Dynamic behaviour and formation mechanism of shear band during high speed cutting Inconel 718

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Research Article

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Dynamic behaviour and formation mechanism of shear band during high speed cutting Inconel 718

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Abstract: In this paper, the shear zone storage energy model and strain gradient theory were compiled into a subroutine for secondary development to implement multi-scale finite element simulations. The shear zone storage energy was analyzed based on the variation of stress, temperature, and overall dislocation density. The plastic deformation behavior occurred in cutting was analyzed by combining microscopic and macroscopic based on the change of storage energy in the shear zone. The dynamic recrystallization and periodic fracture theories were also correlated with the variation of shear zone storage energy to investigate the mechanism of adiabatic shear zone formation in depth. It was found that the overall dislocation density, stress and shear zone storage energy change in the same trend, and the temperature and shear zone storage energy change in the opposite trend. The proliferation and annihilation of dislocations affect the change of storage energy. The storage energy reaches a peak of 9.6704 KJ when the overall dislocation density increases to a critical value of $7.7664 \times 10^9$, during which the stress gradually increases to $1.920 \times 10^9$ Mpa. The local interaction between geometric dislocations and grain boundaries will contribute to the increase of stored dislocations due to local work hardening, which causes spontaneous deformation instability and thus the gradual formation of deformation zones. When the shear zone temperature reaches a peak of 886°C, the stress gradually decreases to $6.27 \times 10^8$ Mpa. The aggravation of the stress concentration phenomenon caused the workpiece to release a large amount of heat energy because it could not bear the excessive strain, and the resulting thermal softening effect caused the hardness to decrease. At the same time, dislocations accumulate and new dislocation sources in the vicinity were activated, which caused the overall dislocation density to start decreasing and the material to undergo local shear instability, thus leading to dynamic recrystallization and the formation of a phase transition zone at high temperature. The storage energy decreases to a trough value of 3.1555 KJ when the overall dislocation density decreases to $2.5342 \times 10^9$. Dynamic recrystallization happens at different stages due to the change of storage energy, and the rate of storage energy change will affect the nucleation rate of dynamic recrystallization and thus the rate of adiabatic shear zone formation.

Keywords: Inconel718; Storage energy of shear zone; Adiabatic shear mechanism; Multi-scale simulation

1. Introduction

As is known to all, cutting metal is a highly valuable activity, which can be used to obtain the desired shape of the product. During the cutting process, the material will undergo plastic deformation. The nickel-based alloy Inconel718 is widely used in aerospace industry due to its excellent properties. It is a kind of difficult-to-machine material. The internal micro-structure changes will be contribute to the macroscopic deformation of the material and the formation of chips, shear bands [1], etc. In the formation process,
Macroscopic and microscopic complex phenomena are involved. In order to obtain ideal machining quality, it is necessary to study the formation mechanism behind these complex phenomena.

For the mechanism of shear band formation, most scholars analyze it by experiments, simulations or by combining both. Joakim [2] conducted extensive experiments and learned that shear band is a form of failure and is associated with high strain rates. In the experiments, a thermal softening effect occurs when the temperature increases to a certain level, which in turn leads to the formation of an adiabatic shear zone [3], where the temperature in the adiabatic shear zone is several hundred degrees higher than the surrounding material, and the cooling rate is known to be approximately 10⁷ K/s according to the study [4-5]. Olasumboye and Owolabi [6] performed separated Hopkinson compression bar experiments on cylindrical specimens to analyze the microstructure of the material as well as the mechanical response to derive the potential location of the evolution of the adiabatic shear zone. The adiabatic shear zone will undergo transformation behavior such as deformation zone and transition zone [7] during the formation process, where the deformation zone is a single plastic deformation while the transition zone contains phase change. Gao and Hao [8] combined cutting experiments, Hopkinson compression bar experiments and finite element simulations to analyze the formation mechanism of the adiabatic shear zone. Recht [9-10] suggests that the occurrence of adiabatic shear is the root cause that drives the formation of serrated chips, which occurs when the heat softening effect is superior to work hardening. Komanduri [11-12] suggested that adiabatic shear instability and strain localisation within the shear zone of the first deformation zone would lead to abrupt shear along the shear surface.

The formation of adiabatic shear bands is also inextricably linked to dynamic recrystallization, and many scholars have previously conducted hot compression tests on the nickel-based alloy Inconel 718 and proposed different models to predict the changes in flow stresses during processing and the dynamic recrystallization behavior [13-15]. Wan et al. [16] conducted tensile compression tests on Inconel 718 at different temperatures and different strain rates. Based on the experimental results, it is concluded that the stress changes due to the occurrence of periodic dynamic recrystallization behavior, and a relationship between dynamic recrystallization and crack formation is derived.

The definition of "process signature" was introduced by Brinksmeier [17] in 2011, where the integrity of the workpiece surface during processing can be considered to be determined by the energy loss within the material. The distribution of stress, strain, and temperature during this process [18] causes a change in the energy stored inside the material. McAuliffe and Waisman et al [19] proposed a mathematical model of shear zone and fracture coupling using conservation laws and thermodynamic principles as a way to analyze the formation of shear zones and to propose the relationship between fracture and energy. Tang and Huang [20] et al. developed a mathematical model of stored energy and combined it with finite element simulation to analyze the stress, hardness, temperature and microscopic deformation in the cutting deformation zone, but did not analyze the shear band in depth.

