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Influence of rapid heating and cooling combined with deformation at ultrahigh strain rates on the microstructure evolution of pure titanium shaped charge liner

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ABSTRACT

A slug prepared from pure titanium shaped charge liners was recovered after detonation deformation at an ultrahigh strain rate over $10^5\,s^{-1}$ and high strain over 500%. Optical microscopy, electron backscattered diffraction (EBSD), and transmission electron microscopy (TEM) were employed to investigate the microstructure of the Ti shaped charged liner before and after the detonation deformation. The microstructures of the recovered slug include lamellar α grains, equiaxed α grains within localized shear bands, and jagged α grains. EBSD results indicated that the grain orientation distribution is random and no texture was observed in the slug. TEM observation revealed that the $\alpha \to \beta \to \alpha$ phase transformation occurred owing to the rapid heating and cooling combined with deformation at ultrahigh strain rates in the Ti shaped charge liner. No melting phenomenon was observed during the deformation process. The deformation process consisted of the explosive detonation stage combined with rapid heating and the subsequent penetration stage combined with rapid cooling. In the explosive detonation stage, the $\alpha \to \beta$ phase transformation instantaneously occurred via a martensitic mechanism. In the penetration stage, the high-temperature slug in β state was cooled rapidly and showed different deformation behaviors in three different areas.

1. Introduction

Shaped charge liner (SCL) as an oil well penetrator or armor penetrator has been developed and applied in both commercial and military fields [1,2]. The deformation conditions of SCL are extreme and apparently different from those of the conventional deformations under lower strain rates owing to the high shock pressure (~30 GPa), high strain rate (over $10^5\,s^{-1}$), and large strain (over 5) [3,4]. In addition, the extreme deformation conditions can also cause a drastic rise in temperature in the deformed metal liners [4].

The severe microstructural changes in SCL materials before and after the denotation deformation have been compared to investigate the deformation behaviors and mechanisms in some SCL materials [4–6]. Crystal defects such as cellular structures and sub-grain boundaries existing in the recovered slugs of electroformed Cu liner materials indicate that dynamic recovery and recrystallization occurred in the deformation process [5]. For Ni SCL with nano-sized grain, both melting phenomenon in the jet fragment and dynamic recovery and recrystallization in the slug after denotation deformation were observed [6]. In addition to elongated grains, Murr et al. [7] observed elongated sub-grains induced by severely localized or oriented plastic deformations in Ta. Guo et al. [4] pointed out that the deformation of W liner is similar to that of Cu rather than Ta owing to the different thermal conductivities and heat capacities of W, Cu, and Ta.

Using Ti liner as an anti-concrete material can achieve acceptable combination of penetration depth and aperture reaming simultaneously [8,9] owing to its unique properties such as high strength–density ratio, good plasticity, and high sound velocity [10–13]. During rapid heating and cooling, the solid phase transformation ($\alpha \to \beta \to \alpha$) can occur in pure Ti, in contrast to other liner metals such as Cu, Ni, W, and Ta [14]. The microstructures in pure Ti are evidently affected by the rates of heating and cooling owing to the changing transformation mechanisms [15–18]. At lower rates, the $\alpha \to \beta \to \alpha$ transformations are controlled by long-range diffusion [16]. The α phase can transform into two β forms including the intragranular β and allotriomorphic β [15]. Long plate-like features appear at slow cooling rates [18]. At higher heating rates ($> 3000\,K{\cdot}s^{-1}$), the $\alpha \to \beta$ transformation proceeds via a martensitic mechanism [19]. A massive transformation can occur at intermediate cooling rates [18]. The microstructure formed by martensitic transformation shows multivariants of plate-like features at cooling

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rates higher than 300 $K{\cdot}s^{-1}$ in commercially pure (CP) Ti [18].

However, only limited information is available on the effect of rapid heating and cooling combined with deformation at ultrahigh strain rates on the microstructure evolution of commercial pure Ti SCL [8]. This study deals with the comparison and analysis of the microstructural changes of the CP-Ti SCL before and after explosive testing by using optical microscopy (OM), electron backscattering diffraction (EBSD), and transmission electron microscopy (TEM). The deformation mechanism of CP-Ti SCL under ultrahigh strain rates is also presented.

2. Materials and Methods

2.1. Preparation and Initial State of the CP-Ti SCL

A bar of CP-Ti of diameter 90 mm with a purity of 99.6 wt% was provided by Shanxi Yuhang Nonferrous Metals Co. Ltd. (China) with a homogeneous microstructure along both the radial and axial directions. Chemical analysis results indicated impurities including 0.13% Fe, 0.14% O, 0.01% N, 0.001% H, and 0.01% C by wt%. A conical shape of titanium SCL with a cone angle of 90° was mechanically machined from the bar. The cross-section of the titanium SCL is schematically shown on the left side of Fig. 2 by doubled dashed lines. The surface of the titanium SCL was mechanically polished with care in order to acquire a good match with explosives.

