International Journal of Research in Engineering and Science (IJRES)
ISSN (Online): 2320-9364, ISSN (Print): 2320-9356
www.ijres.org Volume 2 Issue 8 ǁ August. 2014 ǁ PP.57-62

Finite Element Simulation of Serrated Chip Formation in High Speed Cutting

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Abstract*: The description of high speed cutting process with simulation based on finite element method provides huge superiorities compared to analytical and experimental models. This work focused on the study of high speed cutting process with finite element method, using commercial software ABAQUS/Explicit. The chip morphology is predicted, and the stress, strain and temperature in the chip are all simulated vividly when cutting stably. The serrated chip formation is explained by the adiabatic shear theory. The results showed that it is better to use the adiabatic shear theory to explain the formation of serrated chip.*

Keywords-*High speed cutting, ABAQUS/Explcit, chip morphology, serrated chip formation*

I. Introduction

Metal cutting is always the most complicated machining process nowadays. For all kinds of metal cutting operations, though the basic mechanics are almost same, each case is considered different because of the complicity that depends on many geometry factors, material properties and some variables, and so on. With the development of high speed machining, its productivity and quality of machined surface are becoming increasing attractive to the researchers fro industrial developing [1]. But the distinct character is that the cutting force will decrease with cutting speed increasing, and then reaches to a relative plateau [2, 3].

For the complexity of the high speed cutting process, analytical and experimental analyses are maybe not suitable to study them. Thanks to the development of computer power and finite element method, simulations of cutting process with finite element method, using commercial software become more and more popular for researchers in the past twenty years [4-7]. Although the method is popular, it doesn't simulate the real cutting process completely because the mechanism of cutting process hasn't been grasped completely, and some models should be simplified, and then idealizations are necessary. The high speed cutting relates to a lot of parameters, such as strain hardening, rate-dependent hardening and thermal softening, and these main effects can be studied in the speed dependence of chip formation, which is still an advantage of this approach [8].

II. Numerical Simulation

The cutting process is simulated with a finite element model consisted of four parts shown in Fig.1. A thermo-mechanical coupled analysis is developed by using CPE4RT element type, which was plain strain quadrilateral, linearly interpolated, and thermally coupled elements with reduced integration and automatic hourglass control. Here, workpiece is fixed and cutting speed is applied to the tool, the rake angle is -10° and the clearance angle is 3°. The cutting velocity is 2400m/min, cutting depth is 2mm.

2.1 Model Assumptions

The metal cutting process is so complicated that the finite element model should be simplified and some assumptions established as well. The assumptions of finite element model are:

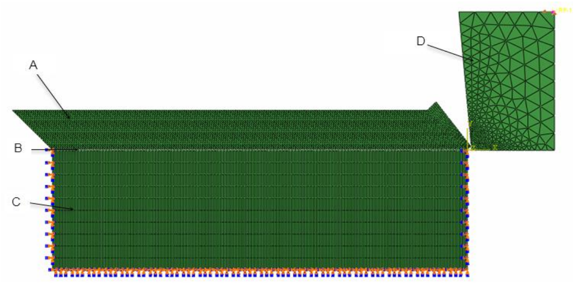
The cutting process is a process of plane stress-strain.

The workpiece material is isotropic.

The workpiece material accords with Von Mises yield criteria.

Tool, machine tool bed and fixture are all rigid in the cutting process.

The workpiece material is noncohesive, and its mechanical property has nothing to do with time and temperature.



A Undeformed chip B Line of separation

C Workpiece D tool

Fig.1 Finite element model

2.2 Material model of workpiece and tool

To simulate the high speed cutting process properly, it is necessary to introduce a classical model called J-C material model [9] to describe the material behavior that is usually presented with an equation (1) below. Material properties for the workpiece and tool are presented in the Table 1.

