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On the characteristics of Portevin–Le Chatelier bands in cold-rolled 7Mn steel showing transformation-induced plasticity

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ABSTRACT

Strain localization during tensile deformation of cold-rolled and annealed 7Mn steel were investigated under various strain rates and deformation temperatures. The retained austenite grain size, strain rate and deformation temperature all have remarkable influences on the appearance of PLC bands. Higher strain rate clearly suppressed the formation of PLC bands whilst deformation temperature had a more complicated influence. During the room-temperature deformation at the quasistatic strain rate of 6.67×10^{-4}/s, Lüders bands appeared in all specimens whilst PLC bands only in the specimens that were annealed above 700 °C. Digital image correlation (DIC) analysis showed the specimen annealed at 700 °C exhibited the type A PLC bands during the entire period of deformation; whilst the one annealed at 720 °C showed the more complicated type A+B bands before 600s and the type A bands afterward. All of these phenomena have been discussed in relation to the interaction of C atoms/C-Mn pairs and dislocations for sound interpretation.

1. Introduction

At present, medium Mn steels receive worldwide attention due to the significant superiority in the combination of strength and ductility as well as the reasonable cost compared to other advanced high strength steels. In the past decade, numerous works have been focused on achieving larger volume fraction of retained austenite with proper stability by optimizing chemical compositions and controlling intercritical annealing (IA) conditions (Merwin, 2007; Suh et al., 2010; Cao et al., 2011, 2012; Park et al., 2013; Lee and De Cooman, 2014a, 2014b; Cai et al., 2015). Updated design of chemical compositions of medium Mn steel could lead to both transformation induced plasticity (TRIP) and twinning induced plasticity (TWIP) effects, which occur during plastic straining to enhance work hardening capacity (Lee et al., 2014a; Lee et al., 2014b; Cai et al., 2015). Whilst different choices of IA process may result in various combinations of strength and ductility, which can satisfy different application demands. In our last paper (Yang et al., 2017), influence of IA temperature on the microstructures and the tensile properties of 7%Mn-0.3%C-2%Al (all in wt.% unless otherwise mentioned) was discussed. Lüders band was found for all IA temperatures but serrated flow only occurred at higher annealing temperatures, *i.e.* 700 °C and 720 °C, when the strain rate was about 6.67×10^{-4}/s. Deformation instability, which was demonstrated in detail by Hall (1970) and Estrin & Kubin (1995) in their monographs, was also researched extensively by the other researches in ferritic steels (Kyriakides and Miller, 2000; Yoshida et al., 2008; Wenman and Chard-Tuchey, 2010; Hallai and Kyriakides, 2013; Schwab and Ruff, 2013; Akama et al., 2014) and even shape memory alloys (SMAs) (Favier et al., 2007; Chan et al.,

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2012; Kato and Sasaki, 2013; Bechle and Kyriakides, 2016; Zheng et al., 2017). In cold-rolled and annealed medium Mn steel, Han et al. (2014) indicated that the globular-shaped ferrite, which contained low densities of mobile dislocations due to active recovery, was softer than the retained austenite (this was testified by He et al. (2013)), thus ferrite would yield first during deformation and exhibit yield point elongation to produce sufficient mobile dislocations. This mechanism is similar to that in ferritic steels. Ryu et al. (2013) studied Lüders strain in medium Mn steel by digital image correlation (DIC) and X-ray diffraction (XRD), he found that the localized strain triggered by Lüders band could cause the unstable austenite transforming to martensite, therefore they concluded that TRIP effect in medium Mn steel is mainly strain-induced. This phenomenon was also observed by Wang et al. (2016). Distinct from the extensively studied Lüders band, to date only Wang et al. (2017) and Sun et al. (2017) concerned the serrated plastic flow and the concomitant Portevin–Le Chatelier (PLC) effect in medium Mn steel, to the author's knowledge. Recently, Yu et al. (2017) observed that PLC bands could cause cracks along grain boundary junctions and mechanical twin boundaries within the edges and side surfaces of a tensile specimen, they concluded PLC effect is detrimental to the post-uniform elongation and the reduction ratio of TWIP steel. Okamoto et al. (1991) observed the similar phenomenon in a martensitic steel. Halim et al. (2007) also observed that the intensified PLC effect is harmful to the ductility of Al alloys. Thus, it is of both theoretical and practical significance to study the PLC effect in metallic materials.

