Characteristics and its formation reason analysis of adiabatic shear band produced by gear fracture

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Abstract—The formation and characteristics of adiabatic shear band during the fracture of gear assembly were studied. It shows that in the fracture process, the strain required by the adiabatic shear band can be achieved near the failure position of the gear, and thus the adiabatic shear band is generated. The distribution of the adiabatic shear band is discontinuous, and the angle with the gear is about 20 ° to 45 °. With the appearance of adiabatic shear band, a high strain rate is produced, and a lot of heat is produced in some areas. And because of the extremely fast speed, these heat can not be transferred in time, resulting in deformation, which leads to the fracture of gear assembly. At the same time, the critical strain and critical temperature are calculated.

1. INTRODUCTION
The adiabatic shear is a typical case of metal materials under high-speed impact loading. And this phenomenon exists in the process of high-speed deformation such as high-speed penetration, high-speed cutting and explosive recombination. Adiabatic shear band appears after adiabatic shear, which is closely related to the failure of metal materials. Therefore, it is very important to study the characteristics and formation reasons of adiabatic shear band. In this paper, we mainly study the adiabatic shear band produced in the fracture process of gear assembly. Through the study of strain, stress and temperature, the generation process of adiabatic shear band is reproduced as far as possible, and the calculation is verified.

2. EXPERIMENTAL METHOD
The gear assembly consists of one primary planetary gear and two secondary planetary gears (step gear and spur gear). During operation, the gear tooth surface is peeled off and the limiting tooth of bearing inner ring is peeled off. The morphology is shown in Fig. 1. The microstructure and characteristics during the period of polishing and corrosion are observed under the optical microscope.
3. RESULTS AND DISCUSSION

3.1 The characteristics of adiabatic shear band

Three gears were analyzed respectively. Because the one primary planetary gear and two secondary planetary gears (step gear and spur gear) are all shear toughness fracture characteristics, so only the second stage gear (spur gear) is selected for fracture edge microstructure analysis. At the edge of the fracture, obvious plastic deformation was found, the microstructure of the surface layer changed, and there were several adiabatic shear bands, which distributed along the direction of plastic deformation and thermal diffusion, with an angle of 20° to 45° with the fracture surface.

![Fig.1 The macro morphology of gear assembly](image1)

![Fig.2 The micro morphology of fracture edge](image2)

![Fig.3 The crack morphology](image3)
It can be observed from Fig. 3 that there is a crack along the adiabatic shear band. From the microscopic point of view, the damage caused by impact load can be roughly divided into the following types: microcracks, micropores and shear bands \[^3\]. Therefore, the generation of the cracks is due to the adiabatic shear band generated at the failure position of the gear, the microstructure uniformity is poor, and the distortion and deformation of the local area produces the crack source; with the operation of the gear, the crack continues to expand and eventually leads to the loss effect.

3.2 Cause analysis
When the gear is running at high speed, it will produce a great impact load on the gear, which will inevitably cause deformation. When the deformation reaches a certain degree, a large amount of heat will be generated, which cannot be transferred in time, resulting in distortion. At this time, adiabatic shear band will also appear. The internal of adiabatic shear band will produce large stress concentration and a large amount of heat will be produced in local area. Due to the extremely fast speed, these heat cannot be transferred in time, resulting in the change of microstructure and the formation of phase change layer. The strength of this part will be reduced, and the uniformity of microstructure will be reduced, which will eventually lead to the fracture of gear assembly.

In the process of plastic deformation of metal materials, it will inevitably produce heat, so that the temperature of metal itself will rise. Low strain rate plastic deformation can be treated as isothermal process \[^4\]. When the strain rate is high, the deformation process can be approximately treated as an adiabatic process, and the deformation work can be converted into the heat that leads to the temperature rise of the specimen, and the temperature rise often leads to the softening of the material. In the process of gear fracture, there are two kinds of effects, which affect the gear continuously in this process, which are deformation hardening and high temperature softening \[^5\]. In the early stage of plastic deformation, deformation hardening plays a major role; with the continuous operation of the gear, its temperature rises continuously. When the temperature reaches a certain degree, the deformation hardening effect decreases, the high temperature softening effect increases, and finally leads to phase transformation and thermal shear band.