The method of finite element simulation is also commonly used to analyze deformation mechanism, but the adiabatic shear band formed in macro cutting is a kind of localization phenomenon by finite element simulation. From the micro perspective, dislocations are the main carrier for plastic deformation of materials. The slip of dislocations and the proliferation of dislocations cause the formation of stored energy in materials, which can represent the microstructure and macro properties of materials under high-speed cutting. The stored energy in the adiabatic shear band can better explain the changes in the shear band due to plastic
Therefore, considering the changes of total dislocation density, stress and temperature, this paper analyzes the change of shear band energy storage during plastic deformation, and on this basis, the formation mechanism of adiabatic shear band is analyzed by combining microscopic and macroscopic analysis. The research results available so far seldom combined energy and multi-scale analysis, the investigation of the deformation mechanism behind cutting is not perfect. The adiabatic shear zone formed in macroscopic cutting simulated using finite element simulation was considered as a localization phenomenon. From a microscopic analysis, dislocations were considered to be the main vehicle for plastic deformation of the material. Dislocation slip and dislocation multiplication will result in the formation of stored energy inside the material, which was thought to characterize the microstructure and macroscopic properties of the material under high-speed cutting, and the stored energy inside the adiabatic shear zone was thought to better explain the changes in the shear zone due to plastic deformation. Therefore, in order to further analyze the formation mechanism of the adiabatic shear zone, this paper used Fortran language to write a subroutine for secondary development, which contains strain gradient theory and shear zone storage energy. The compiled subroutine was mapped to the main program to build a multi-scale finite element model based on Abaqus, and then to obtain the variation of storage energy in the shear zone and the plastic deformation of the material occurring in the cutting. The plastic deformation behavior occurring in cutting was analyzed in conjunction with the fluctuations in shear zone storage energy based on the overall dislocation density, stress and shear zone temperature variations. And correlated the dynamic recrystallization and periodic fracture behavior with the variation of shear zone storage energy based on the above analysis. The formation mechanism of the adiabatic shear zone was investigated in depth by combining macroscopic and microscopic aspects from an energy perspective.

2. Experiment

During the cutting process, macroscopic deformation of the workpiece material occurs, which leads to changes in dislocations and shear zones. The changes in dislocations and stored energy can be analyzed in depth in relation to the changes in stress, strain and temperature during deformation. Changes in internal microstructure will result in changes in internal storage energy (Shear Zone Storage Energy). The above required data can be obtained from the experimental process of the cutting experiment and Split Hopkinson Compression Bar tests (SHPB), so it is necessary to carry out the cutting experiment and Hopkinson compression bar tests.

2.1 Cutting experiments

In cutting process (Dry Cutting), the test machine is a general lathe (CA6140) with a frequency converter to achieve step-less speed control. The specific equipment required and operation are as follows:

(1) The workpiece is made of Inconel 718 (Solid State), a nickel-based high-temperature alloy with nickel as the main metal. The physical properties of Inconel 718 are shown in Table 1 below, and the size of the specimen selected for the experiment was 100mm x 500mm.

<table>
<thead>
<tr>
<th>Density</th>
<th>Modulus of elasticity</th>
<th>Poisson ratio</th>
<th>Coefficient of thermal expansion</th>
</tr>
</thead>
</table>

Table 1  Inconel718 Physical Properties
(2) Workpiece material was cut by carbide tool YG8 on lathe CA6140 (YG8 has good wear resistance, the effect of tool wear is ignored in the acquisition of experimental data). In the experiment the front angle of the tool was 6°. The specific material parameters of the tool YG8 are shown in Table 2 and the cutting device used in the experiment is shown in Fig. 1.

### Table 2 Tool properties

<table>
<thead>
<tr>
<th>Density (kg/m³)</th>
<th>Modulus of elasticity (Gpa)</th>
<th>Poisson ratio (ν)</th>
<th>Specific heat (J/kg°C)</th>
<th>Conductivity (W/m°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8270</td>
<td>240</td>
<td>0.3</td>
<td>14.7</td>
<td></td>
</tr>
</tbody>
</table>

(3) Rapid Explosive Knife Drop Experiment for more accurate chip root morphology (The tool leaves the test piece quickly during the turning process and "freezes" the cutting state at the moment of tool withdrawal, thus preserving the cutting state of the cutting zone). And chip morphology is observed by metallurgical microscope.

(4) The measurement of temperature in experiments is usually done by thermocouple thermometry, which is based on the principle: The workpiece material and tool material used for the experiment were of different materials thus forming a closed loop. A large amount of thermal energy is generated during the cutting so that there is a temperature gradient between the two stages which generates a thermoelectric potential. Using a measuring instrument to record data and import it into a logger so that the temperature can be calculated. The schematic diagram of the measurement system is shown in the Fig. 2.
(5) Compression experiments were carried out using an electronic universal experimental compressor at a room temperature of 20°C and a strain rate of 0.001 s⁻¹, and the experimental setup is shown in Fig. 3(a). Due to the lack of a compression extensometer in this compression experiment, the true stress-strain curve needs to be calculated from the force versus displacement curve. The force versus displacement curve can be obtained from this compression experiment as shown in Fig. 3(b). It is known that the maximum stress value is 199.92 KN and the modulus of elasticity is 7170 MPa. The final true stress-strain curve obtained is shown in Fig. 3(c).

(6) After etching the treated Inconel 718 specimen section for 20 seconds using aqua regia, the microstructure of the workpiece was observed using the super depth-of-field microscope in Fig. 4(a). The
specific distribution of hard points can be known as shown in Fig. 4(b).

![Ultra-deep field microscope and Microstructure distribution](image)

**Fig. 4 Microstructure observation**

### 2.2 Split Hopkinson Compression Bar tests

In high-speed cutting Inconel 718, plastic deformation of the material occurs at high temperatures. The Split Hopkinson Compression Bar (SHPB) tests are performed to determine the stress, strain and strain rate of the material. The data required to calculate the stored energy in the shear band can also be obtained from the SHPB. The strain rate \( \dot{\gamma} \) can be expressed as [21]:

\[
\dot{\gamma} = \frac{v_{ch}}{\Delta_s} = \frac{v_c \cos \gamma_0}{\Delta_s \cos (\varphi - \gamma_0)}
\]

Where \( \Delta_s \) is the shear band width, \( v_{ch} \) is the chip flow rate in the shear zone, \( v_c \) is the cutting speed, \( \varphi \) is the shear angle, and \( \gamma_0 \) is the rake angle. The strain rate required in the experiment can be obtained from the Eq. (1).

