Effect of Inertial on the Adiabatic Shear Instability: Numerical Analysis

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Abstract. Adiabatic shear instability, as a common plastic instability model of metal materials, has attracted more and more attention. In the process of metal cutting, adiabatic shear instability is observed in the chip with different cutting speed. The plastic instability of the chip usually has two effects: one is the quality of the machined parts, and the other is the fatigue service life of the machined tool. These two factors are usually determined by the parameters of the tool (front corner, back corner), the processing parameters (cutting thickness and cutting speed) and other conditions. In order to improve the machining efficiency, the main way is to raise the cutting speed under the condition that the tool parameters are fixed. With the continuous increase of cutting speed, the inertial effect will become stronger and stronger. By means of commercial finite element software Abaqus/Explicit, this paper analyzes the variation of metal cutting morphology, the fluctuation law of cutting force, the change trend of average cutting force, and the role of inertia effect in different machining speed ranges.

1. Introduction
Cutting is a continuous process in which the materials of the processing components are removed by cutting to obtain the desired geometric shape. After the cutting process, the chips and the required workpieces are usually left behind. Although the chip cutting is not desired during the processing process, previous studies showed the morphology of the chip cutting often provides important information for the study of cutting [1-2]. For example, the tool fatigue life and the surface roughness of the workpiece are directly related to the morphology of the chip. In the case of sawtooth-like chips, the tool will bear periodic vibrations, which usually seriously affect the fatigue life of the tool and the surface roughness of the machined workpiece. Under continuous cutting conditions, the above situation will not occur, and the life of the tool and the quality of the machined workpiece will also be correspondingly improved [3-4]. In this way, there will be such a contradiction: that is, processing efficiency, processing quality and tool life cannot be obtained simultaneously. But is it possible to raise the efficiency and quality of the workpiece and the life of the tool? This paper does some such research by numerical simulation.

As the statement above, the efficiency, quality and service life of the cutter can be directly reacted by the morphology of the cutter. Many factors, such as the front angle, back angle, cutting thickness, material of the workpiece and cutting speed will affect the shape of the chip. In this work, we mainly study the inertia effect on the adiabatic shear stability. Previous studies have shown that [1-2] The
adiabatic shear stability of cutting is determined by the competitive relationship between machining hardening and thermal softening; At low speeds, the thermal softening is weaker than the work hardening, the cutting is stable and the chip is continuous; After a certain speed, thermal softening will become the main factor, and adiabatic shear instability will occur at this cutting speed. However, when the speed keeps rising, the inertial effect will become prominent. Limited by the experimental conditions, the inertia effect on machining efficiency, machining quality and tool fatigue life is studied by means of numerical simulation.

2. Numerical Model
The cutting process is recognized as a complex dynamic physical process, involving not only elastic mechanics, plastic mechanics, fracture mechanics, but also the intersection of thermodynamics and tribology. It is difficult to analyze and study the cutting mechanism quantitatively by traditional analytical method. Numerical simulation calculation methods, especially finite element calculations, are considered as an effective method to predict the stress field, strain field, residual stress, and temperature field in workpieces and tools during cutting reliably, as well as the macroscopic state of the chip shape, tool force and tool wear and other parameters. The numerical model used in this paper has been experimentally verified [5]. The undeformed chip is designed as a parallelogram, so that the deformed chip can climb upwards along the front blade surface without mesh distortion in the case of negative front angles. The adiabatic shear phenomenon generally occurs in narrower areas. Therefore, in order to depict the phenomenon of local large deformation within adiabatic shear instability zone, a very refined grid is required. In general, the linear size of the grid that can simulate adiabatic shear should be at least 10 μm, where a grid of 8 μm in length and width is used. The effective front angle and the effective rear angle are -5 ° and 0 °, respectively. At the same time, the tool is set to a rigid body model [5], the numerical model is shown in Figure 1:

![Figure 1 the Numerical Simulation Model Used in This Paper](image)

The Johnson-Cook constitutive model is used in numerical calculation [1]. This model has taken work hardening/strain hardening, strain rate hardening and thermal softening into consideration. The form is simple and suitable for description of metal materials plastic deformation, which leads to its widely application. Its specific form is shown in Eq. (1):

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

(1)

The material parameters used in the numerical simulation are depicted in Table 1[7]:

| A(MPa) | B(MPa) | C | m | n |
|--------|--------|---|---|---|
| 450    | 1700   | 0.017 | 1.3 | 0.65 |
| T_r(K) | T_m(K) | k (S^{-1}) | c_p (J/kg.℃) | α(K^{-1}) |
| 300    | 1570   | 0.001 | 203 | 1.25e-6 |
The Coulomb friction model is used in numerical simulation for the relationship between tool and chip with constant 0.3 [5]. A plastic separation zone between the chip and the workpiece is established. If the equivalent plastic strain of the separation zone is up to 2, the chip and the workpiece will be separated.

The results shown in Figure 2 and Figure 3 demonstrate the validation of finite element model employed in this work by experimental results. The front angle of the tool is 95 degrees, the back angle of the tool is 0 degrees, the cutting thickness is 1.0 mm, and the feed rate is 0.15 mm/rev. [1]. At the same time, two parameters are introduced to characterize the cutting process, the definition of which is shown in Figure 2 and Eq. (2):

\[ G_s = \frac{(h_1 - h_2)}{h_1} \]  

(2)

Figure 2 the Parameters Used in the Simulation [5]

Figure 3 Comparison of Various Parameters between Experiments and Numerical Simulations [5]

3. Chip Morphology At Different Cutting Speed Stages

Before the study of adiabatic shear instability, some definitions of physical quantities in the work need to be made. The first is work hardening, which is usually defined as (3)

\[ Q = \frac{\partial \sigma}{\partial \varepsilon} = nB\varepsilon^{n-1} \left[ 1 + C \ln \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right] (1 - T^m) \]

(3)

Another quantity that needs to be defined is the thermal softening factor, which is defined as (4)

\[ P = \frac{\partial \sigma}{\partial T} = -\left( \frac{m}{T_m - T} \right) \left( A + B\varepsilon^m \right) \left[ 1 + C \ln \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right] (1 - T^m) \]

(4)

According to Bai criterion [2], the condition for adiabatic shear instability of metal material is:

\[ K \sigma P / \rho c^2 Q > 1 \]

(5)

Bai criterion in Eq. (5) shows that when the thermal softening prevails over the work hardening, adiabatic shear plastic instability (ASB) occurs within the material. Metal cutting instability, as an adiabatic shear plastic instability, also follows the instability criterion presented in Eq. (5). However, Bai criterion has not demonstrated the role of inertia in metal cutting stability, which leads to the authors of this work to do some numerical calculation to depict the inertial effect on the adiabatic shear instability.

As for the metal cutting, it can be found that the length of the adiabatic shear instability zone \( L \) has
direct relation among the density of the material, the constitutive parameters of the material $A, B, C, m, n, T_m, T_r, c_p, K, E, \nu, \rho, \alpha, \beta, \varphi, \dot{\varepsilon}_0$, the front angle of the tool $\varphi$, the back angle of the tool $\beta$, the thickness of the chip $h$, The cutting speed $U$, and the time $t$. The relationship between the length of the adiabatic shear instability zone $L$ and other variables can be written as

$$L = f \left( A, B, C, m, n, T_m, T_r, c_p, K, E, \nu, \rho, \alpha, \beta, \varphi, t, h, U, \dot{\varepsilon}_0 \right)$$

(6)

When parameters such as processing materials, tools, and cutting thickness are selected, the Vashy-Buckingham theorem can be used to rewrite Eq. (6)

$$\frac{L}{h} = f \left( R_{inertial} = \frac{\rho U^2}{A}, \ldots \right)$$

(7)

As presented in Eq. (7), it can be seen that when the speed increases, the inertia effect will be highlighted. In this paper, the numerical simulation will be used to study the role of inertial effect on the adiabatic shear instability of metal cutting.

