Analysis characteristics and causes of adiabatic shear bands produced during the artillery barrel explosion

Zh W Zhang¹, F Wang¹, S F Liu¹, Zh J Li², Y D Sun¹ and Y Zhang¹.

¹. No.52 Institute of China Ordnance Industry, Inner Mongolia, Baotou 014034;
². Baotou Research Institute of Rare Earths, Inner Mongolia, Baotou 014034).

Email: zhzhwhero@126.com.

Abstract. It was studied that the characteristics and causes of adiabatic shear bands produced during the artillery barrel explosion when launching medium caliber projectiles. It shows that at the breech position, the strain required for the adiabatic shear band can be achieved, resulting in the adiabatic shear band, which is in a state of discontinuity and has an angle of about 20–45 degrees with the barrel. After the appearance of adiabatic shear band, the strain rate is very high, and high heat is produced locally due to large plastic distortion, which can not be output, resulting in the intensification of deformation and the bursting of barrel. And the same time, the critical shear strain and temperature of the adiabatic shear band are calculated under this condition.

1. Introduction

The adiabatic shear is a typical case of metal materials under high-speed impact load. And this situation exists in the process of high-speed deformation, such as high-speed penetration, high-speed cutting and explosive combination [1]. The occurrence of adiabatic shear band is closely related to the failure of metal materials. So it is very important to study the characteristics of adiabatic shear band and its formation. This paper studies the adiabatic shear band produced by the explosion of Ni-3 system gun barrel when launching medium calibre shell, and studies its characteristics and formation mechanism. And based on the study of the relationship between stress, strain and critical temperature, the generation of adiabatic shear band is inferred, and the results are compared and verified.

2. Experimental method

After the middle caliber shell is loaded, it explodes about 600mm away from the end of the shell, and producing 4 pieces of debris. Among them, the two pieces of fragments are connected at the front section of the explosive part, as shown in a and b in figure 1, and the other two pieces are fragments at the middle section of the explosive part, as shown in c and d in figure 1. After polishing and etching, the microstructure and characteristics were observed under optical microscope and scanning electron microscope.
3. Results and discussion

3.1. The characteristics of adiabatic shear band

Through comprehensive analysis, it is found that the thickest phase-change layer and the largest number of adiabatic shear bands are found in the front segment of the connecting fragment ①.

And close to the inner wall, the surface microstructure of the fracture edge has a phase change layer, and the thickness of the phase change layer in most areas is more than 100 μm. And several white bright adiabatic shear bands start from the fracture edge, about 20° ~ 45° with the fracture direction, about 7μm ~ 20μm in width, and expand to the inside. The microstructure also has obvious plastic deformation, as shown in figure 2.
From the micro point of view, the damage caused by impact load has the following forms: microcrack, micropore and shear band [2]. The micro deformation of the gun tube becomes uneven because of the adiabatic shear band. So it becomes the source of microcracks and micropores, which eventually leads to the initiation and propagation of cracks [3], and finally the explosion of the gun tube. The crack morphology due to adiabatic shear band is shown in figure 3.

3.2. The mechanism analysis of the adiabatic shear band

The adiabatic shear band is formed by the high strain rate of the material under the action of high-speed impact load, and the high heat produced by the large plastic distortion in some parts, which is too late to be output, resulting in the aggravation of deformation. And than there will be stress-strain concentration in the shear band, especially when the temperature rises to a certain extent, phase transformation will occur in the adiabatic shear band, the strength will be reduced, the deformation will increase and be uneven, and the deformation of surrounding materials will not be coordinated, and cracks will easily occur in the subsequent process.

In the plastic processing of metal materials, plastic deformation is often accompanied by the phenomenon of metal temperature rising. The plastic deformation at low strain rate is usually treated as isothermal process. When the strain rate is 10^{-4} to 10^{-3}s^{-1}, the specimen is stretched, and there is no obvious temperature rise [4]. However, the deformation process at high strain rate can be approximately adiabatic, and the deformation work can be converted into the heat that causes the temperature rise of the specimen, and the temperature rise often causes the material to soften [5]. There must be two effects, deformation hardening and high temperature softening, which affect the strain behavior of the material. In the stage of plastic deformation, deformation hardening takes the leading position; because of the factors such as powder combustion and friction between shell and barrel, the barrel temperature increases sharply, high temperature softening gradually takes the leading position, and finally forms adiabatic shear band.

