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# A Study of the Effects of Friction Coefficient on Chip Formation Based on Hard Turning Thermo-mechanical Model

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**Abstract:** The hard turning of AISI 4340 is taken as an example. Firstly, thermo-mechanical coupled cutting model is set up with Abaqus/Explicit software. Then, different friction coefficient for chip formation is studied for the reason of crack and heat softening. Additionally, another increased strain energy release rate is studied with different friction coefficient. Finally, the result shows that the friction coefficient plays an important role in the formation of saw-tooth chip, especially when the strain energy release rate increases.

**Key Words:** Friction coefficient, Saw-tooth chip, Thermo-mechanical model, Hard turning, Strain energy release rate (SERR)

## 1 INTRODUCTION

Friction in metal cutting has been recognized as one of the most important and challenging tasks for researchers who are engaged in modeling of machining operations, so understanding of the friction coefficient in metal cutting is very important in selecting tool material, evaluating dimensional accuracy and surface integrity of the finished product, especially in automated production and high precision part manufacture.

At present, there are many articles concerning the friction model from different aspects. Xiaoping Yanga and C. Richard Liub[1] developed a new stress-based model of friction behaviour in machining and analyzed its significant impact on residual stresses computed by finite element method. Guoqin Shi et al[2], studied friction on thermo-mechanical quantities in a metal cutting process. However, few articles consider effects of friction coefficient on chips formation.

At the same time, in order to study the saw-tooth chip morphology, several different numerical methods were used to simulate segmented chips in 2D representations. These methods were based on different software packages[3,4], which used different damage models for the simulation of chip formation evolution with cutting time, such as the strain-based fracture criterion[5], the Johnson–Cook damage model [6], the energy based fracture criterion. Many researchers have used positive rake angles in order to simulate chips without difficulty. Nevertheless, negative rake angles are used in industrial machining cases to increase cutting edge strength and cutting life, the robustness of such numerical models is strongly dependent on thermo-mechanical parameters. Although there are many significant papers [7–8] presenting different methodologies adopted in studying saw-tooth chip formation, there are few papers considering strain energy release rate on chips morphology.

In this framework, a cutting simulation model is constructed to make a parametric study on friction for chip morphology, considers strain energy release rate and the

heat generating during chip formation. The application focuses on chips morphology resulting from the turning of hardened AISI 4340 steel treated at 47 HRC. The study is based on both adiabatic and coupled temperature displacement, and the negative rake angle is adapted in this model.

## 2 HYPOESIS AND SIMULATION SOFTWARE

The case of 2D coupled temperature and displacement orthogonal cutting model was developed with an explicit dynamic FEM software package, Abaqus/Explicit software [9]. The work piece's mechanical and thermal properties, contact conditions between the tool and the machined work pieces and boundary conditions were defined. Quadrilateral elements were used; CPE4RT for the coupled temperature displacement calculation. It is supposed that the value of feed is lower than that of cutting depth. Consequently, a plane strain assumption for elements of both work pieces and cutting tool is taken into account.

It is underlined that in the Abaqus/Explicit software, the coupled temperature displacement calculation has both displacements and temperatures as nodal variables. It seems important to improve the mesh aspect by adopting a mesh refinement technique in the concerned area, because machining is an extremely dynamic event with considerable changes in geometry.

The model mesh used during simulations is shown by Fig. 1, a representation of the studied orthogonal cutting model. The tool has the following geometrical angles: entering angle  $\chi=90^\circ$ , rake angle  $\gamma=-6^\circ$  and flank (or clearance) angle  $\alpha=5^\circ$ , considered as rigid body. Working parameters tested are feed  $f$  (0.1mm/rev) and cutting speed  $V_C$  (100 m/min). In the case of orthogonal cutting condition, feed corresponds to the material thickness which will be cut (Fig. 1). It is noted also that the cutting speed is affected at all tool-nodes during simulation, the mesh of tool is shown as Fig.1. The cutting operation is realized by the tool movement with a cutting speed  $V_C$ .