The results presented in figure 4 are different snapshots of equivalent plastic strain when the speeds are at 0.5 m/s, 1.5 m/s, and 2.5 m/s, respectively. As presented by Figure 4, inertial effect is weak results from the fact that the speed is low, the chip is continuous and no plastic instability occurs in the cutting; The increase of equivalent plastic strain is mainly concentrated in the main shear region, that is, the plastic deformation mainly occurs in this region. The results show that at low speed, the machining hardening takes the leading role, and the cutting will not produce plastic instability.

![Figure 4](image1.png)

**Figure 4** The Snapshots Of Peq At the Cutting Speeds of 0.5 m/s, 1.5 m/s, 2.5 m/s

The results presented in figure 5 are different snapshots of equivalent plastic strain at cutting speeds of 4 m/s, 10 m/s, and 30 m/s, respectively; As presented by Figure 5, the continuous chips has transformed from the continuous chip to the sawtooth-like chip, which means that adiabatic shear instability occurs when the cutting speed increases from a low speed to a certain value. At this time, the thermal effect has exceeded the work hardening. At this stage, the adiabatic shear zone can arrive at the free surface of the chip and form a sawtooth-like chip. And with the continuous rise of the speed, the previlige of thermal softening will become more obvious, as demonstrated in Figure 6.

![Figure 5](image2.png)

**Figure 5** The Snapshots Of Peq At the Cutting Speeds of 4 m/s, 10 m/s, 30 m/s
When the cutting speed increases further and up to a certain value, the inertial effect will be significant. Inertial effect will delay the time of adiabatic shear instability zone to spread from the separated surface of the cutting to the free surface of the chip, and reduce the effect of thermal softening on adiabatic shear instability. Fig. 7 shows the snapshots of the morphology and equivalent plastic strain of the chips at cutting speeds of 150m/s, 170m/s, and 190m/s, respectively. Comparing Figure 7 and Figure 6, this phenomenon can be more clearly observed.

If the speed continues to increase, the inertial effect becomes more and more obvious and dominates the plastic deformation. This will result in the fact that the adiabatic shear instability zone cannot propagate from the separated surface to the free surface of chip, as presented in Figure 8. The larger of the speed, the shorter the length of the adiabatic shear instability zone. And the adiabatic shear instability zone will be limited within a thin layer of the separate surface. At this stage, the sawtooth-like chip will not form. The higher the cutting speed, the stronger the inertia effect. Because of the fatigue life of the cutter and the surface quality of the workpiece are mainly determined by the periodic adiabatic shear instability of chip, cutting at ultra-high speed can weaken this vibration and greatly improve the processing efficiency. It provides a bright prospect for the development of high-speed processing. However, due to the limitations of experimental conditions, there are many aspects that require further experimental validations.

In summary, the stability of cutting is dominated by different factors at different speed stages. At the low speed stage, the work hardening plays a dominant role, and its effect is greater than the thermal softening. At this stage, the chip is continuous and adiabatic shear instability will not occur. When the speed reaches a certain value, the effect of thermal softening is greater than that of work
hardening. At this stage, sawtooth-like chip will be observed and adiabatic shear instability will happen. If the cutting speed keeps rising, the inertia effect begins to play an important part in the plastic deformation. If the speed is large enough, the adiabatic shear instability zone cannot arrive at the free surface of the chip. The following section will explore the effect of inertia on the cutting force at different cutting speeds to illustrate the influence of inertia on tool fatigue life.

4. Cutting Force At Different Stages
As statement above, the life of the tool is closely related to chip morphology. This section will demonstrate the effect of inertia on cutting force at different cutting speeds to illustrate the influence of cutting speed on the tool fatigue life.