Table 1 Material properties of the workpiece and tool

Material properties	Workpiece	tool
Material	GH4169	Carbide tool
Young's modulus (GPa)	220	-
Poisson's ratio	0.3	-
Thermal conductivity, k(W m^{-1} °C^{-1})	13.53	46
Specific heat (J kg^{-1} °C^{-1})	203	20000
Thermal expansion coefficient (°C^{-1})	1.26×10^{-5}	4.7×10^{-6}

$$\sigma = \left(A + B\varepsilon^{n}\right)\left(1 + C\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\left(1 - \left(\frac{T - T_r}{T_m - T_r}\right)^{m}\right) \quad (1)$$

where σ is the equivalent flow stress, ε is the equivalent plastic strain, $\dot{\varepsilon}$ is the equivalent plastic strain rate, $\dot{\varepsilon}_0$ is the reference equivalent plastic strain, *T* is the workpiece temperature, T_{m} and T_{r} is the temperature of the material melting and room, respectively. *A*, *B*, *C*, *n* and *m* are constitutive constants. The material strain, strain rate hardening and the thermal softening phenomenon are taken into account in this J-C law.

2.3 Frictional Model

Whether the cutting simulation results are accuracy and reasonable, to a great extent, depends on the foundation of the frictional model, so it is important to choose a reasonable frictional model. Because of the inhomogeneous force on the rake face during cutting, the rake face can be divided into two workspaces, the sticking zone and the sliding zone, which is illustrated in Fig.2.

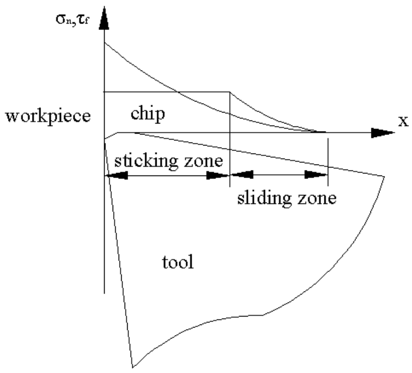


Fig.2. Curves representing normal and frictional stress distributions on the tool rake face

When considering machining simulations of GH4169, friction coefficient 0.1 is used. In this study, friction at the tool-chip interface is controlled by a Coulomb limited Tresca law which is expressed by the following relations:

$$\tau = \mu\sigma_n, \qquad if \quad \mu\sigma_n < \overline{m}\frac{\sigma_0}{\sqrt{3}} \qquad \text{（the sliding zone）} \tag{2a}$$

$$\tau = \overline{m}\frac{\sigma_0}{\sqrt{3}}, \qquad if \quad \mu\sigma_n > \overline{m}\frac{\sigma_0}{\sqrt{3}} \text{ (2b)} \qquad \text{(the sticking zone)} \tag{2b}$$

The shear stress (τ) is either expressed by the product of Coulomb friction coefficient (μ) with normal stress (σ_n) or by a fraction ($\overline{m}$) of permissible shear stress of the workpiece material.

2.4 Heat transfer model

In the finite element model, because of the influence of plastic deformation and friction at the tool-chip interface, heat generation is modeled as a volume heat flux [10]. Heat conduction is assumed to be the primary model of heat transfer, which occurs between the workpiece and tool. The equation of heat transfer is formula,(3) as follows:

$$\int_V \rho_m \dot{U} dV = \int_S q dS + \int_V \dot{Q} dV \tag{3}$$

where V is the volume of solid material with surface area S, $\dot{U}$ is the material time rate of internal thermal energy, ρ_m is the mass density, q is the heat flux per unit area of the body flowing into the body, and $\dot{Q}$ is the heat supplied externally into the body per unit volume.

III. Result and discussion

3.1 chip morphology and stress analysis

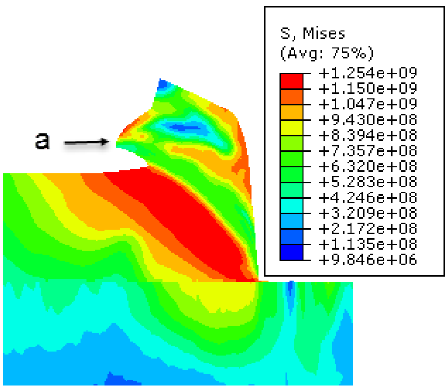
As shown in Fig.3a-3d, when serration *a* (Fig.3a) forms, the meshes attached to the shearing band in first formation zone distorts greatly. The stress in this region is the largest in the workpiece during the cutting process because of the distortion. As the tool advances, the serrated chip formation continues. The end of the second serrated chip formation (Fig.3b) is the beginning of the third (Fig.3c), and several adiabatic shearing bands can be found between the adjacent serrations as well as the little stress in them. Until the seventh serration ends, it can be found that the shapes of serration are regular, and there are clear adiabatic shearing bands between these sawteeth, and the shearing angles are almost same during serrated chip formation.