The experimental schematic diagram is shown in Fig. 5, which is mainly composed of an impact bar, an incident rod, a transmission rod, a heating device, a strain gauge, a waveform memory and a computer. The speed of impact bar is adopted as the cutting speed, the size of the samples used in the experiment is \( \phi 4 \text{mm} \) in diameter and 2mm in length, and the heating device used in the experiment is shown in Fig. 6. Under the impact of the air gun, the impact bar hits the incident rod at a certain speed, and an incidence pulse is generated in the incident rod, and the incident rod collides with the samples under the impact force thus forming a stress wave. When the stress wave is transmitted to the contact interface between the incident rod and the samples, due to the impedance caused by the mismatch, only part of the stress wave is transmitted to the samples, and then the stress wave is transmitted to the transmission rod through the samples to form the transmitted wave. The rest is reflected from the specimen surface to form the reflected wave. Strain gauge is used to measure the strain and the experimental strain value is recorded by computer. The test was conducted at high speed, so the one-dimensional stress wave theory was considered, and the stress, strain and strain rate were expressed as follows [22]:

\[
\sigma_s = \frac{A_i}{A_s} E \dot{\varepsilon}_t
\]

\[
\varepsilon_s(t) = -\frac{2C_0}{l} \int_0^t \varepsilon_R(t) dt
\]

\[
\dot{\varepsilon}_s(t) = -\frac{2C_0}{l} \varepsilon_R(t)
\]
Where $A_i$ is the cross-sectional area of the compression bar used in the experiment; $A_s$ is the cross-sectional area of the samples used in the experiment; $E$ is the elasticity modulus of the compression bar used in the experiment; $C_0$ is the wave velocity of the longitudinal wave generated in the experiment.

3. Model establishment

The process of cutting experiments is more complicated and costly, so some of the more difficult to obtain data can be obtained through finite element simulation. The finite element modelling is divided into two main parts, the first part is the selection of a more suitable architecture and its revision based on the analysis. The Johnson-Cook (JC) constitutive model was chosen for this modelling, which can well reflect the strengthening effect of strain rate and the softening effect caused by temperature increase in the material deformation process, and is widely used in finite element software. However, the original principal structure does not take into account the storage energy and the stress changes caused by hard points, so the structure needs to be improved. The second part of the process involved the creation of a finite element cutting model, which required the compilation of a subroutine to redefine the corrected intrinsic structure prior to modelling.

3.1 Constitutive model

Before correcting the Johnson-Cook constitutive, the parameters of the original JC constitutive need to be obtained, and the values of each parameter can be obtained from the experimental data. The stress-strain
curves were obtained through experimental results. Fig. 7 shows the stress-strain curves at different temperatures and the variation curves of stress-strain at different strain rates during the SHPB experiments, respectively. In Fig. 7(a), the stress increases rapidly from 0 to 429.9 MPa at 600°C. The stress continues to increase until 300μs when the stress increment decreases to 2.3 MPa. As the experiment continued, the stress increment gradually changed to about 2.5 MPa, and the change trend of the stress-strain curve tends to be gradual.

The dynamic temperature variation is also known from the experimental curve. In order to capture the dynamic temperature variation due to stress-strain correspondence, the time interval between the start of the recorded data and the stress wave being transmitted out at the incident rod is determined. In addition, the temperature change converted from the voltage signal is collected, and it can be seen that the dynamic temperature gradually increases as the stress decreases.

Fig. 7(b) shows the variation of plastic strain with different strain rates at the same temperature. With a strain rate of 7000s⁻¹, for example, the stress increases rapidly, but the stress-strain curve eventually flattens out gradually, at which point we assumed that all the plastic work is converted into heat energy.

When the relationship between stress, strain, temperature and strain rate needs to be combined, the Johnson-Cook (JC) constitutive model is usually used, with the following expression:

\[
\sigma_{JC} = (A + Be^n)(1 + C \log \dot{\varepsilon}) \left[1 - \left(\frac{T - T_{ref}}{T_m - T_{ref}}\right)^m\right]^{1/n}
\]

In Eq. (5), \(A\) is the initial yield strength of the material in MPa; \(B\) is the work-hardening modulus and \(n\) is the work-hardening index; \(\dot{\varepsilon}\) is the strain rate; \(C\) is the strain rate sensitivity coefficient; \(T\) is the dynamic change temperature; \(T_{ref}\) is room temperature, and \(T_m\) is the temperature at which the material is melted; \(m\) is the softening coefficient during processing. The above parameters can be obtained by SHPB experiments and compression tests as shown in Table 3.

<table>
<thead>
<tr>
<th>Table 3 Parameters of the constitutive model</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A/\text{MPa})</td>
</tr>
<tr>
<td>716</td>
</tr>
</tbody>
</table>

Since the nickel-based alloy contains interphase hard points such as TiC and NbC, the JC constitutive...
A model is modified based on the strain gradient theory. As the dislocation line will bend in cutting due to the presence of dislocations generated by the hard points, and the dislocation line tension $T_i$ is known as \[23\]:

$$T_i \approx \frac{E b^2}{2}$$  \hspace{1cm} (6)

Where $T_i$ is the dislocation line tension; $E$ is the elasticity modulus; $b$ is the Burgers constant.

The shear stress $\tau_i$ can be expressed as:

$$\tau_i = \frac{T_i}{\lambda b/2} = \frac{E b}{\lambda}$$ \hspace{1cm} (7)

Where $\lambda$ is the distance between two adjacent hard points.

The flow stress is:

$$\tau_2 = \frac{\sqrt{3} E b}{\lambda}$$ \hspace{1cm} (8)

Based on the non-local shaping theory proposed by Gao \[24\], the flow stress is written using Taylor’s relation as:

$$\tau_s = 3\alpha G b \sqrt{\rho_t} + \frac{\sqrt{3} E b}{\lambda}$$ \hspace{1cm} (9)

Where $\alpha$ is the Taylor coefficient; $G$ is the shear modulus; $\rho_t$ is the total dislocation density which consists of geometric necessary dislocation density and statistical storage dislocation density.