Figure 9 Cutting Force Of the Tool At Different Speed
To explore the effect of inertia on tool life at different speeds, we illustrate the tool cutting force fluctuation during the cutting process, as shown in Figure 9. As shown in Figure 4 and Figure 9 (a), if the speed is at 1.5 m/s, the chip morphology is continuous and fluctuation of cutting force cannot be observed. When the cutting speed is 25 m/s, it can be seen from Figure 6 that, under this condition, the cutting is unstable and the chip will transform from continuous chip to the sawtooth-like one. And obvious fluctuation of the cutting force can be observed. In order to present a comprehensive depiction of the inertial effects on the fluctuation of cutting force over the wide cutting speed range, the variation of cutting force at different cutting speed is measured separately, as depicted in Table 2 and Figure 10.

Table 2 Fluctuation of Cutting Force At Different Cutting Speeds

| Speed(m/s) | 1.5 | 10 | 25 | 50 | 80 | 100 | 170 | 190 | 210 | 290 | 360 |
|------------|-----|----|----|----|----|-----|-----|-----|-----|-----|-----|
| ΔF(N)      | 0   | 15 | 125| 175| 210| 250 | 280 | 300 | 270 | 250 | 200 |

Figure 10 Fluctuation Value of Cutting Force At Different Cutting Speeds

It can be seen from Table 2 and Figure 10, when the speed is at 1.5 m/s, the plastic deformation is stable, the chips are continuous, and the force fluctuation is 0. This is because the work hardening is greater than the thermal softening and the inertial effect is weak. The tool will not bear vibration. Under this condition, the tool has the longest fatigue life. With the rise of speed, the chip morphology has transformed from the stable one to the unstable one. The fluctuation value of cutting force has also increased, and the vibration intensity of the tool has also been increased. The fatigue life of tool will also be more and more threatened. Within this speed stage, thermal softening plays a dominant role. If the cutting speed further increased to about 200 m/s, the inertial effect began to dominate the plastic deformation process. Within this stage, the length of the adiabatic instability zone decreases with the rise of the speed, the fluctuation value force also decreases, and the vibration intensity of the tool becomes less and less. This is beneficial to the fatigue life of tool, but can also improve the processing efficiency. Within the ultra-high speed stage, although it can increase the tool fatigue life, it will also raise the force of the tool. Therefore, within this speed range, it is necessary to raise the static strength of the tool material, as depicted in Figure 11.
5. Conclusions
In this paper, the effect of inertial on the adiabatic shear instability during metal cutting has been explored through commercial software ABAQUS/Explicit. At the same time, a comprehensive depiction of the variation of cutting force and chip morphology within different speed stages have been demonstrated. The results show that, within the low speed stage, the work hardening is the dominant factor. The chip morphology is continuous without the occurrence of plastic instability, and the fluctuation value of the cutting force is 0, which means that the fatigue life of the tool is almost unaffected by the inertial effect.

Within the middle and high-speed stage, thermal softening dominates the plastic deformation, and the chip morphology will transform from the continuous one to sawtooth-like one. During this speed stage, obvious plastic instability can be observed, and the vibration intensity of the tool increases with the rise of the speed. The fatigue life of tool is will be increasingly threatened.

Within the ultra-high speed stage, because of inertia effect, the adiabatic shear instability zone will not have enough time to propagate from the separated surface to the free surface of the chip, and no sawtooth-like chip can be observed; And the higher the speed, the shorter the length of the adiabatic shear instability zone; If the cutting speed can be up to a certain value, a thin layer with high temperature will only form on the contact surface of the tool and the chip. What’s more, the fluctuation value of the cutting force of the tool decreases with the rise of the cutting speed. It is beneficial to improve tool fatigue life and machining efficiency. At the same time, it will increase cutting force of the tool.

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