

# Numerical Simulation of Chip Formation in Metal Cutting Process

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## Abstrak

Untuk mempelajari mekanisme pembentukan kepingan dalam proses pemotongan logam berdasarkan perangkat lunak ABAQUS untuk metode elemen hingga, telah dibangun model elemen hingganya, dan telah dilakukan simulasi numerik saat pembentukan kepingan bergerigi berbahan Ni-basa superalloy GH4169 dan pembentukan kepingan berbentuk pita baja 45 # . Selain itu, analisis telah dilakukan dengan memperhatikan pengaruh tiga faktor (kecepatan potong, percepatan pemberian bahan baku, kedalaman pemotongan latar) pada gaya pemotongan dan aturan distribusi pemotongan panas untuk pembentukan kepingan bergerigi GH4169.

**Kata kunci:** ABAQUS, kekuatan pemotongan, kepingan berbentuk pita, kepingan bergerigi, pemotongan panas

## Abstract

In order to study the chip formation mechanism in metal cutting process, based on finite element software ABAQUS, the paper established finite element model and carried out numerical simulation on serrated chip formation of Ni-base superalloy GH4169 and ribbon chip formation of 45# steel respectively. In addition, this paper also analyzed the influence law of three factors (cutting speed, feed rate, back cutting depth) on cutting force and the distribution rule of cutting heat in serrated chip formation of GH4169.

**Keywords:** ABAQUS, cutting force, cutting heat, ribbon chip, serrated chip

## 1. Introduction

The metal cutting process is a complex dynamic process, which is resulted by the interaction of workpiece and cutting tool. The traditional analytical method is difficult to carry out quantitative analysis and research on metal cutting mechanism. Besides, if take experiment study method, the experimental equipment is expensive and has a long life cycle, a large consumption of manpower and material resources, and a high comprehensive cost [1]. The cutting process simulation recreates the relative motion of workpiece and tool in the whole process in computer, dynamically displays the distribution of heat flow, phase change, temperature and stress, ect . It makes a breakthrough to defect of test and other ways, which becomes an effective method of cutting mechanism research [2, 3]. Based on finite element software ABAQUS, this paper established finite element model of Ni-base superalloy GH4169 and 45# steel and carried out research and analysis on cutting force and cutting heat respectively in the formation process.

## 2. Serrated chip formation simulation of Ni-base superalloy GH4169

### 2.1 Orthogonal cutting finite element model and formation of Ni-base superalloy GH4169

In the metal cutting mechanism study, it usually use orthogonal cutting model to observe and study the numerous phenomenon in deformation area, and convert the actual cutting form to dual orthogonal right angle cutting process to consider [4]. GH4169 belong to Ni-base superalloy due to its good plasticity, great toughness, high strength under high temperature and inferior thermal conductivity. It becomes one of the difficult processing materials. Figure 1 shows the established finite element model of orthogonal cutting which is the workpiece and cutting

tool both adopt four nodes with simplified integral, displacement-temperature bilinear, and rectangle unit. The stress and strain nature of cutting analysis model is two-dimensional plane strain[5]. The cutting speed ranges from  $70\text{ m/min}$  to  $250\text{ m/min}$ .

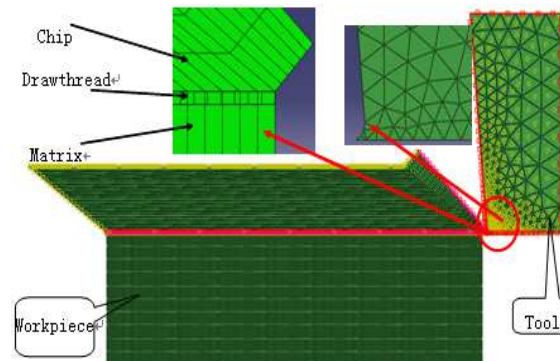


Figure 1. Orthogonal cutting finite element model of GH4169 material

Figure 2 describes the first chip formation process of serrated chip, which originates from generation and then develops until full formation.