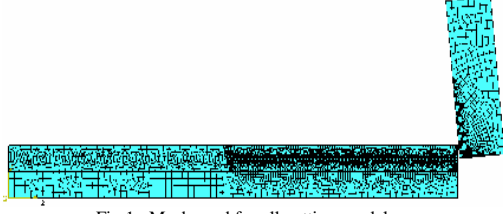


Fig 1. Mesh used for all cutting model

### 3 MODEL PARAMETER SETTING

#### 3.1 Material behaviour

For the material behaviour of the machined workpiece (AISI4340), a Johnson–Cook model [10] is used. This model is a strain-rate and temperature dependent viscous-plastic material model suitable for problems where strain rates vary over a large range (102 to 106 s<sup>-1</sup>), and where the temperature changes, due to plastic deformation caused by thermal softening. This model uses the following equivalent flow stress, as Eq. (1).

$$\bar{\sigma} = \underbrace{(A + B\bar{\epsilon}^n)}_{\text{Elastic-plastic term}} \underbrace{\left[ 1 + C \ln\left(\frac{\dot{\bar{\epsilon}}}{\dot{\bar{\epsilon}}_0}\right) \right]}_{\text{viscosity term}} \underbrace{\left[ 1 - \left( \frac{T - T_{room}}{T_{melt} - T_{room}} \right)^m \right]}_{\text{softening term}} \quad (1)$$

Where  $\bar{\sigma}$  is the equivalent stress,  $\bar{\epsilon}$  is the equivalent plastic strain,  $\dot{\bar{\epsilon}}$  is the plastic strain rate,  $\dot{\bar{\epsilon}}_0$  is the reference strain rate (1.0s<sup>-1</sup>),  $T_{room}$  is room temperature, and  $T_{melt}$  is the melting temperature.  $A$  is the initial yield stress (MPa),  $B$  is the hardening modulus,  $n$  is the work-hardening exponent,  $C$  the strain rate dependency coefficient (MPa), and  $m$  is the thermal softening coefficient. The Johnson–Cook parameter values and the physical properties of workpiece and cutting tool used to simulate the behavior of AISI 4340 workpiece are specified in T.Mabrouki's model [11].

#### 3.2 Chips separation criterion

In order to simulate the appearance of chip formation, a fracture damage model that evokes chip detachment behaviour was used. This is a separation criterion allowing tool tip movement. This fracture damage is modeled with Abaqus/ Explicit software, according to a cumulative damage law:

$$D = \sum \frac{\Delta \bar{\epsilon}}{\bar{\epsilon}_f} \quad (2)$$

Where  $\Delta \bar{\epsilon}$  is the increment of the equivalent plastic strain. According to the Johnson–Cook model, the cumulative strain  $\Delta \bar{\epsilon}_f$  is updated at every analysis increment and  $\bar{\epsilon}_f$  is the equivalent strain at failure and expressed as the following equation:

$$\bar{\epsilon}_f = \left[ D_1 + D_2 \exp\left(D_3 \frac{P}{\bar{\sigma}}\right) \right] \times \left[ 1 + D_4 \ln\left(\frac{\dot{\bar{\epsilon}}}{\dot{\bar{\epsilon}}_0}\right) \right] \times \left[ 1 + D_5 \left( \frac{T - T_{room}}{T_{melt} - T_{room}} \right) \right] \quad (3)$$

Where  $\bar{\epsilon}_f$  depends on the equivalent plastic strain rate  $\dot{\bar{\epsilon}}$ , the ratio  $\dot{\bar{\epsilon}} / \dot{\bar{\epsilon}}_0$ , the ratio of hydrostatic pressure to equivalent stress  $P / \bar{\sigma}$  and the temperature. It also depends on the damage constants ( $D_i$ ,  $1 \leq i \leq 5$ ), which are determined experimentally.

This shear failure model is used to carry out the chip detachment. It is based on the value of the equivalent plastic strain at element integration points; failure is assumed to occur when the damage parameter  $D$  exceeds 1.

In the proposed model, in order to save calculation time, this damage behaviour concerns only a zone of 0.26mm in width as shown in Fig.1 with refined mesh.

#### 3.3 The parameter of SERR in the model

The strain energy release rate is described as Eq. (4).

$$g = \frac{(1 - \mu^2) K^2}{E} \quad (4)$$

Where  $\mu$  is poisson's rate,  $E$  is elastic modulus,  $K$  is the stress intensity factor in crack. For AISI 4340, SERR,  $g$ , its value is 12.5 N/mm.

#### 3.4 Friction on the tool–chip interface

The study of tool-chip interaction in finite element simulation concerns force transmission at the interface, and thus determines surface integrity of a machined layer. The key issue is the variation of frictional and normal stress on the rake face. Experiment observations [8] have shown that there are two distinct regions on the rake face of the cutting tool, i.e., sticking and sliding regions: in the sliding region, a constant coefficient of friction,  $\mu$ , is assumed; whereas in the sticking region the equivalent shear stress limit,  $\bar{\tau}_{max}$ , is imposed. The friction stress,  $\tau_{fr}$  on the interface can therefore be expressed as:

$$\begin{aligned} \tau_{fr} &= \mu \sigma_n \quad \text{if } \tau_{fr} < \bar{\tau}_{max} \\ \tau_{fr} &= \bar{\tau}_{max} \quad \text{if } \tau_{fr} \geq \bar{\tau}_{max} \end{aligned} \quad (5)$$

In this study,  $\mu=0.2$  and  $\bar{\tau}_{max}=500\text{Mpa}$  are obtained from [11].

