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Influence of adiabatic shear bands intersection on the ballistic impact of Ti–6Al–4V alloys with three microstructures

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ABSTRACT

The intersection of adiabatic shear band (ASB) and its effect on the ballistic performance of the Ti–6Al–4V plates with equiaxed, bimodal, and lamellar microstructures were studied using transmission electron microscopy (TEM). Focused ion beam (FIB) technology was used to accurately prepare TEM samples at specific locations around the ASB intersections. The effect of different microstructures on the number and morphology of subgrains in ASB intersections was investigated.

Multiple ASBs and their interactions were observed in the Ti–6Al–4V plates with equiaxed, bimodal, and lamellar microstructures impacted by armor-piercing projectiles. The ASBs mainly expanded along two directions, which were top-to-down and left-to-right. All the ASBs comprised dynamically recrystallized equiaxed grains and some partial dynamically recrystallized strip subgrains. The arrangement directions of these subgrains were different between the top-to-bottom and left-to-right ASBs. The expansion range of the left-to-right ASBs was the largest in the bimodal microstructure and the smallest in the equiaxed microstructure. The existing subgrains in the previously formed ASBs were elongated and fragmented during the intersection process, and decreased with the expansion of later-formed ASBs. Some of the subgrains were sheared again, which probably inhibited the expansion of the later-formed ASBs. The least amount of fragments and the smallest craters were observed in the Ti–6Al–4V plates with the equiaxed microstructure because of the lowest amount of ASB intersections and cracks, as well as the smallest expansion range of sideward ASBs. More and larger fragments and the largest craters were observed in the bimodal and lamellar microstructures because of more intersections, cracks and the largest expansion range of sideward ASBs.

1. Introduction

Ti–6Al–4V alloy has been used as armor materials for decades because of its excellent strength, fracture toughness, corrosion resistance and light weight [1]. Under high strain rate loading conditions, adiabatic shear bands (ASB) are prone to forming in Ti–6Al–4V alloy because of the high strength and low thermal conductivity [2–8]. Cracks could form and expand in and along the ASB, which would cause severe damage of the materials. However, the formation of ASBs could coordinate the deformation of materials near the craters during the impact process. Besides, ASB could absorb more energy and weaken the damage capability of the projectiles. Therefore, ASB is beneficial for the ballistic performance of the targets to a certain extent.

Multiple ASBs form with complicated interactions between them during the high speed impact process in the targets, such as the ASB bifurcations and intersections. ASB bifurcation would cause more ASBs along which the cracks would form and expand. This phenomenon has been studied in the authors' previous work [9]. ASB intersections would connect different ASBs. When cracks connect along with these intersected ASBs, a local fragment is formed. Grebe and Meyers discovered the ASB intersection phenomenon as early as in 1985 [10], however, the detailed intersection process was unclear as of this writing.

Numerous studies have proven that microstructure can greatly affect the ballistic impact properties and performance of Ti–6Al–4V alloys [11–14]. Bar and Rosenberg studied the ballistic behavior of five Ti–6Al–4V plates that have been subjected to different heat treatments and found that the failure mode of the

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alloys changed from the ASB-induced plugging to the ductile hole growth [11]. Lee et al. found that Ti–6Al–4V plates with equiaxed and bimodal microstructures both failed via ductile growth mode with some radial cracking [12]. Burkins et al. found that α+β-processed Ti–6Al–4V had higher V_{50} ballistic limit compared with β-processed Ti–6Al–4V against 12.7 mm armor-piercing projectiles and 20 mm fragment-simulating projectiles [13]. Study of B.B. Singh et al. showed the presence of a lower quantity of ASBs and ASB-induced cracks in Ti–6Al–4V plates, which were solution-treated below β-transus temperature and aged, than in the as-received or β-solution treated and aged plates [14]. In addition, Liu and Tan et al. found that Ti–6Al–4V alloys with different microstructures had obviously different distribution of ASBs and fracture characteristics under various loading conditions with high strain rates [15,16]. Apparently, ASBs and their interactions varied in different microstructures, which would affect the ballistic performance of the targets. Therefore, studying the ASB interactions, especially the ASB intersections could further clarify the

Table 1
Chemical compositions of Ti–6Al–4V alloy (wt. %).