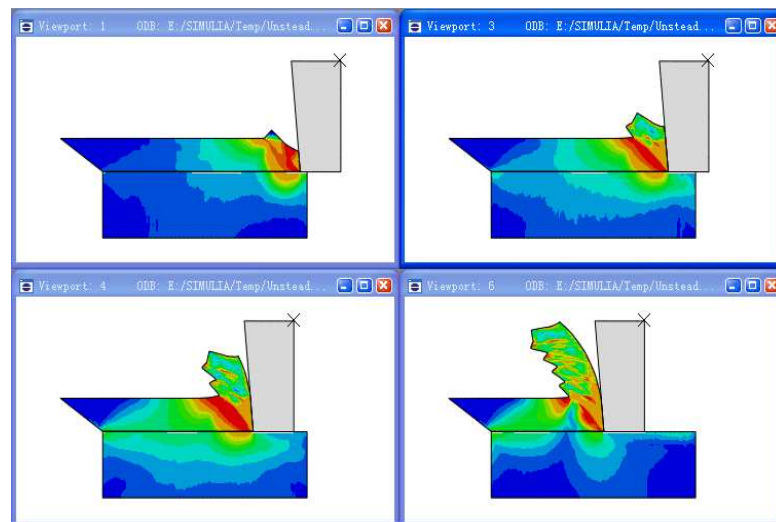


Figure 2. Serrated chip formation process of GH4169 material

### 3. Cutting analysis of Ni-base superalloy GH4169

#### 3.1 Chip shape change and analysis under different cutting velocity

Figure 3 is the serrated chip simulation Figure of GH4169 at different cutting speed. As can be seen, obvious serrated chip forms when cutting speed  $v$  reaches  $250\text{ m/min}$ , but when cutting speed is less than  $70\text{ m/min}$ , serrated chip is not obvious and it is basically successive ribbon chip [6,7]. It can be learned that the increase of cutting speed is beneficial for the serrated chip formation.

(a), (b) and (c) in Figure 4 is the cutting force simulation curve when cutting GH4169 at different velocity. As can be seen, during the process of cutting velocity reaches  $70\text{ m/min}$ ,

the main cutting force  $F_c$  changes from an instantaneous amplification to later period of relative stationary state. With the increase of cutting speed, the stable amplitude in later stage gradually transforms to periodic huge fluctuation, main cutting force  $F_c$  no longer changes stably, but exists regular inflexion, in addition, it can be seen from the comparison of (b) and (c) in Figure 4, the higher the cutting speed, the larger the periodic inflexion. This is because during the working piece material chip formation, as the cutting process before the material breaks up, the cutting force gradually increases, when the equivalent plastic strain value reaches the setted value of fracture criterion, the material gradually breaks up, and the cutting force rapidly decreases to nearly zero [8]. When new chip forms, the cutting force gradually increases. With the chip formation, the cutting force ceasesly repeats the process from increase to decrease and so on.

Besides, it can be seen from comparison of main cutting force curve change in Figure 4, in the high speed cutting of superalloy GH4169, the main cutting force  $F_c$  presents a decreasing trend with the increase of cutting speed, the high speed cutting of superalloy produces high cutting temperature, thus leads to the reduction of material strength, shear strength, hardness and friction force of chip interface, so the cutting force decreases [9]. The decrease of cutting force is beneficial for the reduction of process deformation, which is one of the reasons for application and dissemination of high speed cutting technology in aviation thin-wall parts processing.