3.2 cutting force analysis

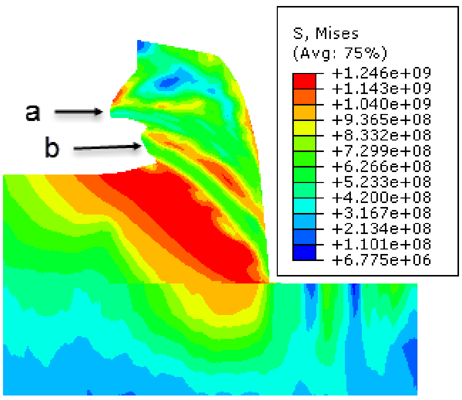
It can be seen in Fig.3e that cutting process fluctuates greatly and presents high frequency, periodically. It is hard to detect the change of cutting force by dynamometer because of the high frequency. The figure suggests that the mean value of cutting force is about 620N when cutting steadily. The point 1-7 points correspond to the serration a-g, indicate the value of these force when they forms. It also can be found that these forces are not equal because of the organization structure inner workpiece material and the vibration in cutting process.

3.3 Temperature and strain analysis

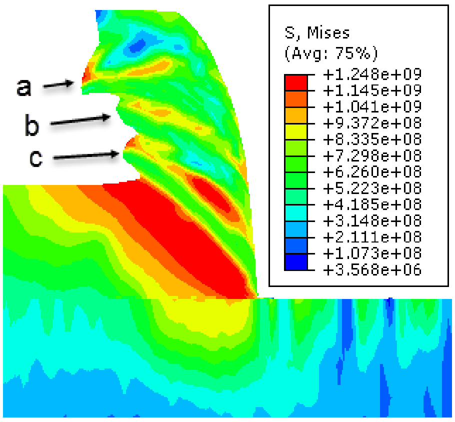
Fig. 2f suggests that the value of strain is highest in the primary shearing zone and the chip closed to tool rank face, which can also indicates that the temperature in these zones are also highest. But these regions have lower stress, which shows in Fig. 3c. Fig. 3g shows the distribution of temperature in serrated chip when cutting steadily. It can be seen in the figure that the high temperature zones include adiabatic shearing bandings (Ⅰ, Ⅱ, Ⅲ) and region in front of tool rank face besides primary shearing zone. And the adiabatic shearing band Ⅰ, Ⅱ, Ⅲ, which present high temperature, correspond to *A*, *B*, *C*, which is shown in Fig.3f, respectively. The highest temperature reaches to 1400° because of the high strain of metal material in primary shearing zone, and the temperature in adiabatic shearing band also reaches to a relatively high for the heat does not transfer out just in time. The high temperature zone in front of tool rank face is caused by friction between tool and chip and high strain which is also shown in Fig. 3f. It also can be found that temperatures of zones between the adiabatic shearing bands are not too much high, because their heat sources all come from the heat transition, but the time is too short.



