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Correlation between deformation behavior and austenite characteristics in a Mn-Al type TRIP steel

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ABSTRACT

We investigate here the correlation between deformation behavior and retained austenite characteristics in a medium-Mn transformation-induced plasticity (TRIP) steel. The sample was characterized by a dual-phase microstructure consisting of ultra-fine grained ferrite and retained austenite with relatively high mechanical stability after annealing at 700 °C for 5 h. Both lath-like and blocky (granular) retained austenite with volume fraction of 38.7% and relatively inhomogeneous grain size was obtained. The tensile specimen exhibited outstanding mechanical properties with yield strength of 745 MPa, tensile strength of 1005 MPa and total elongation of 46%, as well as a distinctive work hardening behavior. The in-depth investigation on deformation behavior demonstrated that the transformation mechanism of retained austenite during deformation was strain-induced and the yielding behavior was controlled mainly by the deformation of soft ferrite phase. As to the multi-peak work hardening behavior, it is believed to be attributed to the inhomogeneous and discontinuous occurrence of TRIP effect, which resulted from the inhomogeneous stability of retained austenite. Moreover, the orientation of retained austenite (Schmid factors) was proved an important factor in determining the mechanical stability of retained austenite upon deformation, in addition to the heterogeneity of grain size. These two factors together resulted in the inhomogeneous stability of retained austenite.

1. Introduction

Currently, significant research on automotive steels is aimed at decreasing gas emission and increasing fuel efficiency by reducing vehicle weight. One of the effective ways to reduce vehicle weight is to use steels of high specific strength and outstanding ductility. Thus, medium-Mn steel, as the third generation advanced high strength steel (AHSS), has received widespread concern due to its excellent combination of strength and ductility [1–9]. It is well known that the mechanical properties and deformation behavior of medium-Mn steel are extremely sensitive to retained austenite characteristics, such as the volume fraction, mechanical stability, grain size and morphology [10–16]. The investigation on retained austenite characteristics hence becomes a hot issue.

Chen et al. [12] studied the effects of retained austenite characteristics on tensile properties and low-temperature impact toughness of medium-Mn steel, and claimed that it was the difference in mechanical stability and morphology of retained austenite resulted in different mechanical properties. The film-like retained austenite possessed relatively higher mechanical stability can greatly improve low-temperature toughness, but its contribution to strain hardening capacity is limited. While, the blocky retained austenite with poor mechanical stability has the opposite effect. Lee et al. [14] changed the deformation mechanism of Fe-0.26C-10.1Mn-6.3Al (wt%) steel from simplex transformation-induced plasticity (TRIP) effect to coupled TRIP + twinning-induced plasticity (TWIP) effect by fabricating an inhomogeneously grained structure of retained austenite. The studied steel was hence endowed an excellent combination of strength and ductility of ~37 GPa %, which was comparable with that of high-Mn lightweight steel. Cai et al. [15,16] described an intriguing and unique serrated flow behavior in medium-Mn TRIP steel, which was characterized by the serrated fluctuation on the engineering stress-strain curves. They attributed this deformation behavior to a so-called discontinuous TRIP effect involving stress relaxation and transfer during deformation. In-depth study demonstrated that the discontinuous TRIP effect was a consequence of heterogeneous degree of austenite stability, which resulted from the non-uniform manganese distribution [16–18]. Later, they found that the different austenite grain size was also an important factor that resulted in the heterogeneous of austenite stability as well as the discontinuous TRIP effect, which finally resulted in the serrated

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fluctuation behavior [19]. Similar strain hardening behavior was found in a low-carbon medium-Mn steel plate by Chen et al. [20]. They considered the multi-peak strain hardening behavior was mainly related to retained austenite characteristics, such as multi-type morphology, multi-scale size and relatively poor mechanical stability.

In the present study, we prepared two medium-Mn steel samples with retained austenite of different mechanical stability but similar volume fraction and morphology. The deformation behavior was investigated in relation to the retained austenite characteristics. Particular interest was focused on the correlation between multi-peak work hardening behavior and inhomogeneous stability of retained austenite, and the underlying reason resulted in the inhomogeneous retained austenite stability was clarified.

2. Experimental procedure

Chemical composition of the Mn-Al type TRIP steel in wt% was Fe-0.2C-5.0Mn-0.5Si-1.5Al-0.05V. The studied steel was melted in a vacuum induction furnace and cast as 100 kg ingot, followed by forging into slab with thickness of 60 mm. The slab was then homogenized at 1200 °C for 2 h and hot rolled to 12 mm via 6 passes. The finish rolling temperature was controlled at 950 °C. Subsequently, the plate was quenched to room temperature with an average cooling rate of 80 °C/s. Two as-hot-rolled steel plates were subjected to intercritical annealing process, which involved isothermally holding at 700 °C and 715 °C for 5 h, respectively, and finally air cooling to room temperature.

