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Effect of strain rate on spatio-temporal behavior of Portevin–Le Châtelier bands in a twinning induced plasticity steel

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ABSTRACT

Uniaxial tensile tests at three strain rates are performed with the aid of the digital image correlation (DIC) technique to experimentally investigate the spatio-temporal behavior of PLC bands in a twinning induced plasticity (TWIP) steel. The whole strain fields of tensile specimens are acquired throughout the tests. Significant serration crests corresponding to band nucleation are observed on the true stress vs. true strain curves derived from DIC results beyond a critical true strain. The work hardening exponent (n-value) increases from ~0.08 to ~0.5 when true strain increases to the critical true strain, and beyond that, the n-value exhibits serrations with increasing true strain. Two typical nucleation modes of Type-A Portevin–Le Châtelier (PLC) bands are observed in all tests. Nucleation and propagation of PLC bands are described in details based on these two nucleation modes of Type-A PLC bands. The PLC band orientation, which indicates the angle between the normal direction of a PLC band and tensile direction, fluctuates during propagation, and the fluctuation amplitude increases during the development of a localized necking band from a PLC band before fracture. In particular, the effect of strain rate on the kinematics of Type-A PLC bands (band strain, band width and band propagating speed etc.) in the TWIP steel is quantitatively analyzed, and a new algorithm based on the DIC results is presented which includes the elongating effect of tensile specimens during deformation to show the actual kinematics of Type-A PLC bands.

1. Introduction

Austenitic twinning induced plasticity (TWIP) steels with high manganese content exhibit significant superiority in combination of strength and ductility compared to the other parts in the family of advanced high strength steels (Chung et al., 2011). It is employed to manufacture automotive structural components to reduce vehicle weight and improve crashworthiness due to high strength and high energy absorption capability. The twin formation is involved during plastic deformation of the steel due to low stacking fault energy (SFE) (Iker et al., 2007; Sato et al., 1989), which results in a high work hardening component since the increasing twin boundaries act as obstacles to dislocation glide by a dynamic Hall–Petch effect (Bouaziz and Guelton, 2001; Huang et al., 2006). The mechanism of twin formation in TWIP steels is explored in a recent report (Idrissi et al., 2010a).

The TWIP steels also typically show macroscopic unstable plastic flow in a wide temperature and strain rate range during plastic deformation, which leads to appearance of wave crests on stress strain curves. It is generally accepted that the serrated flow curve, which is characterized by negative strain rate sensitivity and limited post-uniform elongation (Chen et al., 2007), is due to dynamic strain aging (DSA) (Kim et al., 2009), i.e., the dynamic interaction between mobile dislocations and solute atoms whereby the dislocations are temporarily arrested by local obstacles (forest dislocations, precipitates, etc.) (Cuddy and Leslie, 1972; Kubin and Estrin, 1990). The DSA leads to localized deformation and gives rise to Portevin–Le Châtelier (PLC)

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bands due to the repetitive aging and depinning of dislocations by obstacles (Bouaziz et al., 2011). In addition, add of Al to TWIP steels results in less obvious PLC effect because the Al reduces the activity and diffusivity of carbon in austenite (Shun et al., 1992; Zuidema et al., 1987). Nevertheless, it is also questioned whether the diffusion coefficient of carbon in austenite is sufficiently high at room temperature to account for the PLC effect (Allain et al., 2008; Lebedkina et al., 2009).

According to the dynamic appearance characters, the PLC bands can be classified into three types. Type A bands show continuous propagation across the tensile specimen, and the propagation of Type B bands is discontinuous and hopping, while the nucleation of Type C band looks random (Chihab et al., 1987; McCormick, 1971). Type A bands have been observed in TWIP steel at room temperature or lower temperatures, and Type B bands at higher than room temperatures (Bouaziz et al., 2011). Portevin–Le Châtelier effect has already attracted interests of lots of metallurgists and was investigated by using a series of methodologies, digital image correlation (Hector et al., 2010; Renard et al., 2010; Zavattieri et al., 2009), infrared cameras (Allain et al., 2008; Kim et al., 2009) and laser extensometers (Hähner et al., 2002).

In order to provide a further insight into the spatio-temporal behavior of PLC bands in TWIP steels at room temperature, tensile tests were conducted with the aid of DIC technique. Two nucleation modes of Type-A PLC bands in the TWIP steel are described in details, and some equations are proposed to determine the band width and the band propagation speed; hence, the effect of applied strain rate on the kinematics of PLC bands are quantitatively analyzed.

