the unit.In the cutting model, the cloud charts of the nodes temperature and the total plastic dissipation energy of the unit are generally consistent with the distribution trend.Most of the heat generated during the cutting is carried away by the chip,while the work done by the tool is mainly used to overcome the plastic deformation of the chip.

3.2 Influence of Cutting Variables on Chip

3.2.1 Influence of Cutting Depth on Chip

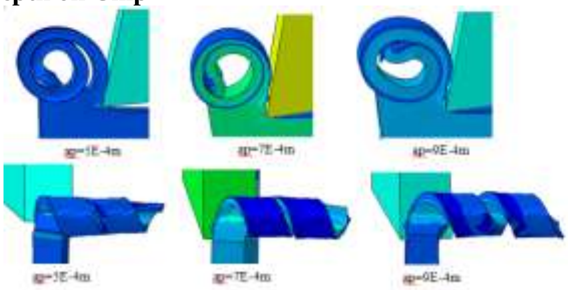


Fig.5 The status of chip which under the different cutting depth

In Fig.5,the experimental conditions are: Vc=20m/s, Th=1.5E-3m, ap as the experimental variable,the variable ap is 5E-4,7E-4,9E-4 m.Cutting simulation model are as follows:The tool is a simplified model which the thickness is 0.0025m and the workpiece is a rectangular body which the length is 0.02m, the width is 0.01m and the thickness is 0.0015m.The inclination angle is 100 in the oblique cutting model.Under the same cutting length,the more the number of weeks of chip curling, the smaller radius of chip curling is.The bigger the magnitude of ap is, the greater the radius of the chip curl is in the orthogonal and oblique cutting models.

3.2.2 Influence of Cutting Speed on Chip

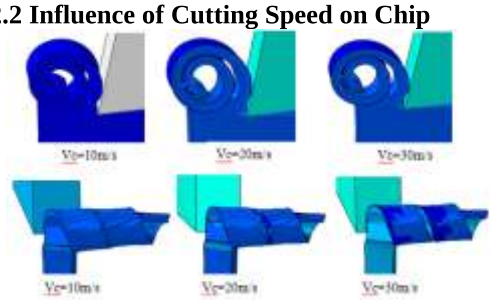


Fig.6 The status of chip which under the Different cutting speed

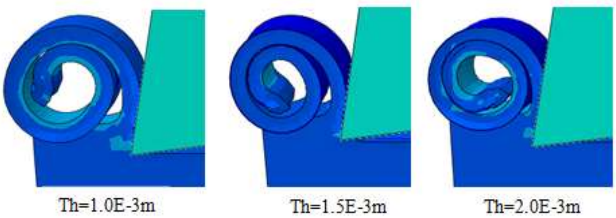


Fig.7 The status of chip which under the different Workpiece Thickness

In Fig.6,the experimental conditions are: ap=5E-4m, Th=1.5E-3m, Vc as the experimental variable,the variable Vc is 10,20,30 m/s.Cutting simulation model are as follows:The tool is a simplified model which the thickness is 0.0025m and the workpiece is a rectangular body which the length is 0.02m, the width is 0.01m and the thickness is 0.0015m.The inclination angle is 100 in the oblique cutting model.The radius of chip curling is basically consistent at different cutting speeds in the orthogonal and oblique cutting models.Thus the cutting speed has no obvious effect on the radius of chip curling.

3.2.3 Influence of Workpiece Thickness on Chip

In Fig.7,the experimental conditions are: ap=5E-4m, Vc=20m/s, Th as the experimental variable,the variable Vc is 1.0E-3,1.5E-3,2.0E-3m.Cutting simulation model are as follows:The tool is a simplified model which the thickness is 0.0025m and the workpiece is a rectangular body which the length is 0.02m, the width is 0.01m and the thickness is 0.0015m.From the previous two sections, the orthogonal cutting and oblique cutting have the same change rule, but the change of orthogonal cutting is obvious. Therefore, orthogonal cutting is used in this part.The bigger the magnitude of Th is, the smaller the radius of the chip curl is in the orthogonal cutting model.

IV. Conclusions

In this paper, the Johnson-Cook material constitutive models and damage laws were introduced and the three-dimensional orthogonal and oblique cutting models were established based on them.The trend of simulation chip bending curling is consistent with the experimental results by comparative analysis.The formation of chip curling radius was analyzed by the orthogonal cutting model.Then the Influence of cutting variables on chip were researched.Finally,obtained some results through analysis of numerical simulation experiment data, as follows:

(i)The trend of simulation chip bending curling is consistent with the experimental results.

(ii)Most of the heat generated during the cutting is carried away by the chip,while the work done by the tool is mainly used to overcome the plastic deformation of the chip in the process of chip curling.

(iii)The formation of chip curling is influenced by cutting variables(Vc,ap,Th),the cutting speed has no obvious effect on the radius of chip curling,the bigger the magnitude of ap is, the greater the radius of the chip curl,the bigger the magnitude of Th is, the smaller the radius of the chip curl.

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