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Dynamic shear response and evolution mechanisms of adiabatic shear band in an ultrafine-grained austenite–ferrite duplex steel

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ABSTRACT

The dynamic properties of an intercritically annealed 0.2C5Mn steel with ultrafine-grained austenite–ferrite duplex structure were studied under dynamic shear loading. The formation and evolution mechanisms of adiabatic shear band in this steel were then investigated using interrupted experiments at five different shear displacements and the subsequent microstructure observations. The dynamic shear plastic deformation of the 0.2C5Mn steel was observed to have three stages: the strong linear hardening stage followed by the plateau stage, and then the strain softening stage associated with the evolution of adiabatic shear band. High impact shear toughness was found in this 0.2C5Mn steel, which is due to the following two aspects: the strong linear strain hardening by martensite transformation at the first stage, and the suppressing for the formation of shear band by the continuous deformation in different phases through the proper stress and strain partitioning at the plateau stage. The evolution of adiabatic shear band was found to be a two-stage process, namely an initiation stage followed by a thickening stage. The shear band consists of two regions at the thickening stage: a core region and two transition layers. When the adjoining matrix is localized into the transition layers, the grains are refined along with increasing fraction of austenite phase by inverse transformation. However, when the transition layers are transformed into the core region, the fraction of austenite phase is decreased and almost disappeared due to martensite transformation again. These interesting observations in the core region and the transition layers should be attributed to the competitions of the microstructure evolutions associated with the non-uniformly distributed shear deformation and the inhomogeneous adiabatic temperature rise in the different region of shear band. The 0.2C5Mn TRIP steel reported here can be considered as an excellent candidate for energy absorbers in the automotive industry.

1. Introduction

The introduction of new types of steels in the automotive industry, such as transformation-induced-plasticity (TRIP) steels with metastable austenite and twinning-induced-plasticity (TWIP) steels with stable austenite, has been driven by the requirements to obtain high strength, high ductility and high energy absorption in meeting the demands for both lightweight and safety (Fischer et al., 2000; Jacques, 2004; Grässel et al., 2000; Frommeyer et al., 2003). A new type of TRIP steel with both high strength and excellent ductility has been developed by increasing the volume fraction of retained austenite and refining the grain size into the submicron region through intercritical annealing of 5 wt.% Mn steel (Miller, 1972; Niikura and Morris, 1980; Han et al., 2009; Shi et al., 2010a; Luo et al., 2011). Formation of the austenite

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phase during intercritical annealing, the strain-hardening behaviors and the mechanical stability of individual retained austenite grains of such 5Mn TRIP steels have been reported recently (Shi et al., 2010a; Luo et al., 2011; He et al., 2013).

It is known that both TRIP effect and grain size refinement contribute to the increase of strength in steels (Miller, 1972; Niikura and Morris, 1980; Valiev and Langdon, 2006; Zhilyaev and Langdon, 2008; Meyers et al., 2006; Dao et al., 2007). The grain size was found to have a strong effect on the transformation behavior of austenitic grains, and two contradictory conclusions could be found on this grain size effect in the previous research (Somani et al., 2009; Huang et al., 2011; Iwamoto and Tsuta, 2000; Shi et al., 2010b). Somani et al. (2009) and Huang et al. (2011) reported that martensite transformation could be enhanced significantly by ultra-fined austenite grains in 301LN stainless steel, which was contrary to the common observations that smaller austenite grains are more stable against transformation (Iwamoto and Tsuta, 2000; Shi et al., 2010b). Other factors, such as strain rate, temperature and stress triaxiality, were also found to have strong influences on TRIP effect: (i) at the low strain rate range (<1/s), TRIP effect happens at earlier strain for higher strain rate, while the maximum volume fraction of martensite decreases with increasing strain rate (Das and Tarafder, 2009; Lee et al., 2014; Prüger et al., 2014; Zaera et al., 2014); (ii) TRIP effect is suppressed with increasing temperature at the low temperature range (77–332 K) (Prüger et al., 2014; Zaera et al., 2014; Lebedev and Kosarchuk, 2000); (iii) increasing stress triaxiality intensifies TRIP effect (Lebedev and Kosarchuk, 2000; Jacques et al., 2007).