In order to make the calculation of flow stress more accurate, correction factors $\chi$ are introduced, so the final model after correction on the basis of JC constitutive model is expressed as:

$$\sigma_y = \sigma_{JC} \sqrt{1 + \left(\frac{18\alpha^2 G^2 b \eta}{\sigma_{JC}^2}\right)^x + \frac{\sqrt{3} E b}{\lambda}}$$ \hspace{1cm} (10)

### 3.2 Cutting Model

For the initial modeling using Abaqus, the customized JC constitutive model program was used, but the program does not consider the interphase hard points such as TiC and NbC and the strain gradient, and does not directly define the stored energy due to the dislocation accumulation resulting from cutting. For these two reasons, the Fortran language is used in this study to write user subprogram to define the improved constitutive model.

In the process of writing the subprogram, the flow stress, yield criterion and work hardening criterion need to be considered. The strain component resulting from the occurrence of plastic deformation can be prepared by Eq. (11):

$$g(\sigma_{ij}, \varepsilon_{ij}, k_r) = 0$$

$$dg = \frac{\partial g}{\partial \sigma_{ij}} d\sigma_{ij} + \frac{\partial g}{\partial \varepsilon_{ij}} d\varepsilon_{ij} + \frac{\partial g}{\partial k_r} dk_r$$ \hspace{1cm} (11)

Where $\sigma_{ij}$ is the total stress; $\varepsilon_{ij}$ is the total strain; $k_r$ is the hardening parameter.

The yield criterion used is the Von Mise yield stress criterion, which can be expressed as:
\[ f(\sigma_y) = \sigma_n - \sigma_y = \sqrt{\frac{3S_y^2}{2}} - \sigma_y \]  

(12)

In Eq. (12), \( \sigma_n \) is the equivalent force, which can be introduced through the partial stress tensor. \( \sigma_y \) is the yield stress.

The work hardening criterion uses an equivalent hardening criterion, which uses the equivalent force value to calculate the strain increment resulting from the process in which the deformation occurs. It can be expressed as:

\[ \Delta \varepsilon^{pl} = \frac{\sigma_n - \sigma_y}{3G + h_y} \]  

(13)

where \( h_y \) is the hardening rate after the start of the strain increment.

According to the change of stress-strain, the total dislocation density and each parameter are defined in the subprogram, and the defined guidelines and the total dislocation density are combined to write the formula of storage energy into the program. The storage energy in the subprogram can be expressed as follows:

\[
\text{stateNew}(k, 7) = 0.25 \times G \times (\text{burgus}^{**2}) \times \text{stateNew}(k, 6)
\]

The compiled subprogram is connected with the main program, and the connection flow chart is shown in Fig. 8. The storage energy model was implemented using the finite element software Abaqus through the VUMAT subprogram. Through the data post-processing, the variation of shear zone storage energy during cutting can be obtained based on the variation of total dislocation density, stress and temperature data.

![Connection flow chart between subprogram and main program](image)

Fig. 8 Connection flow chart between subprogram and main program

The subroutines are compiled and interfaced with the main program before the finite element 2D model is constructed. According to the compiled subprogram, a multi-scale finite element model can be established. During modeling the tool is set as a rigid body. The geometric model of the workpiece containing TiC, NbC and other inter-phase hard points is also established in Abaqus. The specific properties of the hard points are
shown in Table 4, and the established finite element model is shown in Fig. 9.

Table 4 Material properties of hard points

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m³)</td>
<td>7500</td>
</tr>
<tr>
<td>Modulus of elasticity (MPa)</td>
<td>185</td>
</tr>
<tr>
<td>Poisson ratio (v)</td>
<td>0.3</td>
</tr>
<tr>
<td>Specific heat (J/kg °C)</td>
<td>103</td>
</tr>
<tr>
<td>Conductivity (W/m °C)</td>
<td>28.85</td>
</tr>
</tbody>
</table>

Fig. 9 Cutting model containing hard points

More serious deformation and shear damage can occur during the cutting process, and the shear damage criterion can accurately describe the separation and fracture of chips and workpiece, so the shear damage criterion is applied in the finite element simulation. The JC-damage criterion is used in the modeling, and the material failure is based on this criterion, and the critical value of plastic strain is obtained by calculation.

$$\bar{\varepsilon}^{pl}_f = \left[ d_1 + d_2 \exp \left( d_3 \frac{P}{\sigma} \right) \right] \left( 1 + d_4 \ln \frac{\bar{\varepsilon}}{\bar{\varepsilon}_0} \right) \left( 1 + d_5 \frac{T - T_{ref}}{T_{mech} - T_{ref}} \right)$$  \hspace{1cm} (14)

Where $d_1, d_2, d_3, d_4, d_5$ are the fracture parameters of the material, which can be obtained from the study of Borja Erice [25]:

$$d_1 = 0.04, d_2 = 0.75, d_3 = -1.45, d_4 = 0.04, d_5 = 0.89$$

$$\mu = \sum \left( \frac{\Delta \bar{\varepsilon}^{pl}}{\bar{\varepsilon}^{pl}_f} \right)$$  \hspace{1cm} (15)

Whether or not failure occurs depends, and failure occurs when the value of $\mu$ is taken as the equivalent plastic strain increment.

4. Results and discussion

4.1 Shear band storage energy

The internal energy of the workpiece material in cutting will increase due to strain, and the strain energy per unit volume is half of the stress multiplied by the strain in each set of stress components. Therefore, it can be concluded that the elastic strain energy per unit volume of element in cutting can be expressed as:
The microstructure of the material changes during cutting, so the elastic deformation occurs around the dislocation, and the cylindrical elastic material can be used to represent the general situation of deformation. According to the symmetry, the above volume unit can be regarded as a cylinder with thickness \(d\) to simulate the deformation in the dislocation, as shown in Fig. 10.

