Penetration Damaging Behavior of Two Kinds of Bimodal Microstructure of Ti-6Al-4V Alloy

Cheng Miao¹,², Hailing Wu ¹, Wei Yuan¹, Tao Zhong¹,², Weiling Yang ¹,²,
Lihong Bai¹, Lin Yang¹, Guofei Li¹, Sujie Sun¹
¹No. 52 Institute of China Ordnance Industries, Yantai 264003, China.
²National Key Laboratory of Science and Technology on Materials under Shock and Impact, Yantai 264003, China.

Abstract. Penetration tests of two kinds of bimodal microstructure of Ti-6Al-4V alloy were conducted using 7.62mm piercing incendiary projectiles. Damage appearance of crater, microstructure evolution and characteristics of adiabatic shear band were analyzed. The results showed: 1) Bimodal microstructure included equiaxial and acicular grain. The plasticity of acicular grain was lower than exuiaxial grain, which resulted in more dynamic recrystallization subgrain and bifurcations. 2) The characteristics of adiabatic shear band in two kinds of bimodal microstructure had obvious differences. The adiabatic shear bands in 1# Ti-6Al-4V alloy were reticularly distributed, and the density of adiabatic shear bands was obviously larger than that of

1. Introduction
Titanium alloy is one of the most important light metals in recent years. Titanium alloy has been used in conventional weapons as a new structural material because of high specific strength, ductility, toughness, high/low temperature resistance and excellent corrosion resistance. Titanium alloy has high specific strength and dynamic performance, which can greatly reduce the weight and improve the maneuverability of armored vehicle [1]. Compared to the traditional armored steel, titanium alloy has great advantages. However, titanium alloy is a kind of adiabatic shear sensitive material because of its low specific heat and thermal conductivity. It is prone to collapse, dynamic shear failure in armor protection [2]. At present, the research on the ballistic performance of titanium alloy is less. In this paper, penetration tests of two kinds of bimodal microstructure of Ti-6Al-4V alloy were conducted using 7.62mm piercing incendiary projectiles, and then damage appearance of crater, microstructure evolution and characteristics of adiabatic shear band were analyzed by optical microscopy and scanning electron microscope, which could provide theoretical support and experimental data for the further application of titanium alloy in armored vehicles.

2. Experiment
2.1. Experimental materials
Two kinds of bimodal microstructure of Ti-6Al-4V alloy were selected in the experiment. The microstructures were shown in Figure 1 and 2. The primary α phase of the target plate 1# was about
30%, and the heat treatment system was 960 ℃/1h AC+600 ℃/4h AC. The primary α phase of the target plate 2# was about 50%, and the heat treatment system for 940 ℃/1h AC+600 ℃/4h AC. The phase transition point of the material was 990 ℃. The chemical compositions of two kinds of titanium alloy were shown in table 1.

**Table 1. Chemical composition of Ti-6Al-4V alloy (ω/%)**

|     | Ti   | Al  | V   | Fe  | C    | N    | H    | O    |
|-----|------|-----|-----|-----|------|------|------|------|
| Bal.| 6.03 | 4.11| 0.18| 0.021| 0.012| 0.004| 0.15 |

**Fig. 1** Microstructure of 1# Ti-6Al-4V alloy after heat treatment.

**Fig. 2** Microstructure of 2# Ti-6Al-4V alloy after heat treatment.

**Table 2. Parameters of Ti-6Al-4V alloy**

| Number | R_{p0.2} (MPa) | R_{m} (MPa) | A (%) |
|--------|----------------|-------------|-------|
| 1#     | 870            | 945         | 14.0  |
| 2#     | 900            | 975         | 16.0  |

2.2. **Experimental method**

The standard projectile velocity of 7.62mm API was $808 \pm 7$ m/s. The size of the target plate was 200mmx200mmx30mm. The firing distance was 10m. According to the routine test requirements of armor protection, the power experiment should be carried out before target test, and the penetration depth of homogeneous armor steel (RHA) was obtained, which was the basis for evaluating the anti-ballistic capability of target plate. The penetration depth of the blank power experiment was 17mm.
3. Results and discussion

3.1. Macroscopic damage analysis

The ballistic performance of armor is described by its ability to resist penetration, impact and anti-caving [3]. The anti-penetration performance for projectile and shrapnel depends on the energy consumption of armor. The impact resistance is the ability of armor to absorb the energy of projectiles without cracking. The anti-caving performance is the ability of armor to prevent cracking or delamination. Therefore, in order to have excellent ballistic performance, the armor must have good anti-penetration, anti-impact and anti-caving performance. In terms of mechanical properties of the material, armor materials must have good comprehensive performance, which is a combination of strength and toughness.

Figure 3-4 are the damage images of 1# and 2# Ti-6Al-4V alloy. The results of experiment are showed in table 3. The penetration depths of 1# and 2# titanium alloy target plate are respectively 19.8mm and 18.4mm. The surface caving diameters of the two target plates are about 12mm.