Since the adiabatic shear band has deformation and thermal softening, it can be studied by thermal simulation and material plasticity theory. In the theory of material plasticity, there is a generalized Hooke's law:

\[
\tilde{\xi}_{ij} = \frac{1}{2G} \sigma'_{ij} + \frac{1-2\mu}{E} \sigma_m \delta_{ij} \quad (1)
\]

\[
\delta_{ij} = \begin{cases} 
1 & \text{if } i = j \\
0 & \text{if } i \neq j 
\end{cases} \quad (2)
\]

Inside, \( G \) is the plastic shear modulus, \( \tilde{\xi} \) is the stress of the material, \( \mu \) is the Nuxy, \( \sigma \) is the strain. When adiabatic shear band production, \( i \neq j \). From this we can see that

\[
\tilde{\xi}_{ij} = \frac{1}{2G} \sigma'_{ij} \quad (3)
\]

At the moment of the failure, the principal directions of stress and strain should coincide, so

At the moment of failure, the direction of stress resultant force is consistent with that of strain resultant force.
\[ \xi = \frac{1}{2G} \sigma' \] (4)

Therefore, when the adiabatic shear band is produced due to gear failure, the strain and stress are linear. At the moment of gear fracture, the work generated by deformation can be approximately considered as heat energy, and the plastic work per unit volume can be expressed by the following formula (5) \(^{(6)}\):

\[ W = \int_{0}^{\xi} \sigma(\xi) d\xi = \frac{\rho C_\Delta t}{\eta} \] (5)

Inside, \(C\) is the specific heat of the material, \(\rho\) is the density of the material, \(\Delta t\) is the temperature change value, \(\eta\) is the thermal conversion coefficient of the material.

Olson G B proposed the strain-stress relationship \(^{(7)}\):

\[ \xi = (\tau_0 + h \sigma)(1 - \alpha \Delta t) \] (6)

Inside, \(\alpha\) is the thermal softening coefficient, \(h\) is the strengthening factor, \(\tau_0\) is the Shear ratio limit under static load \((\tau_0 = \sigma_s / 2)\).

Based on the above formula, the relationship between strain-stress and strain-temperature at adiabatic shear band can be calculated

\[ \xi = (\tau_0 + h \sigma)e^{-\frac{\eta \alpha}{2\rho C}(2\tau_0 \sigma + h \sigma^2)} \] (7)

\[ \theta = \frac{1}{\alpha} \left[ 1 - e^{-\frac{\eta \alpha}{2\rho C}(2\tau_0 \sigma + h \sigma^2)} \right] \] (8)

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**Fig.4** The relation diagram of \(\xi - \sigma\)
The relationship between strain and stress at the adiabatic shear band can be obtained by formula (7), as shown in Fig. 4; and through formula (8), the relationship between strain and temperature at the adiabatic shear band can be obtained, as shown in Fig. 5.

When the failure occurs, the gear must be in a high temperature state. When the temperature reaches 1000 °C, the material has been fully austenitized.

When the gear is fractured, its temperature must be very high. When the austenitizing temperature is reached, the temperature must exceed 1000 °C. Therefore, we can take \( \eta = 0.97 \) \(^{[1]} \), \( \alpha = (1/1000)°C \), \( C = 540J/Kg°C \), \( G = 8 \times 10^4\)MPa, \( \sigma_s = 1040\)MPa, \( \rho = 7.85 \times 10^3\)Kg/m\(^3\), \( h = 0.2\)G.

Through calculation, it can be concluded that when the adiabatic shear band is produced, the critical temperature is \( t’ = 390 °C \) and the critical strain is \( \sigma’ = 0.52 \).

By observing the microscopic morphology of the gear, it can be found that the adiabatic shear band is discontinuous, which is also reflected in Fig. 4. In Fig. 4, it can be found that the strain and stress change in a parabola shape. When the strain reaches the peak value, the stress also reaches the peak value. As the deformation energy is converted into thermal energy, the value decreases.

It can be observed from the graph of strain and temperature, i.e. Fig. 5, that the temperature of the gear keeps rising during the whole process until it reaches the critical temperature, resulting in adiabatic shear band.

Through the observation of the fracture position of the gear, it can be found that the fracture location is near the top of the tooth, and the gear contacts with other gears more at this position. During the operation of the gear assembly, the gears rub against each other to produce a lot of heat, which makes the strain increase continuously. When the strain reaches the critical value, the adiabatic shear band will be generated, which will cause the gear to crack and finally lead to fracture.

4. CONCLUSION

(1) During the operation of the gear, a lot of heat is generated by friction between the gears, which makes the strain increase continuously. When the strain reaches the critical value, the adiabatic shear band will be formed, which is characterized by the obvious plastic deformation at the fracture edge, the surface microstructure changes, and there are several adiabatic shear bands distributed along the direction of plastic deformation and thermal diffusion, which is about 20 ° ~ 45 ° to the fracture surface, and presents a discontinuous state.

(2) Through the calculation, we get the result that the critical strain and the critical temperature of the gear (carburized steel) are 0.52 and 390 °C respectively when the adiabatic shear band is produced. At the same time, the relationship of strain-stress and strain-temperature at adiabatic shear band are drawn.
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