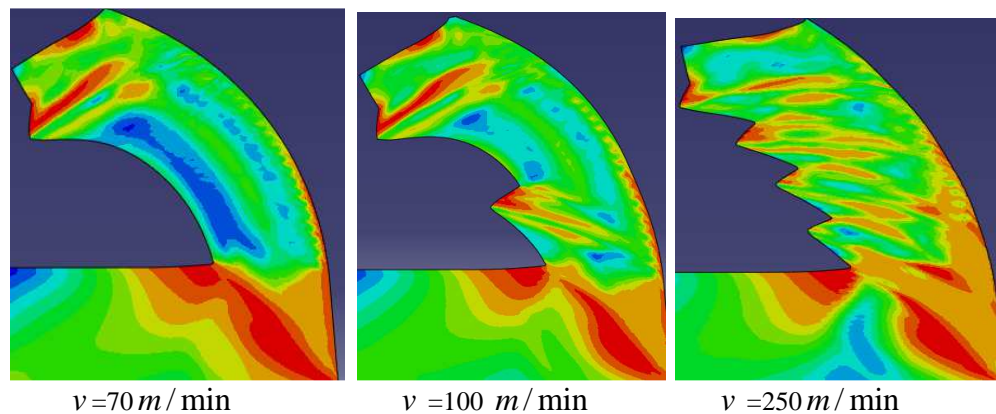


Figure 3. Serrated chip Figure of GH4169 at different cutting velocity

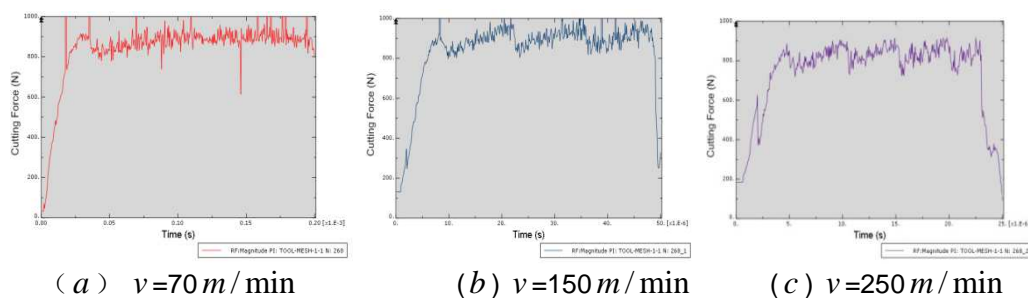


Figure 4. Main cutting force change with time of GH4169 at different cutting velocity

### 3.2 Cutting force analysis of Ni-base superalloy GH4169

As shown in Figure 5, the serration piece I and adiabatic shear belt I form at  $0.0224 \text{ ms}$ , and the shear stress with lowest state makes the cutting force value at this time be the low ebb at the domain curve of cutting force.  $0.0224 \text{ ms} \sim 0.0292 \text{ ms}$  is the most important stage when the serration piece II forms. As the forming velocity exceeds heat transfer velocity, the

high temperature of adiabatic shear belt can hardly effect the serration piece II, in Figure 4, a continue rising of cutting force can be seen at I stage.  $0.0292\text{ ms} \sim 0.0348\text{ ms}$  is the most important stage when the adiabatic shear belt corresponds to the II stage of cutting force curve in Figure 6, and the cutting force value basically remain at 625 N or so. At stage III, the adiabatic shear continue occur, whereas the serration piece II no longer deforms. Therefore, the cutting force keeps a downward trend.

From the analysis above, it can be concluded that stage II and III is main stage when adiabatic shear phenomenon occurs.