The dilatometer experiments were performed using a Formastor-FII full-automatic thermal dilatometer and cylindrical specimens with dimensions of $\phi 3 \times 10$ mm were used. Tensile tests were conducted with a CMT5105-SANS universal testing machine at room temperature using tensile samples with gauge length of 30 mm and diameter of 6 mm. The crosshead speed was 3 mm/min. Microstructures of specimens were examined by JXA-8530F electron probe micro-analyzer (EPMA), Zeiss Ultra-55 field emission scanning electron microscope (SEM) equipped with electron backscattered diffraction (EBSD) and TECNAI G220 transmission electron microscope (TEM). The measurement of volume fraction of retained austenite before and after tensile deformation was performed on D/max2400 X-ray diffractometer (XRD) with Cu-Kα radiation, and the integrated intensities of the $(200)_\alpha$, $(211)_\alpha$, $(200)_\gamma$, $(220)_\gamma$ and $(311)_\gamma$ diffraction peaks were calculated to accurately determine the austenite fraction. Thermo-Calc software was used to determine the concentrations of C, Mn, Si and Al in ferrite and retained austenite. The specimens for EPMA observation were metallographically polished and etched by 4 vol% nital solution. The EBSD and XRD specimens were prepared by electro-polishing using a perchloric acid solution of 800 ml (alcohol: perchloric acid: distilled water = 14:1:1) to remove the residual stress. The TEM specimens were mechanically thinned to 50 µm, followed by punching to 3 mm diameter disks. Subsequently, the disks were electro-polished in a twin-jet machine using 9% perchloric acid solution under a voltage of ~29 V and temperature of ~ −10 °C.

3. Results

3.1. Dilatometer curves and microstructure characteristics

The dilatometric specimens that prepared from the as-hot-rolled plate were heated to 700 °C and 715 °C at a heating rate of 5 °C/s, respectively, and then isothermally annealed for 5 h followed by cooling to room temperature at a speed of 10 °C/s. The corresponding dilatometer curves presented in Fig. 1 show that reverted austenite formed during annealing at 715 °C for 5 h (designated as sample 715 °C@5 h) transformed to martensite, while no martensite transformation occurred in the sample annealed at 700 °C for 5 h (designated as sample 700 °C@5 h). The previous study revealed that austenite stability of medium Mn steel strongly depends on its chemical composition and grain size [21]. Considering there was no significant increase in austenite grain size with increasing annealing temperature from 700 °C to 715 °C, the chemical composition, namely the enrichment of C and Mn in austenite played the dominant role in governing austenite stability. The volume fraction of reverted austenite in two-phase region increased with increasing annealing temperature. Thus, the average concentration of C and Mn in reverted austenite decreased, leading to the decrease of austenite thermal stability and the corresponding martensite transformation in sample 715 °C@5 h.

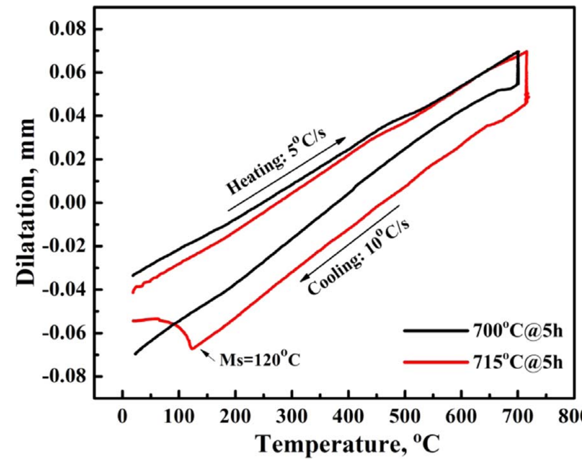

Fig. 1. Dilatometer curves showing reverted austenite formed in sample 715 °C@5 h transformed to martensite, while no martensite transformation occurred in sample 700 °C@5 h.

Fig. 2 shows typical SEM micrographs of the as-hot-rolled and annealed specimens. After hot rolling and quenching, lath martensite initial microstructure was obtained, without any retained austenite and coarse precipitates, as shown in Fig. 2(a). Based on the dilatometer experimental results, we can conclude that sample 700 °C@5 h possessed a dual-phase microstructure consisting of fine ferrite and retained austenite (Fig. 2b), while there must be a small amount of martensite in sample 715 °C@5 h besides ferrite and retained austenite (Fig. 2c) though they had the similar micrographs. It is noteworthy that both blocky and lath-like retained austenite was observed (Fig. 2b). Fig. 2(d) is the high-magnification view of the area denoted by red ellipse in Fig. 2(b). We can see that lath-like retained austenite with width of ~150–250 nm was always displayed between ferrite laths.

In the attempt to confirm the partitioning behavior of C and Mn during intercritical annealing, elements distribution analysis of sample 700 °C@5 h using EPMA was conducted and the results are presented in Fig. 3. It is clear that both blocky and lath-like retained austenite had higher C and Mn concentration but lower Al content than the adjacent ferrite laths (Fig. 3b–d), which implies that the partitioning behavior of alloying elements C, Mn and Al between austenite and ferrite did take place during intercritical annealing. Moreover, no obvious difference in C and Mn concentration was observed either between austenite grains with different morphology (blocky or lath-like), or at different locations (interior or boundary) of austenite grain. This means that annealing time of 5 h was enough for elements, C and Mn, to complete partitioning and homogenization in the studied steel. This is because the addition of Al increased the intercritical annealing temperature, and as a result, the diffusion of Mn was enhanced. In addition, Al can also optimize the austenite stability by suppressing cementite formation.

Fig. 4 shows the volume fraction of retained austenite before deformation and after fracture in sample 700 °C@5 h and 715 °C@5 h. Sample 700 °C@5 h contained 38.7 vol% retained austenite, and after tensile deformation to fracture, 9.3 vol% retained austenite still remained. In contrast, there was only 2.2 vol% retained austenite remained in sample 715 °C@5 h after fracture though it possessed relatively higher volume fraction of retained austenite (39.6%) before