![Fig. 3 Damage image of 1# Ti-6Al-4V alloy.](image1)

![Fig. 4 Damage image of 2# Ti-6Al-4V alloy.](image2)

The impact of armor piercing projectile on target plate is the failure process of high-speed deformation. The strain rate is in the range of $10^2-10^4$s$^{-1}$ with the projectile velocity [4]. Under the action of the projectile, the target is partially hardened and produces a shear band, and the strong deformation in the shear band further strengthens the material in the band. At the same time, due to the large deformation of the shear band material, the heat generated by the deformation, which is less conductive to the surrounding material makes the temperature of the material in the band increasing greatly. Then the material softens and strength decreases. When the degree of strength reduction due to the increase of temperature greatly exceeds the improved strength of work hardening, the sudden instability of the shear band material occurs, which is called adiabatic shear process. The shear bands in the target continue to develop, connect and intersect into cylindrical plug, while the shear bands also continue to enter the thermoplastic instability state. Then the plug is completely formed and pushed to the back of the target by the projectile. Finally the whole plug process is completed.
Table 3. The results of experiment

| Number | Velocity (m/s) | Depth (mm) | Average depth (mm) |
|--------|----------------|------------|--------------------|
| 1-1    | 836            | 19.5       |                    |
| 1-2    | 837            | 20         |                    |
| 1-3    | 841            | 19         |                    |
| 1-4    | 833            | 20         | 19.8               |
| 1-5    | 833            | 20         |                    |
| 1-6    | 828            | 20.8       |                    |
| 2-1    | 839            | 19         |                    |
| 2-2    | 841            | 18         |                    |
| 2-3    | 835            | 18         | 18.4               |
| 2-4    | 838            | 18.7       |                    |
| 2-5    | 839            | 18.2       |                    |
| 2-6    | 837            | 18.5       |                    |

3.2. Microscopic damage analysis

The process of penetration process involves high temperature, high pressure, high speed, high strain rate, large deformation of projectile body and target plate, propagation and reflection of shock wave, which is a very complicated process.

After the adiabatic shear band is formed, the stress and strain will be concentrated in the shear band, especially when the temperature rises to a certain extent, while the strength decreases and the inhomogeneous deformation increases. Then the inhomogeneous deformation is inconsistent with the surrounding deformation, which leads to microcracks and microvoids. Microcracks and microvoids rapidly aggregate along the adiabatic shear band and form macroscopic cracks, which eventually result in fracture of the material along the shear band (shown in Fig. 5).

![Fig. 5](image1) Microcracks and microvoids in the adiabatic shear bands of 2\# Ti-6Al-4V alloy.

![Fig. 6](image2) Fractographs of crater of 2\# Ti-6Al-4V alloy.
Fractographs of crater of 2# Ti-6Al-4V alloy are shown in Fig.6. The grain on the crater is elongated. The surface of blullet hole shows a large number of shear dimples and plastic tear dimples. Traces of melting and splashing, holes formed by metal gasification can be observed on the surface of blullet hole.

**Fig. 7** Morphology of adiabatic shear band of 1# Ti-6Al-4V alloy.

**Fig. 8** Morphology of adiabatic shear band of 2# Ti-6Al-4V alloy.

**Fig. 9** TEM images of adiabatic shear band of 1# Ti-6Al-4V alloy.

(a) equiaxial α phase region; (b) acicular α phase region

Fig.7 and Fig.8 are the morphologies of adiabatic shear bands of 1# and 2# titanium alloy targets. TEM images of adiabatic shear band of 1# Ti-6Al-4V alloy are shown in Fig.9. In the process of penetration, the clear and visible shear bands are all formed in two kinds of titanium alloy target plates, which initiate basically along 45° direction of the target plate and the force. Bimodal microstructure includes equiaxial and acicular grain. The plasticity of acicular grain was lower than exuiaxal grain, which resulted in more dynamic recrystallization subgrain and bifurcations. The adjacent shear bands of 2# titanium alloy target are approximately parallel and keep the same spacing. There are bifurcation and interaction in the shear bands of 1# Ti-6Al-4V alloy. For example, confluence, intersection, multiple intersection, separation and bifurcation were observed in two adjacent shear bands. The
adiabatic shear bands of 1\textsuperscript{st} titanium alloy plate are connected with the reticular formation, and the density of shear bands was significantly higher than that of 2\textsuperscript{nd} titanium alloy target, which led to higher adiabatic shear sensitivity. So the penetration depth of 1\textsuperscript{st} titanium alloy is deeper.

4. Summary
1) Bimodal microstructure includes equiaxial and acicular grain. The plasticity of acicular grain was lower than equiaxial grain, which resulted in more dynamic recrystallization subgrain and bifurcations.
2) The characteristics of adiabatic shear band in two kinds of bimodal microstructure had obvious differences. The adiabatic shear bands in 1\# Ti-6Al-4V alloy were reticularly distributed, and the density of adiabatic shear bands was obviously larger than that of 2\# Ti-6Al-4V alloy, which led to higher adiabatic shear sensitivity.

References
[1] Li Jinquan, Huang Dewu, Duan Zhanqiang et al. The study of the properties of adibatic shear bands in high strength armor steel under high velocity penetration. Journal of Ballistics [J], 2003, 15 (3): 86.
[2] Sun Kun, Wang Fuchi, Cheng Xingwang et al. Formation mechanics of adiabatic shear band for the different microstructures of TC6 alloy. Rare Metal Materials and Engineering[J], 2009, 38 (2): 233.
[3] Sherman D. Impact failure mechanisms in alumina tiles on finite thickness support and the effect of confinement. International Journal of Impact Engineering [J], 2000, 24 (4): 313.
[4] Tan Chengwen, Liu Xinqin, Chen Zhiyoung et al. Study on the relationship between adiabatic shear susceptibility and critical fracture velocity for Ti-6Al-4V alloy. Rare Metal Materials and Engineering [J], 2008, 37 (8): 1400.
[5] Deepak R, Chichili KT. Adiabatic shear localization in α titanium: experiments, modeling and microstructural. J Mech Phys Solids 2004, 52: 1889.