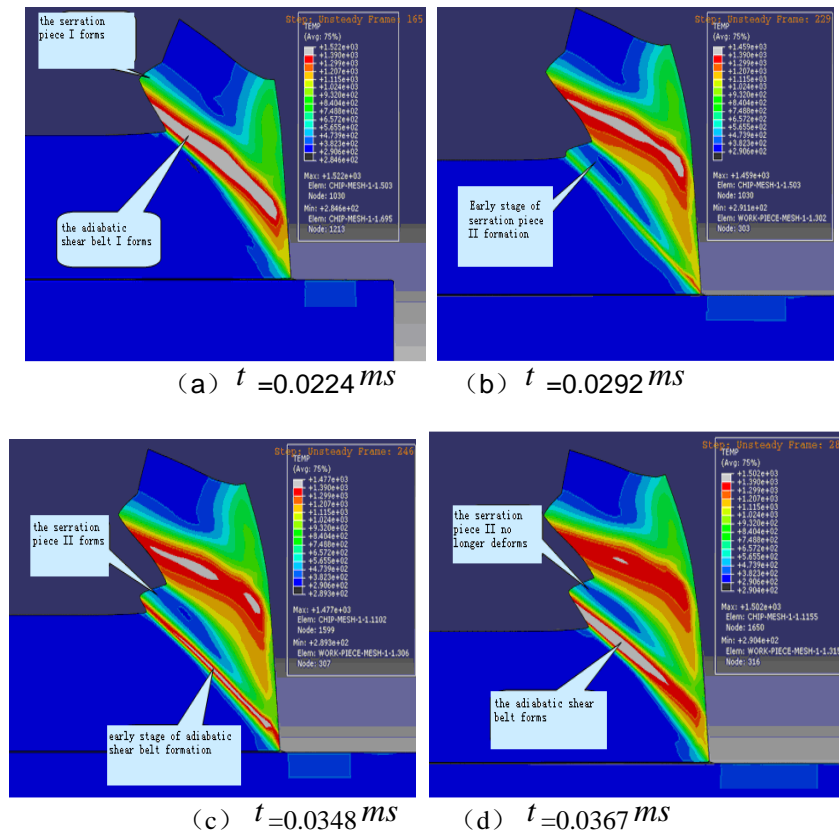


Figure 5. The change nephogram of serration piece and shear belt of serrated chip

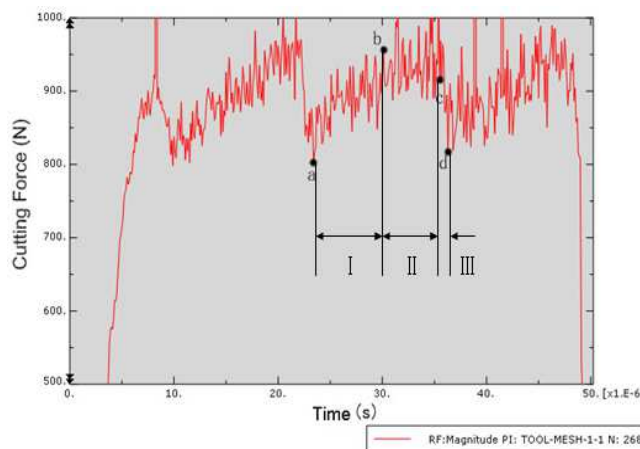


Figure 6. Time domain curve of the main cutting force

### 3.3 Cutting Heat Analysis of Ni-base Superalloy GH4169

Figure 7 is the temperature distribution nephogram of serrated chip when cutting velocity reaches  $150\text{ m/min}$ , the four points  $P_2$ ,  $P_3$ ,  $P_4$  and  $P_5$  located at the free surface, the center of prediction shear area and nearby the tool nose point, and the three points  $P_1$ ,  $P_6$  and  $P_7$  located on the upper surface in the early stage of three serration piece.