### 4. THE EFFECT OF DIFFERENT FRICTION COEFFICIENT ON CHIP MORPHOLOGY

In order to study the effect of different friction coefficient on chip morphology, the values of 0.205 and 0.206 are selected for the sensitivity of different friction, and the simulation results are as Fig.3 and Fig.4.

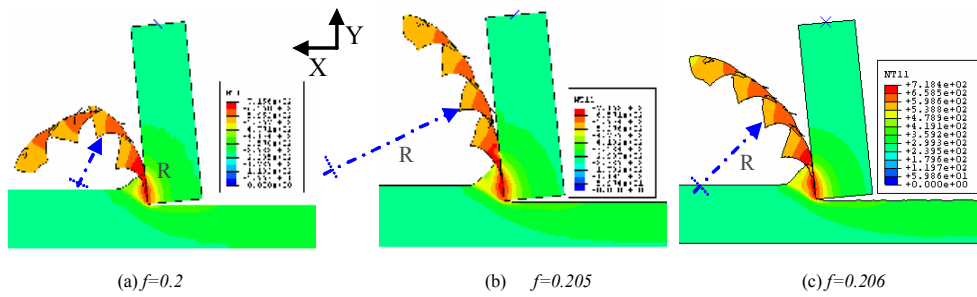


Fig 3. The temperature field analysis of different friction coefficient on chip morphology

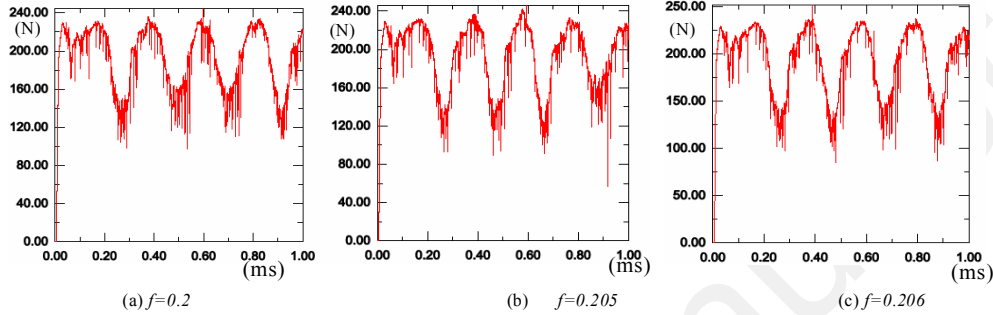


Fig 4. The contact force analysis of different friction coefficient on chip morphology

It is obviously that the chip in fig.3 (a) take on the serrated type with periodicity, and the corresponding cutting force curved line is shown in fig.4 (a): the contact force between tool and chip lies in the position of wave crest on the time of 0.2, 0.4, 0.6, 0.8, and 1ms, and lies in the position of wave hollow on the time of 0.3, 0.5, 0.7, 0.9ms, and the fluctuate period is 0.4ms. when the tool point locates in the middle of two serial serrated chip, the contact force is the least, lying in the position of wave hollow; by contrast, when the tool point locates in the middle of one serrated chip, just as the place in fig4 (a) (in the time of 1ms), the contact force is the largest, lying in the position of wave crest. The similar rule can be found in Fig.3 (b), and Fig.3(c) with Fig.4(b) , and Fig.4(c).

The reason of above phenomenon is that: during the process of cutting, the metal in the chip layer occur shear slippage and slip out towards the rake face, the tool and the metal in the chip layer keep in a certain dynamic balance. When the SERR is relatively little, the local strain energy in the uncut free face is easily to reach the critical SERR caused by the load, then the balance is broken ,therefore the cracks appear and changed with period.

As shown in Fig.3, the chip formation is seriously affected by the friction coefficient. The bending radius,  $R$ , increases from  $f=0.2$  to  $f=0.205$  and decreases form  $f=0.205$  to  $f=0.206$ , but the temperature keeps increasing with the increased friction coefficient (715.6k, 716.8k, 718.4k), this is the reason that the increased friction force in  $-Y$  direction prevents the chip from bending, so the  $R$  increases, but with

the increase of the  $f$ , the temperature in the chip increases, and the chip will be softened for the friction heat, thereby the heat reduces chip bending radius,  $R$ . The magnitude and distribution of stress in the chip and workpiece seems not change. The contact force changes with time by period, and the maximum value appears when  $f=0.206$  in the second wave crest, and the surface seems roughness compared with the former two conditions.