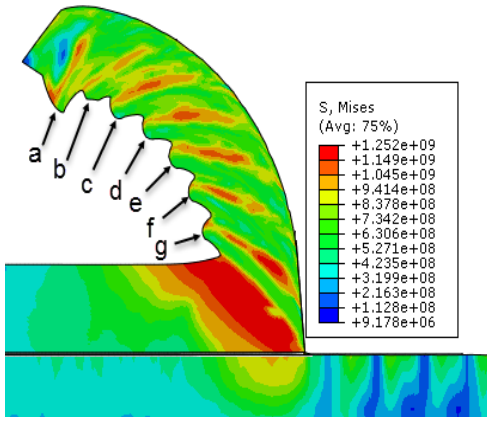
a) The formation of serration a



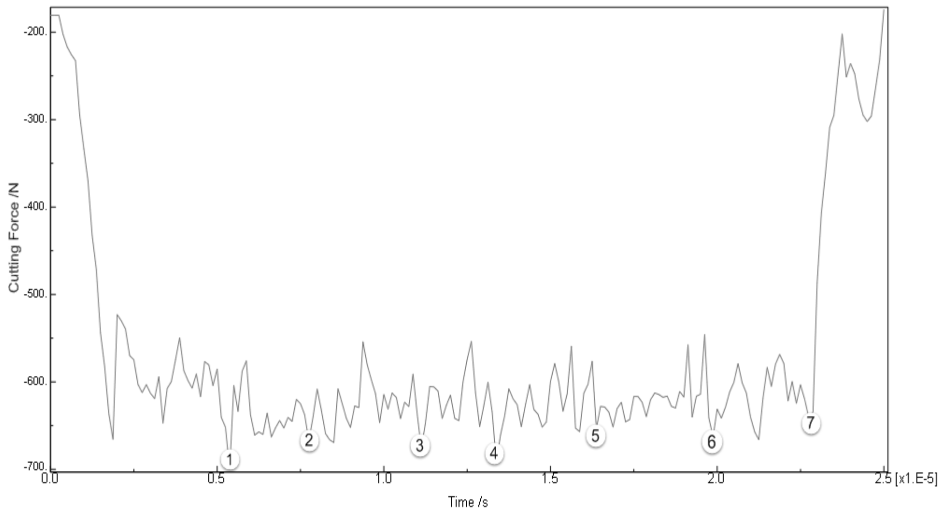
b) The formation of serration b



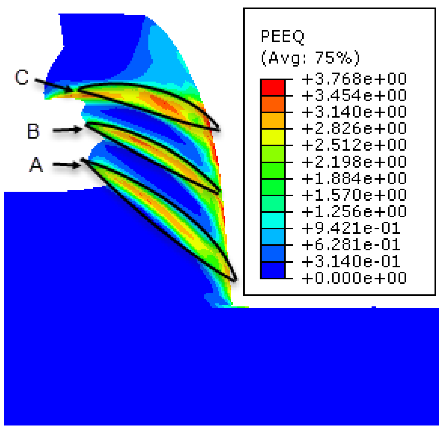
c) The formation of serration c



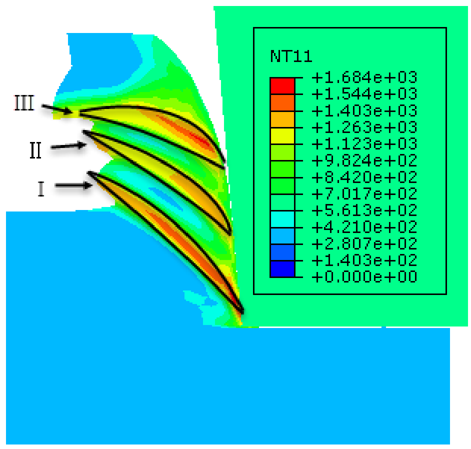
d) The end of cutting process



e) The cutting force in cutting process



f) The strain when serration c formed



g) The temperature distribution when serration c formed

Fig. 3. The simulation of high speed cutting process

IV. Conclusions

The formation of serrated chip is simulated in this paper with ABAQUS/Explicit, in a foundation of Finite Element Method (FEM), and obtained many useful data. This phenomenon can be explained by adiabatic shearing theory, and to some extent, get satisfactory conclusions. Extra works can be done to study the cutting feature with different tools and workpiece materials under different cutting conditions, to provide reference for tool designing or optimization of cutting parameters, for the purpose of optimizating the cutting process and least production cost.

V. Acknowledgements

The authors would like to thank the financial support from Scientific Research Innovation Fund of Shanghai University of Engineering Science (No. EI-0903-14-01004) and the school's lab conditions to this research.

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