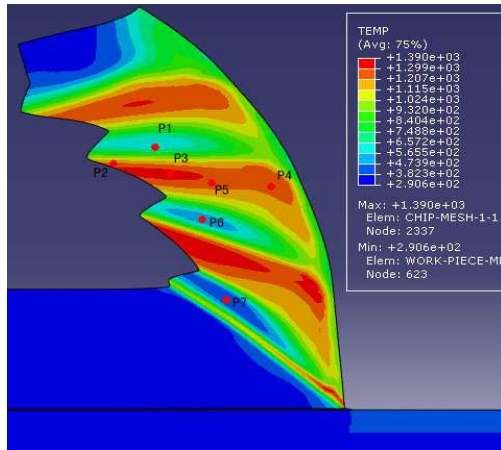


Figure 7. The temperature distribution nephogram of serrated chip

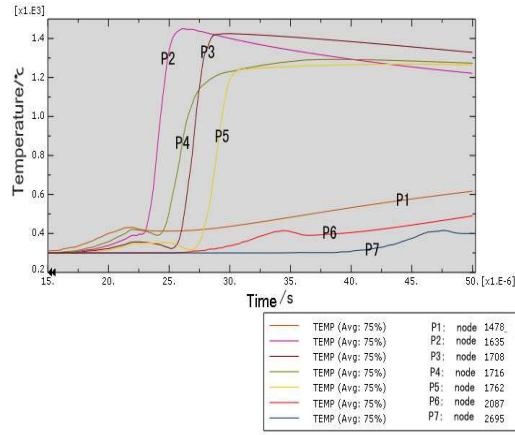


Figure 8 The temperature variation with time

The curve in Figure 8 records temperature changes of the six points shown in Figure 7. It can be seen that, within this time period, the temperature rising of  $P_2$ ,  $P_3$ ,  $P_4$  and  $P_5$  all exceeds  $700\text{ }^\circ\text{C}$ , but the temperature of  $P_1$ ,  $P_6$  and  $P_7$  increases the curve and the temperature rising is only  $100\text{ }^\circ\text{C} \sim 300\text{ }^\circ\text{C}$ . The comparison illustrate that the temperature rising occurs within a narrow ribbon area. The temperature rising only occurs within a short time period from  $0.0025\text{ ms}$  to  $0.005\text{ ms}$ , which is the most obvious feature of the adiabatic shear phenomenon. Owing to the periodic thermoplastic instability, the serrated chip form emerges.

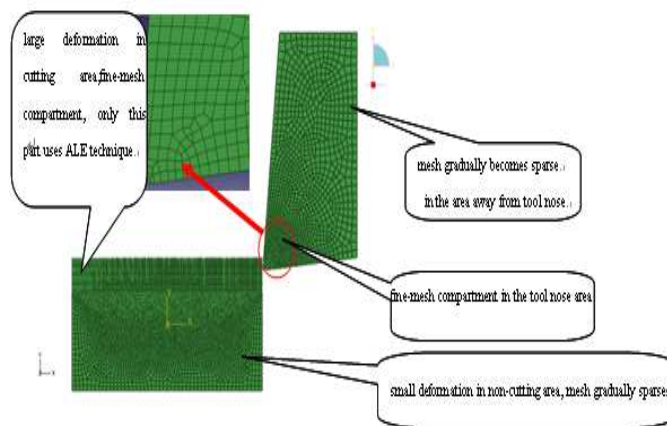


Figure 9. Orthogonal cutting process simulation of 45# steel

## 4. Ribbon chip formation simulation of 45# steel

### 4.1 Orthogonal cutting finite element model and formation of 45# steel

As is shown in Figure 9, in this model, 45# steel workpiece is a rectangle with a certain thickness, and the grid unit uses 4 node linear shrinkage integral plane strain unit [10]. When

conduct cutting simulation, Set workpiece a relative motion towards the tool along X direction, and Y direction is fixed. The tool cuts in workpiece from the initial position, and the chip constantly forms with the tool cutting in.

In Figure 10, the four state Figures (a), (b), (c) and (d) display the formation process of ribbon chip, which can be separated into four stages: tool collision, cutting in, forming and steady-state forming.