2. Experimental

The material used in this work is a TWIP steel sheet with a nominal thickness of 1.5 mm, and its chemical compositions are listed in Table 1. Tensile specimens follow the ASTM B557M.9023-1 standard with a parallel 76 mm gage length and 12.7 mm gage width as shown in Fig. 1. The tensile specimens were oriented at 0° to the rolling direction. Prior to testing, one surface of each specimen was coated with a thin layer of white paint. After a short drying period, black paint droplets (0.5–2.0 mm) were applied such that no single black droplet filled an entire pixel subset in the DIC post processing step. Testing was conducted on an Instron 5582 Universal Testing Machine, where a load cell (30 kN) with a resolution of 0.01 N was installed, and the crosshead speeds were set to 0.6, 3 and 15 mm/min giving nominal strain rates ($\dot{\varepsilon}_N$) of 1.33×10^{-4}, 6.67×10^{-4} and $3.33 \times 10^{-3}\ \mathrm{s}^{-1}$, respectively. Stereo digital image correlation (Orteu and Schreier, 2009) was employed to measure full-field strains during testing of each specimen to fracture. Digital images were recorded using two-5 Megapixel Grasshopper™ CCD Cameras with a maximum framing rate of 30 frame/s from Point Grey Research, Inc. and the computer acquisition software Vic-Snap from Correlated Solutions. The framing rates were set as 1/4, 2 and 10 frame/s for the specimens tested at 0.6, 3 and 15 mm/min, respectively. For calculation of displacements and strains, a grid point spacing of 7 pixels in 29 × 29 overlapping square pixel subsets was chosen for post-processing the deformation fields over a 98 mm × 12.7 mm region of interest positioned on the specimen including two transition areas between parallel length section and gripper end. Each image was tagged with a load and crosshead displacement from the analog output of the Instron testing machine. Two specimens were repeated at each strain rate to confirm reproducibility of the measured strain fields.

Table 1
Chemical compositions of the TWIP steel (wt.%).

C	0.59	Cu	0.04
Mn	17.2	P	0.02
Al	1.0	Mo	0.01
Cr	0.56	V	0.004
Ni	0.23	Ti	0.002
Si	0.12	S	0.002

3. Results and discussion

3.1. Mechanical properties

When processing the flow curves of the TWIP steel, the following method (Zavattieri et al., 2009) is employed. From volume constancy of plastic deformation and force equilibrium along the tensile direction, the true stress ($\bar{\sigma}$) is

$$\bar{\sigma} = F \cdot \exp(\bar{\varepsilon}_1)/(w_0 \cdot t_0) \tag{1}$$

where F is the crosshead load, w_0 and t_0 are the initial specimen width and thickness, respectively. Note that $\bar{\varepsilon}_1$ is an averaged axial true strain, also known as the global true strain, corresponding to a standard tensile test with an extensometer where the gage length is 50 mm that converts the two-dimensional strain field, $\varepsilon_1(i,j)$ at each grid point (i,j), to a uniaxial field.

$$\bar{\varepsilon}_1 = \frac{1}{M \cdot N} \sum_{j=1}^{N} \sum_{i=1}^{M} \varepsilon_1(i,j) \tag{2}$$

where M is grid point number computed over a 50 mm DIC area of interest positioned above the center of the tensile specimen, and N is the grid point number transverse to the tensile axis.

$\bar{\sigma}$ vs. $\bar{\varepsilon}_1$ curves of TWIP steel specimens pulled at three nominal strain rates are shown in Fig. 2. At the same global true strain, the true stress of TWIP steel decreases with increasing applied nominal strain rate, namely, the TWIP steel shows negative strain rate sensitivity, which is a typical character of dynamic strain aging (DSA) (Rizzi and Häner, 2004). The stress difference increases with increasing global true strain and the nominal strain rate has little influence on the yield strength of the TWIP steel. All three curves exhibit significant serrations when the global true strain is greater than a critical value $\bar{\varepsilon}_{1c}$. Each significant serration on the flow curves (Fig. 2) corresponds to the nucleation of a PLC band.

Fig. 3 shows the evolution of work hardening exponent, n-value, with the global true strain of the TWIP steel. n-va-