The adiabatic shear band is analyzed by material plasticity theory and thermal simulation. The generalized Hooke's law in material plasticity theory is as follows:

$$
\xi_{ij} = \frac{1}{2G} \sigma'_{ij} + \frac{1 - 2\mu}{E} \sigma_m \delta_{ij}
$$

(1)

At the time:

$$
\delta_{ij} = \begin{cases} 
1 & i = j \\
0 & i \neq j
\end{cases}
$$

(2)

Among it, $\xi$ is the stress of the material, $\sigma$ is the strain, $G$ is the plastic shear modulus, $\mu$ is the Nuxy. When an adiabatic shear band is generated, $i \neq j$, so

$$
\xi_{ij} = \frac{1}{2G} \sigma'_{ij}
$$

(3)

At the moment of explosion, the principal directions of stress and strain should coincide, so
It can be seen that the stress and strain have a linear relationship when the adiabatic shear band is produced by explosion from the above formula. The work in the deformation process is basically transformed into heat energy when the barrel is cracked. Plastic work per unit volume is calculated by equation (5)[6]:

$$ W = \int_0^\xi \sigma(\xi) \, d\xi = \frac{\rho C \Delta t}{\eta} $$  \hspace{1cm} (5)

Among it, $\rho$ is the density of the material, $C$ is the specific heat of the material, $\eta$ is the thermal conversion coefficient of the material, $\Delta t$ is the temperature change value.

Combined with the stress-strain relationship proposed by Olson G B: $\xi = (\tau_0 + h \sigma)(1 - \alpha \Delta t)$ \hspace{1cm} (7)

$\tau_0$ is the Shear ratio limit under static load ($\tau_0 = \sigma_s / 2$), $h$ is the strengthening factor, $\alpha$ is the thermal softening coefficient). And the relationship between stress-strain and temperature strain at the adiabatic shear band can be obtained:

$$ \xi = (\tau_0 + h \sigma) e^{-\frac{\rho \eta}{C \alpha} \left[ 2 \tau_0 + h \sigma + \theta \right]} $$  \hspace{1cm} (7)

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

According to the relationship between stress-strain and temperature-strain at the adiabatic shear band, the curve of stress-strain relationship at the adiabatic shear band is shown in figure 4, and the temperature-strain relationship at the adiabatic shear band is shown in figure 5.

**Figure 4.** The relation diagram of $\xi - \sigma$.

**Figure 5.** The relation diagram of $t - \sigma$.

When the explosion occurs, the barrel must be in a high temperature state. When the temperature reaches 1000 °C, the material has been fully austenitized, at this time, $\alpha$ =1/1000°C.
\( \rho = 7.9 \times 10^3 \text{Kg/m}\), \( C = 540 \text{J/Kg}^\circ \text{C} \), \( \eta = 0.97 \) [1], \( \sigma_s = 1040 \text{MPa} \), \( G = 8 \times 10^4 \text{MPa} \). In order to simplify the calculation process, take \( h = 0.2 \text{G} \), and the critical strain of adiabatic shear band \( \sigma_s' = 0.49 \) and the critical temperature \( T' = 379 \circ \text{C} \).

From figure 4 it can be seen that the relationship between stress and strain is similar to parabola change. When the strain reaches the extreme value, i.e. critical value, the stress reaches the maximum value, and then the stress decreases. This situation explains that the adiabatic shear band is always discontinuous from one perspective, which is caused by the release of energy in the form of heat energy. From figure 5 it can be seen that the temperature is rising until it reaches the extreme value, i.e. the critical state. At this time, an adiabatic shear band is generated, and cracks are generated in the subsequent process, eventually leading to the explosion of the barrel.

From the point of view of the position of the explosion of the barrel, it belongs to the position near the end of the gun. In this range, the kinetic energy of the shell is relatively greater. When it has a certain angle with the barrel, it will interact and generate heat energy, so that the strain of the barrel can reach the critical condition of the adiabatic shear, and then generate the adiabatic shear band, thus releasing energy to achieve balance. However, the barrel will generate cracks in the following process, the most important is that Burst at last.

4. Conclusion

(1) In the process of cracking, the barrel is subjected to high-speed impact load. When it is deformed and cracked, a great deal of heat is generated locally, which makes the strain of the barrel reach the critical condition of adiabatic shear, thus generating adiabatic shear band. It is characterized by that it starts at the edge of the fracture, about 20\(^\circ\)–45\(^\circ\) with the fracture direction, is in a discontinuous state, and expands to the inside, and the microstructure around it has obvious plastic change Shape.

(2) Under certain assumptions, the critical temperature of producing adiabatic shear band of Ni-3 gun barrel is 379 \( {\circ} \text{C} \), and the critical strain is 0.49. At the same time, the curves of stress-strain and temperature-strain at the thermal shear band are obtained.

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