## 5. THE EFFECT OF DIFFERENT FRICTION COEFFICIENT FOR CHIP MORPHOLOGY CONSIDERING INCREASED SERR

As the train energy release rate directly influences the cutting process, and the material's crack. The value of SERR 13.2 N/mm is endowed in the cutting simulation, while keeping other parameters constant. Three conditions with different friction coefficients are analyzed. The coefficient of friction is very important to the chip formation, as Fig.5, it is obviously that the chip is still the flow chip when the friction coefficient is 0.2, but when the coefficient increases to 0.205, the chip becomes saw-chip for the increased SERR, which strengthen chip's critical crack energy. The cutting force curved line also varies with saw-chip, and the surface quality is not good, seems roughness, as can be seen from Fig5 (b). With the increase of the coefficient, the chip is still shown in the type of serrated chip, but the  $R$  decreases as the thermal

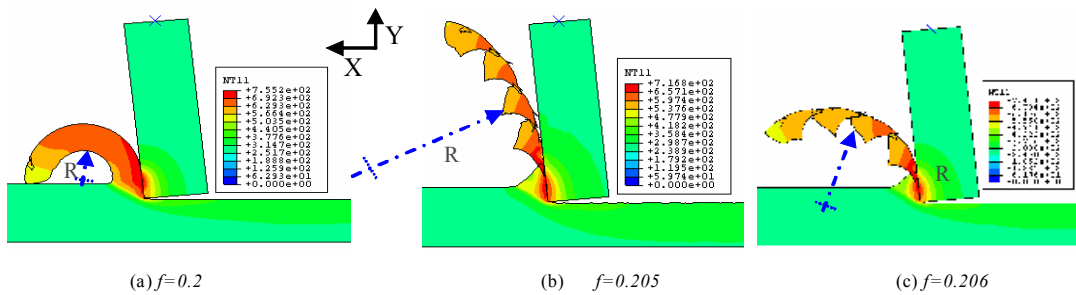


Fig 5. The temperature field analysis of different friction coefficient on chip morphology

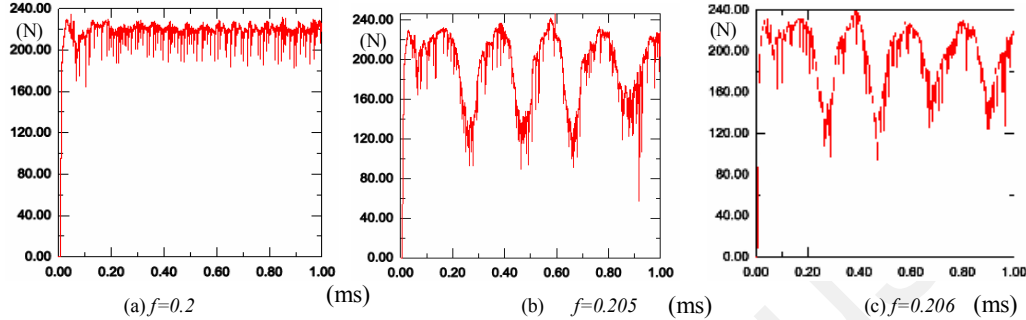


Fig 6. The contact force analysis of different friction coefficient on chip morphology

softening caused by increased friction coefficient, ( $t=741.1$  k when  $f=0.205$ , and  $t=716.8$  k when  $f=0.206$ ), and the

## 6. CONCLUSION

1. In order to study the hard turning of chip morphology theory, a thermal coupling cutting model is developed with Abaqus/Explicit software for the material of AISI4340 in this paper.
2. The chip morphology theory is studied in accordance with established cutting model, and the result shows that: serrated chip is due to low SERR which lead to chip's free surface producing mutational local shear crack. What's more, the bending radius,  $R$ , is seriously affected for the frictional force and produced heat, and the surface seems roughness with increase of friction coefficient.
3. Different SERR is considered in the simulation, the increased SERR (13.2N/mm) improves the material toughness, and the flow chip is formed. With the increase of friction coefficient ( $f=0.205$ ), the saw-tooth chips appear again, the bending radius,  $R$ , becomes small for the further increase of friction coefficient, as the heat soften phenomenon.
4. The effect of the friction coefficient for chip morphology and surface quality is very serious in the simulation study, so it should be careful to choose the machined material and the cutting tools for the precise machining.

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relation of force and time can well demonstrate the changed process as Fig.6.

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