![Simulation of deformation generated in screw dislocations](image1)

![Simulation of the deformation generated in edge dislocations](image2)

**Fig. 10 Deformation in simulated dislocations**

When the elastic cylinder in Fig. 10(a) is deformed, a narrow radial slit LMNO is cut in the cylinder parallel to the \(z\)-axis, and the relative displacement of the cut surface in the \(z\)-direction is \(s\), which is the vector size of the screw dislocation. It can be seen from the figure that no displacement is produced in both \(x\) and \(y\) directions, and the displacement in \(z\) direction is expressed as:

\[
\varepsilon_s = u_z = \frac{s\theta}{2\pi} = \frac{s}{2\pi} \tan^{-1}(y/x)
\]

(17)

In the three-dimensional diagram, there are nine components of strain, and the first-order partial derivative of the displacement component is used to represent the strain component with the expression:

\[
\begin{align*}
\varepsilon_{xx} &= \varepsilon_{yy} = \varepsilon_{zz} = \varepsilon_{xy} = \varepsilon_{yx} = 0 \\
\varepsilon_{xz} &= \varepsilon_{zx} = -\frac{s}{4\pi} \frac{y}{\left(x^2 + y^2\right)} = -\frac{s}{4\pi} \frac{\sin\theta}{r} \\
\varepsilon_{yz} &= \varepsilon_{zy} = \frac{s}{4\pi} \frac{x}{\left(x^2 + y^2\right)} = \frac{s}{4\pi} \frac{\cos\theta}{r}
\end{align*}
\]

(18)

The stress component can be derived from Eq. (18), which can be expressed as:
The components of the polar coordinates in a cylinder can be expressed by the following expression:

\[
\begin{align*}
\sigma_{r\theta} &= \sigma_{\theta r} = \sigma_{\theta z} = \sigma_{z\theta} = \sigma_{r\theta} = 0 \\
\sigma_{x\theta} &= \sigma_{x\theta} = -\frac{Gs}{2\pi} \frac{y}{(x^2 + y^2)^{3/2}} = -\frac{Gs \sin \theta}{2\pi} \frac{x}{r} \\
\sigma_{y\theta} &= \sigma_{y\theta} = \frac{Gs}{2\pi} \frac{x}{(x^2 + y^2)^{3/2}} = \frac{Gs \cos \theta}{2\pi} \frac{r}{r}
\end{align*}
\]  

(19)

The components of the polar coordinates in a cylinder can be expressed by the following expression:

\[
\begin{align*}
\sigma_{rr} &= \sigma_{\theta\theta} \cos \theta + \sigma_{r\theta} \sin \theta \\
\sigma_{r\theta} &= -\sigma_{\theta r} \sin \theta + \sigma_{r\theta} \cos \theta
\end{align*}
\]  

(20)

For the shear strain in cutting, the only non-zero component is:

\[
\begin{align*}
e_{r\theta} &= e_{\theta r} = \frac{s}{4\pi r} \\
\sigma_{r\theta} &= \sigma_{\theta r} = \frac{Gs}{2\pi r}
\end{align*}
\]  

(21)

The stress field of the edge dislocation can also be represented by a cylinder, as shown in Fig. 10(b), where the displacement distance in the x direction of the slit surface is s, and the displacement and strain in the z-axis direction are 0. Each stress component is expressed as:

\[
\begin{align*}
\sigma_{x\theta} &= \sigma_{x\theta} = \sigma_{y\theta} = \sigma_{z\theta} = 0 \\
\sigma_{xx} &= -Dy \left(3x^2 + y^2\right) \left(x^2 + y^2\right)^{1/2} \\
\sigma_{yy} &= Dy \left(x^2 - y^2\right) \left(x^2 + y^2\right)^{1/2} \\
\sigma_{xy} &= \sigma_{yx} = Dx \left(x^2 - y^2\right) \left(x^2 + y^2\right)^{1/2} \\
\sigma_{zz} &= \nu \left(\sigma_{xx} + \sigma_{yy}\right)
\end{align*}
\]  

(22)

In Eq. (22), D is expressed as:

\[
D = \frac{Gs}{2\pi(1 - \nu)}
\]  

(23)

Bacon and Hull [26] proposed that the energy present in a dislocation-containing crystal is the strain energy, which is divided into two parts. One is the elastic energy, which can be defined based on the change in stress. The displacement of a point in a strain body from its position in the non-strain state can be represented by vectors, and these vectors are used to represent the shear stress. The distortion will occur when atoms in a crystal containing dislocations are displaced from a perfect lattice site, and then it results in the formation of a stress field in the crystal around the dislocation. The various components of the stress field are represented by the above expressions.

Based on the above expression, the elastic energy stored in the unit dislocation length is expressed as:
\[
\begin{align*}
\text{d}E_{el}(\text{screw}) &= \frac{1}{2} 2\pi r \, dr (\sigma_\| e_\| + \sigma_\| e_\|) = 4\pi r \, dr G e_\|^2 \\
\text{d}E_{el}(\text{edge}) &= \frac{1}{2} \sigma_{\text{s},x} s dA
\end{align*}
\]

Where \( dA \) is the area of LMNO in Fig. 10 (b).

In the displacement process the stress is accumulated from 0 to the final value. The elastic energy stored in the unit dislocation length of the edge dislocation and screw dislocation can be calculated from the change of the stress field around the dislocation, respectively, so that the total strain energy per unit length can be expressed as:

\[
E_{el}(\text{screw}) = \frac{G S^2}{4\pi} \ln \left( \frac{R}{r_0} \right)
\]

\[
E_{el}(\text{edge}) = \frac{G S^2}{4\pi(1-v)} \ln \left( \frac{R}{r_0} \right)
\]

Where \( R \) is the outer circle radius, \( r_0 \) is the inner circle radius.