Elements	Ti	Al	V	Fe	O	C	N	H
Weight percentage	Matrix	6.03	4.11	0.18	0.15	0.02	0.01	0.004

Table 2
Quasi-static tensile mechanical properties of Ti–6Al–4V alloys.

Microstructure	Tensile strength (MPa)	Yield strength (MPa)	Elongation (%)	Reduction of area (%)
Equiaxed	955	890	16.0	44.8
Bimodal	1105	1035	13.0	32.8
Lamellar	978	895	10.3	17.0

Table 3
The penetration depth of Ti–6Al–4V plates impacted by 7.62 mm armor-piercing projectiles.

Microstructure	Number	Velocity (m/s)	Penetration depth (mm)	Average penetration depth (mm)
Equiaxed	1–1	842	20.0	19.6
	1–2	840	19.0	
	1–3	843	19.9	
Bimodal	2–1	841	18.0	18.2
	2–2	835	18.0	
	2–3	838	18.7	
Lamellar	3–1	836	19.5	19.9
	3–2	838	20.0	
	3–3	840	20.3	

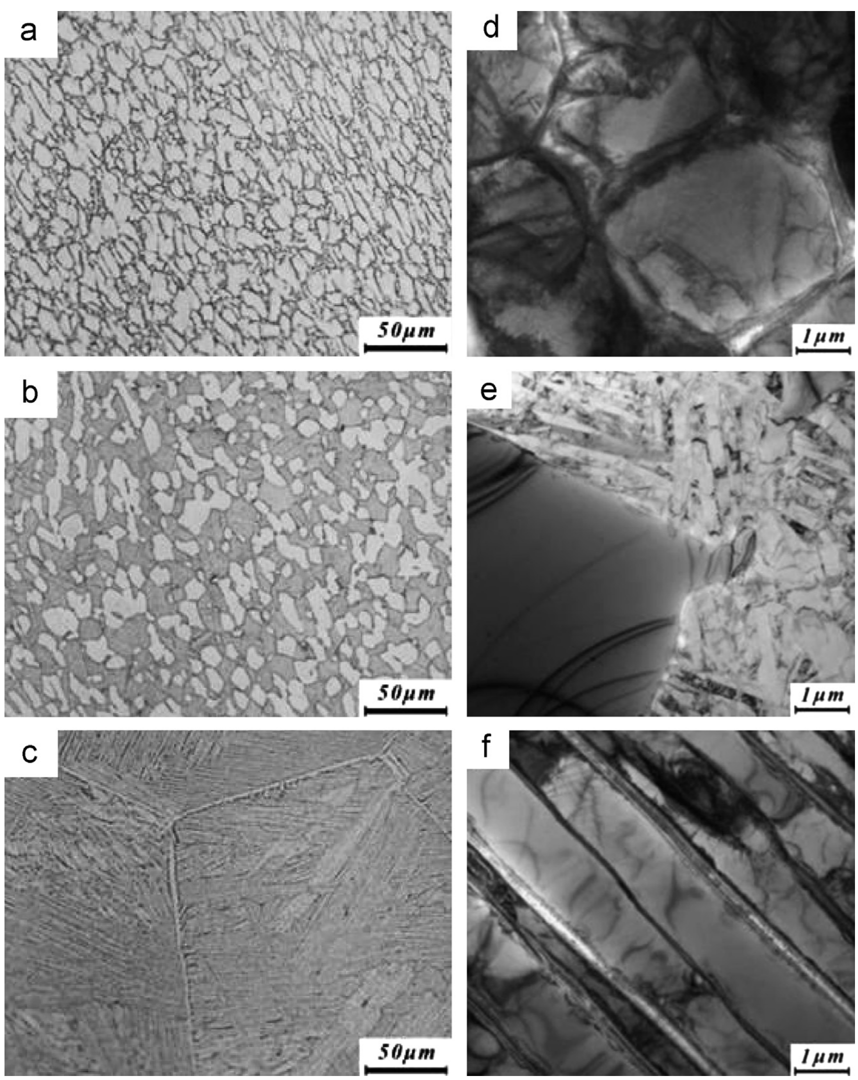

Fig. 1. Optical and TEM microstructures of Ti–6Al–4V alloys: (a) and (d), equiaxed; (b) and (e), bimodal; and (c) and (f), lamellar microstructures.