Available online at ScienceDirect

ScienceDirect

J. Mater. Sci. Technol., 2015, 31(2), 191–198

JMST

www.JMST.org

Analysis of the Transformation-induced Plasticity Effect during the Dynamic Deformation of High-manganese Steel

Huizhen Wang, Xiurong Sun, Ping Yang, Weimin Mao, Li Meng*

School of Materials Science and Engineering, University of Science and Technology Beijing, Beijing 100083, China

[Manuscript received October 31, 2013, in revised form December 9, 2013, Available online 4 April 2014]

The transformation-induced plasticity (TRIP) effect and resistance characteristics to adiabatic shear failure at high strain rates of high-manganese steel were investigated by using scanning electron microscopy and electron backscattering diffraction. Results showed that the high-manganese steel exhibited excellent strain hardening effect and resistance to adiabatic shear failure because of the TRIP effect. The TRIP effect occurred during dynamic deformation and showed two distinct stages, namely, the smooth TRIP process before the formation of adiabatic shear band (ASB) and the inhibited TRIP process during further deformation. In the first stage, the martensitic transformation showed slight orientation dependence and weak variant selection, which promoted the TRIP effect. In the second stage, reverse martensitic transformation occurred. Adiabatic shear bands (ASBs) developed typical shear microtextures $\{111\}<\bar{1}10>$. In microtextures, two groups of fine grains are in a twin relationship and uniform distribution, which restrained the formation of holes and cracks within the ASBs and enhanced damage resistance after ASB formation.

KEY WORDS: High-manganese steel; Martensitic transformation; Adiabatic shear band; Electron backscattering diffraction

1. Introduction

Adiabatic shear bands (ASBs) are special regions of highly localized deformations that occur under dynamic loading in numerous metals and alloys, such as copper[1,2], aluminum alloy[3], titanium alloy[4,5], and steel[6–8]. Since ASBs may induce cracks and ASB formation often implies catastrophic failure, experimental and theoretical efforts have been made to study the microstructural evolution during ASB formation. The microstructural evolutions within ASBs include dynamic/static recovery, recrystallization, phase transformation, melting, and amorphization[9–12].

The use of electron backscatter diffraction (EBSD) with a field emission scanning electron microscope offers many advantages in determining the microstructural evolution in bands. These advantages include the accurate measurement of grain size, phase distribution, boundary distribution, orientation, and misorientation.

In the current study, the resistance to adiabatic shear failure of high-manganese steel (18% Mn) with low stacking fault energy (SFE) was investigated by EBSD. High-manganese steel is well known for its phase transformation-induced plasticity (TRIP) effect during static loading. The TRIP effect improves the strength and plasticity of high-manganese steel, thus making this steel applicable in auto body parts. Previous studies have focused on the phase transformation during dynamic deformation. Meyers et al.[7] reported that γ (austenite) → ε-M (hexagonal close-packed (hcp) martensite) → α′-M (body-centered cubic (bcc) martensite) transformation occurred in the shear bands of 304 stainless steel at a high strain rate of 10^4 s^{-1} and that martensite was particularly generated at the intersection between the shear band and twins. Yang et al.[11] showed that phase transformations occurred inside and outside the shear bands and that these phase transformation products had a certain crystallographic orientation relationship with their parent matrix in Fe–15Cr–15Ni single crystal at a high strain rate of 10^4 s^{-1}.

Nevertheless, the mechanism of the TRIP effect and its role in resisting adiabatic shear failure during dynamic deformation in high-manganese TRIP steel remain unclear. Our previous work[13,14] demonstrated that the size and orientation of austenitic grains significantly influenced the TRIP effect during static deformation. Furthermore, reverse martensitic transformation occurred during heating in some specially oriented grains[14]. However, only a few studies have investigated these grains during dynamic deformation. Therefore, the current study aims to investigate the resistance of high-manganese TRIP steel to adiabatic shear failure and the role of the TRIP effect during

* Corresponding author. Prof., Ph.D.; Tel.: +86 10 82376968; E-mail address: yangp@mater.ustb.edu.cn (P. Yang).

http://dx.doi.org/10.1016/j.jmst.2014.03.027

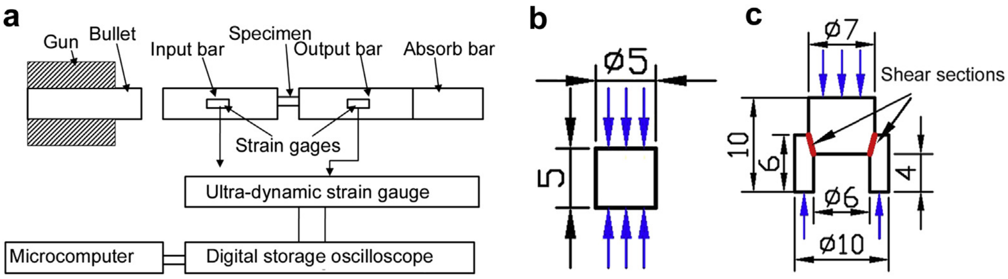

Fig. 1 Configuration of SHPB and specimens (arrows: loading condition): (a) SHPB, (b) cylindrical specimens, (c) hat-shaped specimens.

high strain rate deformation. The results can provide helpful information in the practical application of high-manganese TRIP steel in the prevention of high-speed crashes.