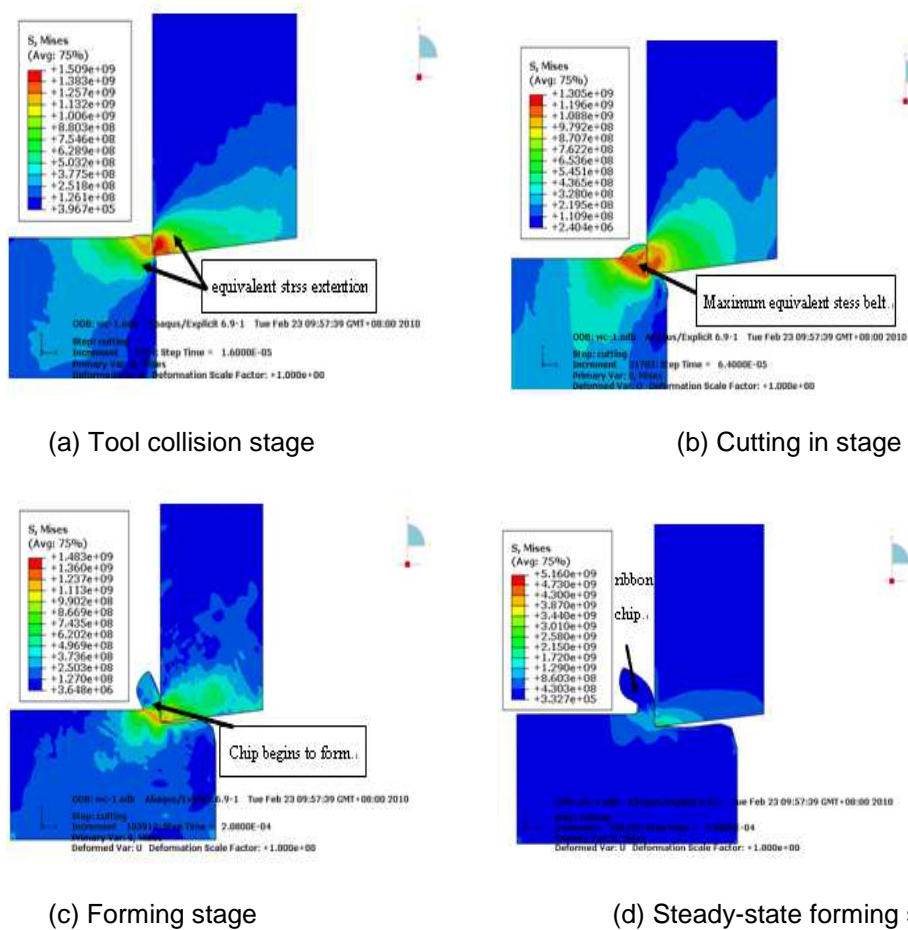


Figure 10. 45# steel chip formation process

4.2 Cutting force analysis of 45# steel

Cutting force varies when every single factor of the three factors cutting speed, feed rate and back cutting depth changes, and all of the cutting force curve have a common feature. It increases dramatically within a transient time period in early stage, then drops slightly, and finally fluctuates around a certain level. Collect the average value of different curves at steady state to obtain Table 1.

Table 1. Collect the average value of different curves at steady state

Cutting velocity $v_c / m \cdot \text{min}^{-1}$	Feed rate $f / \text{mm} \cdot r^{-1}$	Back cutting depth $a_p / \text{mm}$	Cutting force $F_c / N$
200			268.97
400	0.12	0.8	280.48
600			275.14
800.00	0.30	0.80	527.37
	0.50		754.13
800.00	0.12	0.50	175.04
		1.00	349.12

It can be seen that the variation law of cutting force along with cutting velocity is first increases, and then tends to decrease. It can be accounted that under a relative low velocity condition, the material hardening effects in the ascendant, so the cutting force increases. Besides, under a high velocity condition, the temperature of cutting shear area increases, and the material yield limit decreases, so the cutting force decreases.

## 5. Conclusion

This paper is establish the unsteady high-speed cutting machining finite element model of GH4169 based on ABAQUS software and obtain dynamic simulation result of serrated chip formation. This paper also analyzed the cutting force fluctuation and temperature variation at different serrated chip area, thus obtaining adiabatic shear phenomenon is just the cause of serrated chip formation.

Establish the finite element model of 45# steel based on ABAQUS software, and obtain dynamic simulation result of ribbon chip formation. Analyze the universal law of the three factors cutting speed, feed rate and back cutting depth effect on cutting force, and learn that back cutting depth has the maximum influence on cutting force, and cutting speed has the minimum influence on cutting force.

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