From Eqs. (24) and (25), it can be known that the energy per unit length is relatively insensitive to the radius. The actual value of the radius can be taken, and the displacement vector is taken as Burgers’ constant. Therefore, the elastic energy expression can be rewritten as follows:

\[
E_{el} = \alpha G b^2
\]

The total dislocation density is the state variable describing the plastic flow [27]. In order to consider the effect of the total dislocation density evolution on the stored energy, the stored energy can be approximated expressed as follows based on the above expressions.

\[
E_{\text{stored}} = \alpha G b^2 \rho_{\text{tot}}
\]

Where: \( \alpha \) is the Taylor coefficient this paper takes 0.25, \( G \) is the shear modulus, \( b \) is the Burgers constant and its value is taken as 0.3, \( \rho_{\text{tot}} \) is the total dislocation density.

### 4.2 Total Dislocation Density

According to Eq. (20), the change in total dislocation density during this process will result in a change in the storage energy of the shear zone. The variation of the storage energy of the shear band with the total dislocation density is shown in Fig. 11, which is derived from the simulation results. The storage energy of the shear band increases with the total dislocation density.
The calculation formula of storage energy and the total dislocation density are written into the subprogram for secondary development, and SDV7 in the program indicates the storage energy. During the cutting process, the feed is 0.2 mm/r. In this study, the feed is a given value without change, so the effect of feed on the stored energy is not considered. At the end of cutting, a shear zone was selected for analysis, and the curve of shear zone stored energy versus time was output based on ABAQUS as shown in Figure 9. After starting to cut, the tool started to feed according to the analysis step, at which time the stored energy increases rapidly, and starts to decrease rapidly after a slow increase in stored energy during further cutting. When the first sawtooth shape is formed in the removed part of the material, the stored energy shows an upward trend. If this happens repeatedly, the change trend of stored energy will fluctuate. SDV6 indicates the total dislocation density, and the total dislocation density is visualized in ABAQUS, where part of the equivalent nephogram is shown in Fig. 11.
When a certain shear force is applied to a non-homogeneous crystalline material containing dislocations, a large number of dislocations will slide and thus slip, and distortion will occur around the dislocations. This means that the crystalline material containing dislocations is no longer in its lowest energy state. In addition to the externally applied shear forces, the dislocations themselves have a certain line tension, and based on the above two forces the length of dislocation line starts to increase. Therefore, the total dislocation density increases rapidly and the storage energy increases accordingly. Combining with Fig. 12, it can be concluded that the storage energy increases rapidly from point a to point b. When the overall dislocation density increases rapidly to $7.5847 \times 10^9$, the storage energy in the shear band is 9.444 KJ. The formation of dislocations is enhanced during further deformation, and the storage of dislocations begins to increase, leading to the appearance of process hardening. Combining Figs. 11 and 12, it can be concluded that the storage energy slows down during the climb from point b to point c. The critical value is reached when the total dislocation density increases to $7.7664 \times 10^9$ and the storage energy of the shear zone then reaches a peak of 9.6704 KJ.

When the total dislocation density increases to a critical value, the externally applied force induces plastic deformation of the material leading to twisted deformation of grain boundaries. According to Fig. 14(b)(c), it can be found that the twisted deformation of the original grain boundary at the chip root and a large number of dynamically recrystallized grains that evolve around it. The mechanism and law of nucleation for dynamic recrystallization shows that the driving force is the unreleased stored energy, which is formed by the proliferation of dislocations. Since the deformed grains recrystallize by absorbing dislocations, the rate of dislocation annihilation is greater than the rate of accretion during the absorption process, so the total dislocation density decreases and the storage energy decreases. This is consistent with the study of Wang [28]. The evolution of the total dislocation density after the critical value is shown in (a)-(c) in Fig. 13, which clearly shows that the total dislocation density starts to decrease. This is an inevitable trend formed by the annihilation of dislocations and the appearance of dislocation climbing. Combining with Fig. 12, it can be concluded that the annihilation of dislocations reduces the storage energy from point c to d. That is, the storage energy decreases to 3.1555 KJ when the dislocation density decreases to $2.5342 \times 10^9$. 

Fig. 13 Total dislocation density nephogram
It is known from Humphreys and Kalu [29] that the material under high strain rate undergoes continuous dynamic recovery including subgrain growth recovery, continuous recrystallization and normal grain growth, etc. Combined with Fig. 13(d), it can be concluded that when the storage energy is consumed to a certain extent, the dislocations will continue to proliferate and form an equilibrium with dynamic recrystallization so that plastic deformation continues to occur and therefore the storage energy starts to increase again.

4.3 Temperature Analysis

When cutting Inconel 718, the initial temperature was set to 20°C and the depth of cut was set at 0.041 mm when cutting at different speeds. In the cutting process contains many kinds of heat sources, such as the primary shear zone heat source, secondary shear zone heat source and frictional heat source generated by the contact between the workpiece and the tool. The temperature in the shear zone is approximated as an adiabatic process due to the rapid increase, which can be calculated by shear stress. The shear stress based on the JC constitutive model can be expressed as:

$$\tau_{\text{jianqie}} = \frac{1}{\sqrt{3}} \left( A + B \left( \frac{\varepsilon}{\sqrt{3}} \right)^n \right) \left[ 1 + \log \dot{\varepsilon} \right] \left[ 1 - \left( \frac{T - T_{\text{ref}}}{T_{\text{m}} - T_{\text{ref}}} \right)^m \right]$$

(28)

The average shear stress based on the strain gradient plastic deformation theory is expressed as:

$$\tau'_{\text{jianqie}} = \tau_{\text{jianqie}} \sqrt{1 + \left( \frac{18a^2 G^2 b \eta}{\tau^2_{\text{jianqie}}} \right)^2}$$

(29)

Thus the shear zone temperature can be calculated by the following expression:

$$T_{\text{jianqie}} = T_{\text{ref}} + \frac{\beta_i}{\rho C_p} \int \tau'_{\text{jianqie}} d\bar{E}$$

(30)

Where $\beta_i$ is a constant, taken as 0.9 in this paper; $T_{\text{ref}}$ is the room temperature, which is set as 20°C in this study; $\rho$ is the density, and $C_p$ is the specific heat.