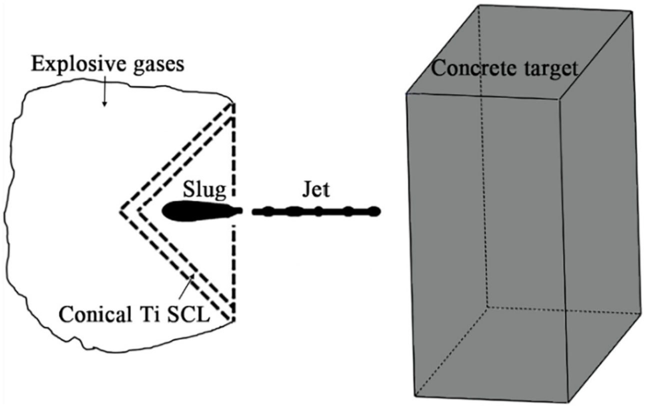

Fig. 2. Schematic illustration showing the high-strain-rate deformation process of Ti SCL. First, the Ti SCL was rapidly heated owing to the extremely high strain and strain rates caused by explosive gases. Subsequently, the formed slug and jet underwent rapid cooling during flying and contacting with the concrete target.

The microstructures of the initial titanium SCL before the explosion were investigated using OM, EBSD, and TEM. As shown in Fig. 1(a), the microstructure of pure titanium SCL before deformation consists of equiaxed α-grains with an average grain size of approximately 80 μm. Notably, no lath-like or deformed microstructures can be observed. Fig. 1(b) shows the bright-field TEM micrograph and the corresponding selected-area diffraction (SAD) pattern of the pure Ti matrix. The results indicate that no abundant dislocations are observed in the grains of the original material. In addition, the second phase, as indicated by the white arrow in Fig. 1(b), existed in the initial CP-Ti material because the content of β-stabilized element Fe is larger than 0.06 wt% [18]. The particles of the second phase are most likely Fe-stabilized β-Ti formed during the original ingot solidification owing to sluggish eutectoid reaction kinetics at 595 °C [14]. The SAD pattern, as shown in the inset of Fig. 1(b), indicates that the pure Ti matrix is in the form of an α phase in the crystal structure. Fig. 1(c) and (d) show the EBSD orientation map and the corresponding {0002} pole figure of the initial microstructures in the CP-Ti, respectively. The results indicate that the orientation distribution of the grains was random and no texture was observed in the initial CP-Ti.

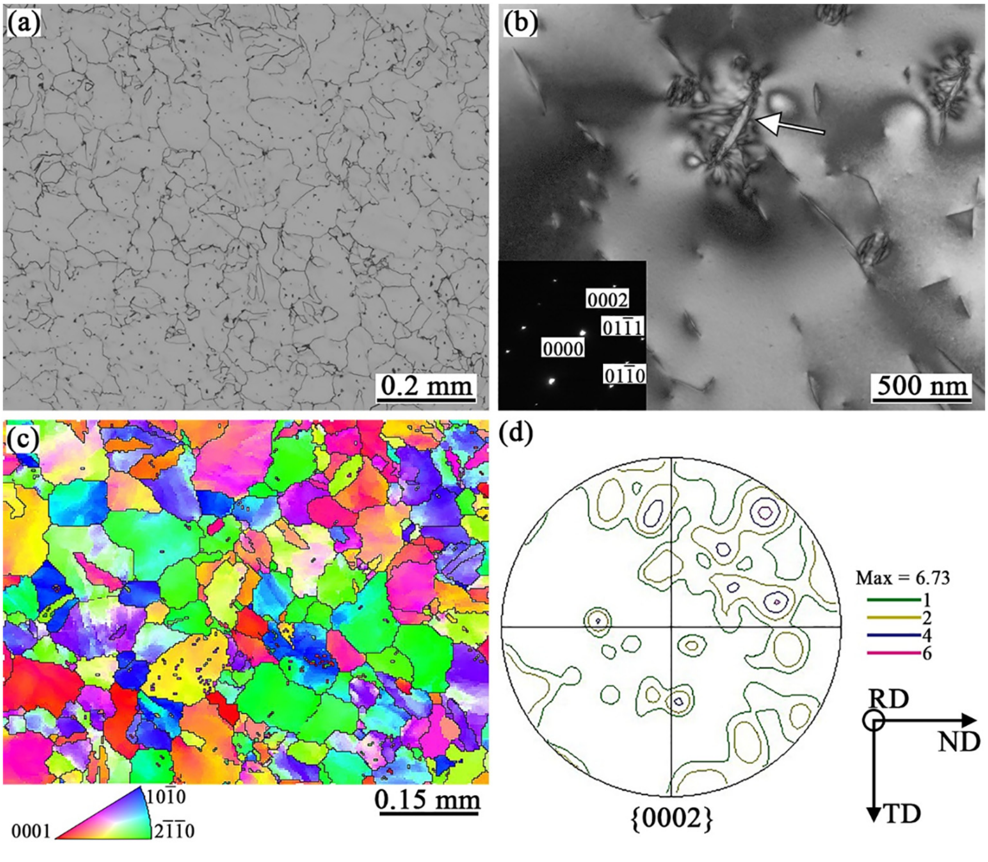

Fig. 1. OM metallurgical structures (a), bright-field TEM image (b) with the corresponding SAD pattern in the inset, EBSD orientation map (c) and the {0002} pole figure of the initial microstructures of the CP-Ti SCL before the denotation explosion. The white arrow in (b) shows the second phase in the initial CP-Ti SCL. RD, TD, and ND represent the radial direction, transverse direction, and longitudinal direction of the bar, respectively. Grains in (c) are colored by the RD using the inverse pole figure convention in the inset.