An important point of interest and concern for TRIP steels in automotive industry is the high strain rate (10^2/s and above) behaviors as crash relevant structures (Prüger et al., 2014). At high strain rates, the generated heat cannot be dissipated to the environment which leads to a temperature rise in the material. So the high strain rate also has a high impact on the temperature dependent driving force for phase transformation. However, the influences of the ultra-high strain rate and the corresponding strain induced adiabatic temperature rise on TRIP effects are still unclear. Moreover, most energy absorbers require materials that are (i) capable of keeping a high value of the stress upon dynamic deformation, and (ii) able to show a large value of strain at failure ε_f. The second requirement is strongly dependent on the onset of strain localization which triggers material failure (Meyer and Manwaring, 1986; Meyers et al., 1994; Subhash et al., 1997; Jia et al., 2003; Wei et al., 2004; Xue et al., 2005; Bronkhorst et al., 2006; Wei et al., 2006a,b; Mishra et al., 2008; Yang et al., 2011; Yuan et al., 2012; Zaera et al., 2014). So the purpose of this paper is to investigate the mechanical properties for the 5Mn TRIP steel with ultra-fined grains (Shi et al., 2010a; Luo et al., 2011; He et al., 2013) under dynamic shear loading at high strain rate. The focus will be on the high strain rate deformation and temperature rise effects on transformation behaviors and how they affect the evolution of strain localization and the overall mechanical performance. In this regard, hat-shaped specimen set-ups in Hopkinson bar experiments were used to study the dynamic shear deformation behaviors for the 5Mn TRIP steel by controlling the dynamic shear displacements in the present study.

2. Experimental procedures

The TRIP steel used in the present study, with a nominal composition of 0.2 wt.% C and 5 wt.% Mn, was first melted in a high-frequency induction furnace under a vacuum and then cast into a 50 kg ingot (Shi et al., 2010a). The ingots were then homogenized at 1250 °C for 2 h, and forged between 850 °C and 1200 °C into rods with diameters of 16 mm, finally cooled in the furnace to room temperature (RT). The forged rods were austenized at 750 °C for half an hour and quenched in oil, and then intercritically annealed at 650 °C for 6 h in a box furnace under a vacuum and finally air cooled to RT. The heating rate was estimated to be around 40–60 °C/s during the intercritical annealing. The microstructure after intercritical annealing was examined by optical microscope (OM), electron backscattered diffraction (EBSD) and transmission electron microscope (TEM). The annealed sample surfaces for EBSD were first polished to 2000 grit and finally polished with 0.25 μm diamond paste and 0.05 μm SiO_2 aqueous solution, and then were electro-polished with 10% Nital at 20 V voltage and -20 °C to reveal the microstructure. Disks for TEM were cut with a thickness of 300 μm and polished down to 50 μm using 2000 grid SiC papers. Final thinning to electron transparency was achieved by ion milling.

All samples for mechanical testing were machined from the intercritically annealed rods by wire saw with loading direction parallel to the axis of rods. The hat-shaped specimen set-up for Hopkinson bar experiment is shown in Fig. 1(a), and the geometry and dimensions of the hat-shaped specimens are given in Fig. 1(b). The hat-shaped design has been widely used to study adiabatic shear band (ASB) in various metals (Meyer and Manwaring, 1986; Meyers et al., 1994; Xue et al., 2005; Bronkhorst et al., 2006; Mishra et al., 2008; Yang et al., 2011; Yuan et al., 2012). The hat shape is designed to concentrate shear deformation in a narrow zone facilitating the formation of a shear band (Meyer and Manwaring, 1986). Details of the Hopkinson-bar technique can be found elsewhere (Subhash et al., 1997; Song et al., 2009; Sunny et al., 2009). According to the one-dimensional elastic stress wave theory, the shear stress, the shear displacement, the nominal shear strain and the nominal shear strain rate can be calculated as:

$$\tau_s = E\left(\frac{A}{A_s}\right)\varepsilon_T \tag{1}$$

$$U_s = 2C_0\int_0^t \varepsilon_R d\tau \tag{2}$$

$$\gamma_s = U_s/t_s \tag{3}$$

$$\dot{\gamma}_s = \frac{2C_0}{t_s}\varepsilon_R \tag{4}$$