Replace $C_p$ in Eq. (29) with the formula ($C_p = 0.015T + 12.53$) to get a new expression for the final shear zone temperature simulation value based on strain gradient theory.

$$T_{\text{jianqie}} = T_{\text{ref}} + \frac{\beta_i}{\rho(0.015T + 12.53)} \int \tau'_{\text{jianqie}} d\bar{E}$$

(31)
The comparison of temperature value between the experimental and the calculated results based on the finite element simulation is shown in Fig. 15, and it can be seen that the data obtained from the simulation model based on the strain gradient theory are consistent with the experimental data.

![Graph showing comparison of experimental and simulated values](image)

**Fig. 15 Comparison of experimental and simulated values**

In order to more accurately analyze the relationship between the temperature change in the shear zone and the storage energy, in the finite element simulation model, the temperature in the shear band (see Fig. 16) was selected to analyze and the temperature data of this shear zone was post-processed. The temperature change curve is shown in Fig. 17. It can be seen from Fig. 17 that a large amount of heat energy is generated in the cutting process resulting in a rapid increase in temperature to 886°C. During this process, thermal deformation occurs and the dislocation will climb at a sufficiently high temperature to produce plastic deformation, and the thermal softening will occur at higher temperatures. The thermal softening phenomenon is associated with the rearrangement of dislocation substructures, which in turn leads to changes in the total dislocation density and shear band storage energy. At high strain rates, the total dislocation density decreases due to the increase in temperature caused by adiabatic heating, and as a result, the flow stress decreases, so the storage energy of the shear zone decreases.

![Image showing shear zone](image)

**Fig. 16 Shear zone used for analysis of temperature**
The annealing of Inconel718 at high temperature will involve the loss of stored energy and the change of microstructure. Some microstructures and properties can be restored to their original values, and some microstructures have undergone a new round of permutations which contain dislocations. When dislocations move, the resulting load will do work on the crystalline material. The whole change process is divided into two parts: recovery and recrystallization, where recrystallization is the core of annealing. This dynamic response will result in a fluctuating trend in the change of storage energy during the cutting process, which will increase with strain, but the peak of the second increase of storage energy is smaller than the peak of the first.

4.4 Stress Analysis

In non-uniform plastic deformation, the deformation field is significantly related to the strain gradient, and the resulting geometric necessary dislocations will in turn affect the local hardening behavior of the material. The geometric necessary dislocation density is influenced by the total dislocation density. It can be concluded that the effect of the evolution of the geometric dislocation density on the stress change is caused by the strain gradient, and thus it can be introduced that the presence of the strain gradient will lead to a change in the storage energy. When the stored energy changes, the stress will also change. The mechanical properties can be determined by the stored energy, and are closely related to the microstructure.

To reveal the relationship between storage energy and stress, the cutting thickness was set to 0.041 mm and the cutting speed was set to 100 m/min. Data post-processing was performed in Abaqus for the model after cutting, and the output stress variation curve is shown in Fig. 18. According to Eq. (16), the stress is proportional to the elastic strain energy, and then the stress is proportional to the storage energy, and the change curve of stress is compared with the change curve of storage energy. The trend of stress variation in the shear zone in the main deformation zone is roughly the same as that of the storage energy, which increases when the stress increases and decreases when the stress decreases. The stored energy cloud diagram and its corresponding stress cloud diagram at the same time are shown in Fig. 19.
Fig. 18 Variation of stress with time

(a-1)  (b-1)  

(a-2)  (b-2)  

(a-3)  (b-3)
The change in material hardness during cutting is another extremely important property that is closely related to the storage energy. In the literature [30], the calculation of hardness is proposed to be related to the flow stress with the following expression and the curve of hardness variation is shown in Fig. 20.

\[ H_v = \frac{\sigma_g}{A_j} \]  \hspace{1cm} (32)

Where \( H_v \) is the hardness; \( A_j \) is a constant, which is taken as 2.63 in this paper with reference to the literature [20]; \( \sigma_g \) is the flow stress.

According to Fig. 20, the hardness increases with the flow stress, and combined with (a-1)-(a-3) in Fig. 18 and Fig. 19, it can be concluded that during the gradual increase of the Mises stress to \( 1.920 \times 10^9 \) MPa, local work hardening is becoming more and more severe, and the local hardening effect is caused by the local interaction between geometric necessary dislocations and grain boundaries. When the material containing dislocations is subjected to a large enough stress, the dislocations will slip and the local work hardening increases the stored dislocations, and the total dislocation density thus increases, which can be seen with the rapid increase in shear band storage energy by combining in Fig. 19 (b-1)-(b-3).

As the cutting continues, the stress begins to decrease as shown in Fig. 19 (a-4), and the Mises stress gradually decreases to \( 6.27 \times 10^8 \) MPa as the temperature increases during this process. According to Voyiadjis and Faghihi [31], it is known that the hardness decreases with the increase in temperature and thus has an effect on the storage energy. After the dislocation moves, the dislocations with the same symbol will repel
each other, thus reducing the total elastic energy. On the other hand, dislocations with opposite symbols will attract each other and thus annihilate. At the same time, due to the stacking of dislocations and the activation of new dislocation sources in the vicinity, the total dislocation density decreases and the material starts to soften under cutting i.e. the hardness decreases. Combined with Fig. 19 (b-4), it shows that the storage energy decreases.

4.5 Formation mechanism of adiabatic shear band

In this paper, based on cutting experiments, SHPB tests and two-dimensional cutting simulations, the reasons for the formation of adiabatic shear bands are investigated in depth based on the variation of shear band storage energy and the microscopic evolution mechanism. At high strain rates, the presence of dislocation slip drives local plastic deformation of the material. The shear slip distribution is shown in Fig. 21(a). The work hardening and thermal softening effects generated in the cutting caused thermal-mechanical instability, experienced a large number of shear strain and material softening after the abrupt change in the thin region to form an adiabatic shear band. The main failure mechanism of crystalline materials and the reason of dynamic deformation is the adiabatic shear zone. The morphology of the shear zone obtained by metallographic microscopy is shown in Fig. 21 (b).