2. Experimental Procedure

High-manganese TRIP steel with Fe–18Mn–3Si–3Al–0.15C (in mass%) was selected, and the starting temperature of martensitic transformation (*M*s) was below room temperature. The forging steel was heated to 1423 K for 1 h followed by water quenching. Typical armor steel and interstitial free (IF) steel were compared with high-manganese TRIP steel to analyze their resistance to adiabatic shear failure. Dynamic compression was performed by applying a modified split-Hopkinson pressure bar (SHPB) (Fig. 1(a)), and the loading period of the shock wave was 80 μs. Cylindrical and hat-shaped specimens were prepared for the dynamic deformation (Fig. 1(b) and (c)). Both specimens were used to analyze the mechanical properties, but the hat-shaped specimens were also used to generate a forced shear section between the punched hat cylinder and base ring. The arrows in Fig. 1(b) and (c) represent the loading condition. The impact pressures were applied on the bullets, and the specimens were impacted at the corresponding strain rates. Thus, 0.7 MPa impact pressure (strain rate $> 2.5 \times 10^3$ s^{-1}) was applied to investigate the mechanical properties of the cylindrical specimens in various steels. Moreover, impact pressures of 0.3, 0.4, and 0.55 MPa were applied to analyze the characteristics of ASB formation in hat-shaped specimens. The strain rates reached up to 10^4–10^6 s^{-1}. The true stress, strain, and strain rate in the cylindrical specimens were calculated by using the method in literature[15]. The shear stress, true strain, and strain rate at the shear sections of hat-shaped specimens were obtained by using the equations in literature[16,17].

Metallographic examination was conducted at the shear sections (Fig. 1(c)). The specimens were grinded, polished in 5% $HClO_4$, and etched in 4% nital solution. Scanning electron microscopy (SEM) (ZEISS ULTRA 55 field emission microscope) equipped with HKL EBSD systems was applied to evaluate the microstructures, phase distribution, and orientation relationships.

3. Results and Discussion

3.1. Comparison of resistance to ASB formation

Two phases existed at room temperature prior to dynamic deformation, namely, austenite (γ) and ferrite (δ), which had volume fractions of 88.7% and 11.3%, respectively (Fig. 2(a)). The austenitic grains were equiaxial with diameters ranging from 80 to 150 μm. During dynamic deformation, the sequence of γ → ε-M → α′-M occurred in the γ of this steel (Fig. 2(b)).

High-strength armor steel with tempered α′-M and cementite, as well as high-plasticity IF steel with single-phase ferrite, was compared with TRIP steel to investigate the resistance to adiabatic shear failure (Fig. 3). The bullet hits the aforementioned steels at a pressure of 0.7 MPa, and the cylindrical specimens were compressed dynamically. The true stress–strain (ε–σ) curves showed that the strength of the armor, TRIP, and IF steels decreased (Fig. 3(a)). After elastic deformation, the true stress of TRIP steel increased, whereas those of armor and IF steels changed slightly. The value of $d\sigma/d\varepsilon$ was calculated (Fig. 3(b) and (c)). In armor steel, the $d\sigma/d\varepsilon$ undulated several times around zero (−2123 to 1575) before unloading under a strain of 0.04–0.19. In IF steel, the $d\sigma/d\varepsilon$ slightly increased and then decreased repeatedly at −457 to 480 under a strain of 0.07–0.42. In TRIP steel, by contrast, the $d\sigma/d\varepsilon$ fluctuated repeatedly at 1524 to 3088 under a strain of 0.05–0.32, which remained above zero. Since the heat energy from plastic work does not loss immediately, the temperature in the specimens increases under high strain rate deformation, thus inducing thermal softening and decreasing stress. The thermal softening effect combined with the strain

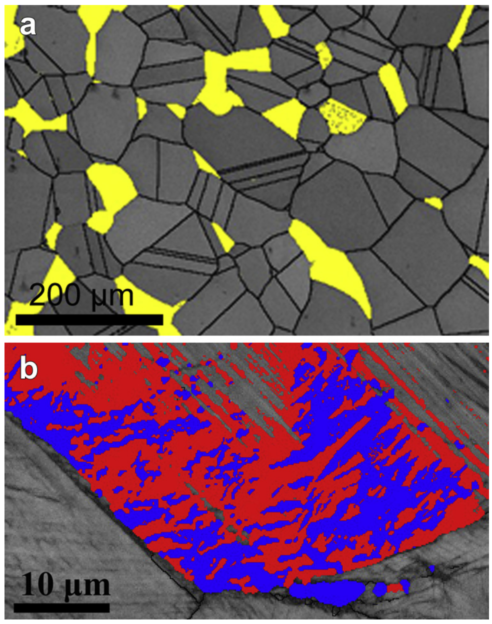

Fig. 2 Microstructures before (a) and after (b) dynamic deformation at 0.3 MPa impact pressure at the shear sections of the hat-shaped specimens (yellow: δ, gray: γ, red: ε-M, blue: α′-M, black lines: grain boundaries).