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High strength-ductility nano-structured high manganese steel produced by cryogenic asymmetry-rolling

Bin Fu[a,b], Liming Fu[a,*], Shichang Liu[c], Huan Rong Wang[d], Wei Wang[d], Aidang Shan[a,*]

[a] School of Materials Science and Engineering, Shanghai Jiao Tong University, Shanghai, 200240, China
[b] School of Materials Science and Engineering, Shanghai Institute of Technology, Shanghai, 201418, China
[c] Shenyang Research Institute of Foundry, Shenyang, 110022, China
[d] Baosteel Research Institute, Shanghai, 201900, China

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ABSTRACT

A bulk nanostructured twinning-induced plasticity (TWIP) steel with high ductility and high strength was fabricated by cryogenic asymmetry-rolling (cryo-ASR) and subsequent recovery treatment. It was found that the cryo-ASRed TWIP steels exhibit simultaneous improvements in the ductility, strength and work hardening. Typical microstructures of the cryo-ASR TWIP steel were characterized by shear bands and intensive mechanical nano-sized twins induced by cryogenic deformation. These mechanical nano-scale twins remain thermally stable during the subsequent recovery treatment. It is believed that the ductility enhancement and high work-hardening ability for the cryo-ASR TWIP steels should be mainly attributed to the high-density pre-existing nano-scale twins.

1. Introduction

During the past two decades, high-Mn austenitic twinning induced plasticity (TWIP) steels with relatively low stacking fault energy (SFE) have received considerably scientific and technological interest, due to their unique comprehensive mechanical property with excellent combination of the high strength and ductility [1–9]. Nevertheless, compared with existing advanced high strength steels (AHSS), high manganese austenitic steels usually show extremely high elongation but relatively low yield strength (YS), which, to some extent, limits their implementation, particularly for anti-intrusion (crash) assemblies [5]. Grain refinement by cold rolling and the subsequent annealing [2,10–12], pre-straining and subsequent recovery treatment [13], precipitation strengthening [14,15] have been proved to be effective ways to improve the yield stress (YS) while maintain relatively high ductility in these steels.

Twinning is one of the prominent modes of deformation for metals and alloys. Formation of mechanical twins is quite common in the deformation process for materials with low stacking fault energies. Recent studies showed that the mechanical nano-twins induced by conventional cold rolling are stable during recovery treatments and therefore, the high YS can be obtained by introducing intensive nano-twins while the ductility is improved due to the decrease of dislocation density [16,17]. It is well known that dislocation glide is dramatically suppressed when the deformation of the materials is done at cryogenic temperatures. It was observed that the copper processed through cryogenic deformation and subsequent annealing exhibits very high strength but simultaneously maintains substantial higher ductility, due to the high density nano-sized twins (NT) induced by deformation [18–20]. Moreover, The tensile behavior and microstructures of the cryo-deformation and annealed treatment were also studied in Ni/Ni alloy [21,22], Al/Al alloy [23,24] and stainless steels [25]. However, rather limited attention is paid on the study of the cryogenic deformation of the TWIP steels.

Unlike symmetric rolling (SR), asymmetric rolling (ASR) involves different circumferential velocities of the two working rolls due to their different diameters or rotation speeds, which greatly enhance the total strain applied to the materials. This method has been proved to be effective for grain refinement [26]. In our previous workASR has been utilized to successfully fabricate the UFG pure Fe [27], pure Al [28], pure Ti [29] and TWIP steel [10]. In this study, we attempt to produce a high strength and high ductility high-Mn austenitic steel by cryogenically asymmetry rolling (cryo-ASR) and the following recovery treatment. The enhanced ductility is mainly attributed to the nano-sized deformation twins formed during cryogenic processing. The plastic deformation mechanism

* Corresponding authors.
E-mail addresses: lmfu@sjtu.edu.cn (L. Fu), adshan@sjtu.edu.cn (A. Shan).

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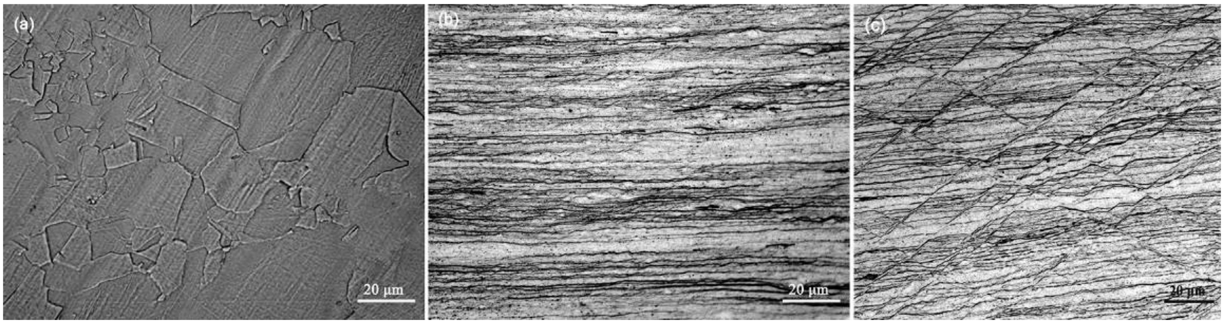

Fig 1. Optical micrographs of the high-Mn steel: (a) hot-rolled and 950 °C annealing, (b) ASR, (c) cryo-ASR.

and work-hardening behavior of this cryo-ASRed steel were also analyzed.