(a) Distribution of shear slips
(b) Shear band

Fig. 21 Microscopic metallography of chip

To investigate the correlation between the adiabatic shear band and the storage energy of the shear band, the stress and temperature clouds are output based on ABAQUS, as shown in Fig. 22. Figs. 22(a) and (c) show the initial stress and the stress when forming shear band. Fig. 22(b) and (d) show the initial temperature and the temperature at which shear bands are formed.
The changes of stress, strain and temperature will affect the formation of shear bands. Combining the stress-strain curves obtained from the SHPB experiments with Figs. 22 (a)-(d), the analysis shows that after starting to feed the tool, the tool moves to the position of contact with the workpiece. The stress, strain and temperature both increase rapidly, and the part of the material is strongly squeezed. As a result, this part of the material undergoes plastic deformation, and the workpiece material near the tool tip undergoes shear slip. During this process, the stored energy gradually increases, and at the same time, work hardening begins.

As the work hardening leads to the dislocation packing, which leads to the stress concentration in the cutting process, the shear band storage energy reaches the peak value, at this time, the anisotropy of the hardening causes the spontaneous deformation instability [32], so that the deformation band is formed as shown in Fig. 23. It can be seen from the figure that the deformation band is the main body of sawtooth chips, without other obvious organizational characteristics, and its formation process is gradual.
The existence of hard points in cutting will aggravate the stress concentration. Since the workpiece cannot bear too much strain, it starts to release a lot of heat energy. The stored energy starts to decrease after reaching the peak value, resulting in thermal softening effect, local shear instability of the material, and dynamic recrystallization. Therefore, a phase change zone appears at high temperatures, as shown in Fig. 24, and finally an adiabatic shear zone is formed. This is consistent with the study of Rittle [33]. Dynamic recrystallization precedes the formation of the adiabatic shear band. The grains of dynamic recrystallization will lead to local softening of the hardened matrix, thus forming the shear band. In the process of forming the shear band, according to the research of Magnus [34], at high temperature, the interphase hard points such as TiC and NbC in Inconel 718 will be completely dissolved in the adiabatic shear band formed during dynamic deformation.

The distribution of adiabatic shear band is related to the strain gradient. The increase of temperature gradient in cutting leads to the increase of strain gradient, and then the width of shear band changes. If only the thermos-viscoplastic constitutive model is considered, the analysis of the shear band is not deep enough, so the change of microstructure and dynamic recrystallization should be considered. Dynamic recovery at high temperature is the main deformation mechanism of the workpiece material. During the whole cutting process, the change of total dislocation density changes the stored energy of the shear band. Dynamic recrystallization is at different stages due to the change of stored energy. The dynamic recrystallization and dynamic changes of dislocation multiplication cause periodic fracture of the cut material.

With the continuous cutting, uneven deformation occurs, and then an adiabatic shear band is formed. During the formation of the shear band, dynamic recrystallization is easy to occur, which makes the material form holes, pores and cracks. The incompatibility between the high-density dynamic recrystallization area and the surrounding environment is the source of the pores and cracks. Fig. 25 shows the microscopic morphology of chip root. In the partial enlarged view of shear band (see Fig. 25 (b)), it can be found pores and cavities at the chip root. The early stage of shear localization is discontinuous nucleation, propagation and growth of dynamic recrystallization. Cracks will be formed in the high-density dynamic recrystallization area, as shown in Fig. 25(a). It will experience severe plastic deformation, accelerate the nucleation process of dynamic recrystallization, and cause local damage, which will further promote the fracture of the workpiece material. The increase of the nucleation rate means that the frequency of storage energy fluctuation is accelerated, which is conducive to the formation of the adiabatic shear band.
5. Conclusions

Based on the strain gradient theory, combined with SHPB tests and cutting experiment, this paper obtains the evolution mechanism of microstructure during the change of stored energy and the change trend of total dislocation density, temperature and stress during the change of stored energy in shear band. On this basis, the formation mechanism of adiabatic shear band is deeply analyzed, and the following conclusions are drawn:

1. Based on the secondary development of Abaqus, it can be seen from the multi-scale simulation model that the dislocation propagates and annihilates in the cutting process, and dynamic recrystallization occurs in this process. The dislocation propagation and dynamic recrystallization induce material softening. The total dislocation density starts to increase or decrease due to the dislocation climbing and annihilation, and the shear band storage energy fluctuates accordingly.

2. The change trend of temperature is opposite to the storage energy of shear band. The thermal softening effect produced when the temperature rises makes the dislocation structure rearrange, and the storage energy decreases accordingly. Recrystallization at high temperature is the core part of annealing. Compared with the change trend of shear band storage energy, the stress is basically the same. Because the local interaction between geometric dislocations and grain boundaries causes work hardening, the storage energy increases slowly. After the thermal softening effect, the flow stress decreases, that is, the hardness decreases, and the storage energy decreases.

3. The evolution of microstructure and dynamic recrystallization during the change of shear band storage energy causes periodic fracture of the workpiece material to form adiabatic shear bands. The competition between strain hardening and thermal softening effects determines the starting time of failure. In the evolution of microstructure, dynamic recrystallization is the main cause of adiabatic shear failure, and dynamic recrystallization is determined by the stored energy during cutting. The comprehensive characterization of dislocation behavior can be reflected by stored energy, that is, this part of energy not dissipated into heat energy will lead to the rearrangement and combination of microstructure. The process of dynamic recrystallization nucleation will cause the material to fracture and crack, and the fluctuation speed of stored energy will affect the nucleation rate, thus affecting the speed of shear band formation, and the hard points in the material will be completely dissolved in the shear band at high temperature.
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Conflict of Interest

The authors have no conflict of interest.

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Code availability

Not applicable

Ethics approval

This article does not contain any studies with human participants or animals performed by any of the authors.

Consent to participate

approval

Consent for publication

approval

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