It is universally accepted that the serrated flow, usually happening in low-Al-content TWIP steels (Chen et al., 2007; Zavattieri et al., 2009; Lee et al., 2011, 2014; Jin and Lee, 2012; Hong et al., 2014; Min et al., 2014; Kim and De Cooman, 2016; Yu et al., 2017) and Al alloys (Benallal et al., 2008; Ait-Amokhtar and Fressengeas, 2010; Cheng et al., 2015; Klusemann et al., 2015; Kim et al., 2017; Shibkov et al., 2016; Cai et al., 2017), is related to the dynamic interaction between gliding mobile dislocations and solute atoms, namely the dynamic strain ageing (DSA) mechanism. Different from TWIP steels and Al alloys, the microstructure of medium Mn steel is composed of sub-micron grained ferrite and austenite, and the unstable austenite may transform to marteniste during plastic deformation. Thus, the serrated flow should be affected by the dynamic martensite transformation during straining. Actually, in the other two categories of alloys, namely SMAs and β-Ti alloys, dynamic phase transformation can indeed cause the deformation instability. Shaw & Kyriakides (1997) indicated that the Lüders-type deformation in NiTi SMA results from the stress-induced martensitic transformation. Feng & Sun (2006) discovered two types of instabilities during the transformation process of polycrystalline NiTi microtube. One was the instability of a homogeneous deformation, which led to the phenomenon of domain nucleation; the other was the instability of the existing domain wall, which led to interface branching and morphology transition. Ahadi and Sun (2013) and Sun et al. (2014) also studied the effects of grain size on phase transition behavior of nanocrystalline SMAs. They found when the grain size falls below a critical value ($\sim$60 nm), both the hysteresis loop area (H) and temperature dependence of phase transition stress ($d\sigma/dT$) decreases rapidly and tend to vanish. Kato & Sasaki (2013) and Ozcan et al. (2017) even observed serrated flow in NiTi and Fe-Mn-Al-Ni SMAs respectively, but it seems there were some differences in the formation mechanisms. Kato & Sasaki (2013) considered that stress-induced martensite transformation coupled with accommodation slip may be the origin of the observed stress serrations, while Ozcan et al. (2017) argued the stress vibrations are related to the transformation of an individual austenite grain to a single variant martensite. In β-Ti alloys, the shearing of ω phase can form ω-free channels and cause load-drops during straining (Lai et al., 2015), then the dynamic precipitation of α phase within the prior ω-free channels could hinder dislocations and cause stress serrations in the flow curves at elevated temperatures (Choudhuri et al., 2016).

In the previous research in medium Mn steel, Wang et al. (2017) described the kinematic and thermal characteristics of PLC bands during straining in 7%Mn-0.14%C-0.23%Si but he didn't elucidate the cause of DSA. Sun et al. (2017) researched the correlation between discontinuously strain-induced martensite transformation and PLC effect in 10%Mn-0.2%C-2.9%Al, he only observed the type A PLC band during straining and he attributed this merely to the value of stacking fault energy of retained austenite. In fact, the mechanism of serrated flow in medium Mn steel might be more complex than that expected, since the IA temperature not only controls the occurrence but also the types of PLC bands, as presented and discussed in the present paper.

2. Experimental procedures

The studied 7Mn steel, 7%Mn-0.3%C-2%Al, was melted in a vacuum induction furnace and then cast into an ingot. The ingot was homogenized at 1200 °C for 2 h and forged between 1200 °C and 850 °C into slabs. The forged slabs were reheated to 1180 °C for 1 h and hot-rolled to 3.8 mm-thick plates. The hot-rolled plates were annealed at 700 °C for 30 min and then cold rolled to about 1.1 mm thickness with the reduction of about 70%. Then the cold-rolled sheets were intercritically annealed at the temperatures of 680 °C, 700 °C and 720 °C for 1 h and finally cooled to room temperature in air, these specimens are designated S680, S700 and S720 for discussion, respectively.

Tensile samples were machined from the annealed strips along the rolling direction with the gauge length and width of 50 mm and 10 mm. Tensile tests with different cross-head speed ranging from 0.2 mm/min to 100 mm/min (the equivalent strain rate was about 6.67×10^{-5}/s$\sim$$3.34 \times 10^{-2}$/s) were performed at room temperature in a WE-300 testing machine. High temperature and low temperature tensile tests were performed at 100 °C (373 K) and −50 °C (223 K) by using a MTS tensile machine at the strain rate of 6.67×10^{-4}/s. Two specimens were tested for each set of condition. The DIC experiment was conducted by PMLAB DIC system (Cheng et al., 2015; Cai et al., 2017) at CAS Laboratory of Mechanical Behavior and Design of Materials in University of Science and Technology of China. During the DIC experiment, the tensile tests were performed at an Instron 5582 testing machine with cross-head speed of 2 mm/min (the equivalent strain rate was about 6.67×10^{-4}/s) at room temperature, digital images were recorded by CCD camera with 4 frames per second. The reconstructed strain field showed strong strain localization along the tensile direction thus only the longitudinal strain was considered to characterize the deformation bands. Microstructures of specimens were analyzed by electron back-scattered diffraction (EBSD) in scanning electron microscopy equipped with field emission gun (FEI, Quanta 650) and