2. Experimental

The high-Mn steel with a chemical composition of Fe-25Mn-2.8Al-2.4Si-0.08C (wt%), which comprises a single phase of austenite at room temperature was used in the present study. An as-received hot-rolled plate of this steel with a thickness of 10 mm was annealed firstly at 950 °C for 2 h followed by air cooling. The steel was immersed in liquid nitrogen and held for 2 h. The steel was then asymmetrically rolled (ASRed) to a thickness of 2.5 mm with a total reduction of 75%. The rolling was done in multiple passes under lubrication. At the interval between the two rolling passes, the sample was immersed in the liquid nitrogen and held for 30 min to ensure that the cryogenic deformation was performed at 77 K. The cryogenically rolled sheet was subsequently annealed at 400 °C for 30 min. Uniaxial tensile tests were performed at ambient temperature using dog-bone-shaped specimens with a gauge length of 12 mm and a gauge width of 4 mm at strain rate of 5×10^{-4} s^{-1}. X-ray diffraction (XRD) measurements at a scan rate of 0.02°/s with a Cu target were made to identify the coexisting phases in the samples, which were chemically polished to eliminate the effects of cutting and machining. Transmission electron microscopy (TEM) observations were performed using a JEM-2100F microscope operating at 200 kV. TEM specimens were prepared by twin-jet electropolishing in a solution of 5% $HClO_4$ and 95% CH_3CH_2OH at −30 °C.

3. Results and discussion

The optical micrographs of the high-Mn steels for different processes are shown in Fig. 1. The hot-rolled and 950 °C annealed steel comprises equiaxed grains with an average grain size of about 25 μm and some annealing twins (Fig. 1(a)). After 75% ASR and cryogenic ASR (cryo-ASR), the elongated grains and some very narrow fluid-like shear bands are clearly observed, indicating that the severely plastic straining occurs in the material, as shown in Fig. 1(b) and (c). During the rolling deformation processing, the nano-sized banding structure involving high dislocations density is often formed in high-Mn steels, which is believed to significantly enhance the formation of recrystallized grains upon subsequent annealing [2]. Moreover, some shear bands are clearly observed in the cryo-ASRed steel, as presented in Fig. 1(c).

Fig. 2 displays the stress–strain curves and the corresponding strain hardening rate curves of the testing specimens for different processes. The strength of the samples by ASR and cryo-ASR processing are both significantly improved in contrast to the as-received coarse-grained (CG) TWIP steel. Especially, the yield strength (YS) and ultimate tensile strength (UTS) increases from 285 MPa and 618 MPa for as-received steel to 1420 MPa and 1540 MPa for the cryo-ASRed steel, respectively. Compared to the ASR steel, the strength and ductility for the cryo-ASR are both enhanced, as shown in Fig. 2(a) and (b). The YS, UTS and total elongation are improved from 1360 MPa, 1374 MPa and 7.4% to 1420 MPa, 1540 MPa and 12.3%, respectively. Noticeably, the yield strength of cryo-ASRed high-Mn steels by recovering at 400 °C even exceeds 1000 MPa, which is a very high value for TWIP steels [2]. More importantly, cryo-ASR samples still maintain a substantial work-hardening ability (Fig. 2(c)), which is different from the ASR samples, in which necking occurs immediately after yielding. This implies that the deformation behavior and strengthening mechanism of the cryo-ASRed steel are different from the normal ASRed TWIP steel. Moreover, the steel shows higher strain-hardening rate and larger uniform elongation for both cryo-ASR and cryo-ASR annealing at 400 °C in comparison of the RT-ASR steels. In addition, the yield stress of the steel after recovering at 400 °C is reduced about 400 MPa, which indicates that 400 MPa has been recovered by the thermal treatment through removal of dislocations from the rolled microstructure.

Fig. 3 demonstrates the XRD patterns for the RT-ASR and cryo-ASR high-Mn steels before and after tensile testing. The diffraction peaks are obviously broadened for ASR steels, indicating that the residual stresses and high density dislocation are induced by the deformation. The analysis shows that RT-ASR and cryo-ASR steels before tension are only composed of austenite, which shows no phase transformation occurrence during ASR and cryogenic ASR processing. However, the small but visible ε martensite peaks are found in the tensioned ASR samples and the obvious α'-martensite peaks are observed in the tensioned cryo-ASR samples. Evidently, the strain induced martensite (SIM) transformation (γ-α' or/and γ-ε-α' transformation) occurs during the tensile.

Typical TEM microstructures of the high-Mn steels are shown in Fig. 4. It is shown that the microstructure of ASR steel after recovering at 400 °C, mainly consists of a large number of deformation twins, where most of them have a width of 100 nm, dense tangled dislocations or dislocations cells and the overlapped stacking faults that are formed during the ASR processing. Microstructures of the cryo-ASRed steel contain high-density nano-sized twins (NTs) and shear bands, as illustrated in Fig. 4(b). Fig. 4(c) displays the detailed structural features of these intensive NTs. The corresponding selected area electron diffraction (SAED) pattern inset in the image indicates a regular twin relationship, as indicated in Fig. 4(d). The twin boundaries are straight and parallel to the compression and these twin lamellae have a narrow thickness of about 15 nm. These nano-sized deformation twins remain stable in the subsequent recovering at 400 °C, as presented in Fig. 4(d), which is consistent with the results in recent studies [16,17].

Quite different to the ASRed steel, shear bands (SB) that are narrow sheet-like regions of concentrated plastic flow, are observed in cryo-ASR steel (Fig. 4(b)). In terms of metals and alloys with low stacking fault energy (SFE), shear banding is an important

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