Materials Science & Engineering A 682 (2017) 164–167

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

Effect of initial grain size on the microstructure and mechanical properties of high-pressure torsion processed twinning-induced plasticity steels

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ARTICLE INFO

Keywords:
TWIP steel
Mechanical property
Twinning
High-pressure torsion
Initial grain size

ABSTRACT

The initial grain size of TWIP steel can affect the deformation mechanism during the HPT processes and the mechanical properties of severely deformed TWIP steels, contrary to the common belief that responses to the severe plastic deformation of metallic materials are not affected by initial grain size.

1. Introduction

Second generation advanced high-strength steels exhibit great strength and high ductility due to multiple deformation mechanisms [1]. In particular, twinning-induced plasticity (TWIP) steels containing 15–30 wt% Mn, develops deformation twinning during plastic deformation [2,3]. Because of this active deformation twinning, gliding of mobile dislocations is interrupted, a process called the dynamic Hall-Petch hardening effect, and the TWIP steels exhibit high strain-hardening exponents. This high strain hardening by active deformation twinning induces high strength and substantial, uniform elongation [4].

Deformation twinning has been reported not only in TWIP steels but also in other face-centered cubic (FCC) structured metallic materials. Shen et al. achieved a tensile strength of 1100 MPa with 15% elongation in ultra-fine-grained copper with nano-twinned structures [5]. Nano-twins are believed to behave as a grain boundary that interrupts dislocation glides [6].

Recently, many researchers have tried to generate nano-twins in TWIP steels by subjecting them to high strain using equal-channel angular pressing (ECAP) [7,8], cold rolling [9], and high-pressure torsion (HPT) processes [10,11]. According to the results of Langdon et al., the HPT-processed TWIP steel had sufficient deformation twins at the initial deformation stage, while ε-martensitic transformation occurred at the later deformation stage [12]. Moreover, Lapovok et al. reported that the appearance of deformation micro-bands and twinning was enhanced with an increase in processing temperature during the ECAP process [13]. However, most of the research has been concentrated on the acceleration of deformation twinning by increasing the processing temperature without any change of the initial microstructural variables (e.g., grain size). Recently, some researchers found a relation between twin formation and initial grain size during tensile deformation of TWIP steels, and demonstrated that enhanced deformation twinning occurs in initially coarse-grained TWIP steels (ICG-TWIPs) [14]. This enhanced deformation twinning in ICG-TWIPs is due to reduced twinning-initiation stress caused by an energy barrier that is lower than for initially fine-grained TWIP steels (IFG-TWIPs). This result implies that initial grain size changes deformation mechanisms during plastic deformation. Interestingly, most of the research mainly deals with a small deformation regime and large strain behavior has not been investigated, as far as the authors know. Indeed, it is common belief that severe plastic deformation (SPD) behavior of metallic materials is not affected by the initial grain size. However, this belief might not be true.

In this paper, the mechanical and microstructural behaviors of HPT-processed TWIP steel having different initial grain sizes were investigated in order to unveil the initial grain size effect in the large deformation regime. The mechanical properties of the TWIP steels were evaluated using tensile tests and microstructures were observed using transmission electron microscopy (TEM). In particular, X-ray peak profile analysis was performed to estimate the evolutions of dislocation density and twin boundary density during the HPT process. The twin boundary density in face-centered cubic materials (defined as an average number of twin boundaries) can be measured in the < 111

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http://dx.doi.org/10.1016/j.msea.2016.11.050
Received 23 October 2016; Received in revised form 13 November 2016; Accepted 14 November 2016
Available online 17 November 2016
0921-5093/

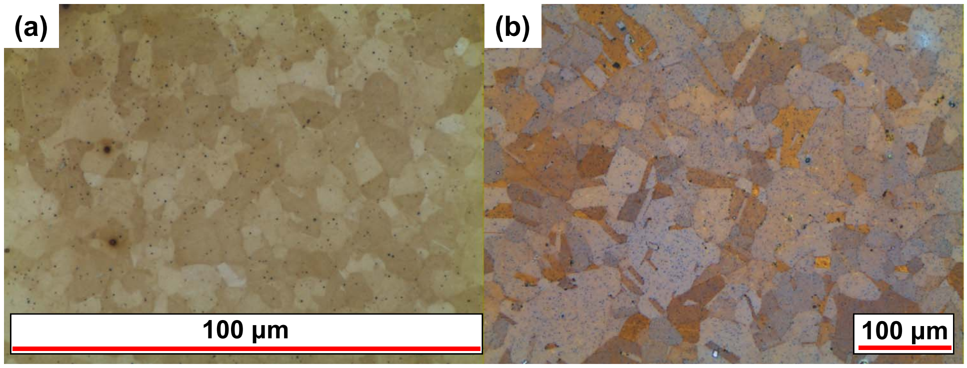

Fig. 1. Initial grain morphologies of the TWIP steels after annealing at (a) 850 °C for 2 h (IFG-TWIP), and (b) 1050 °C for 2 h (ICG-TWIP).

> directions in the {111} lattice planes [15].

2. Experimental

Commercial TWIP steels (Fe-17 wt%, Mn-1.8 wt%, Al-0.65 wt%, C) produced by POSCO were investigated. The received TWIP steels were annealed at 850 or 1050 °C for 2 h in an argon atmosphere; then air cooled. Fig. 1(a) and (b) represent the grain morphologies after annealing at 850 °C for 2 h (IFG-TWIP) and annealing at 1050 °C for 2 h (ICG-TWIP), respectively. The average grain sizes of the IFG-TWIP and ICG-TWIP were 7 and 50 μm, respectively. The HPT process was performed at room temperature by imposing 6 GPa pressure with 1/2, 1, 3, and 5 turns to disk shape specimens of 10.0 mm diameter and 1.4 mm thickness.

Tensile tests were performed at room temperature with a quasi-static strain rate of $1\times10^{-3}\ s^{-1}$ using a universal testing machine (Instron 1361, Instron Corp., Canton, USA). The center of the 1.5 mm gage length tensile specimens was located 2.5 mm away from the center of the disk specimen. The tensile strain was measured using digital image correlation (DIC; ARAMIS v6.1, GOM Optical Tech., Germany) with black and white speckles on the surface of the tensile specimen [16]. The dislocation density and twin boundary density of the HPT-processed TWIP steels were estimated using x-ray peak profile-analysis based on the convolutional multiple whole profile (CMWP) method [17]. The X-ray diffraction (XRD) patterns of the TWIP steels were measured from 30° to 100°. The microstructural evolution of the TWIP steels was observed using transmission electron microscopy (TEM), and selected area diffraction (SAED) analyses were performed in order to characterize the phase transformation in the HPT-processed TWIP steels. The TEM samples were prepared using a focused ion beam (FIB) 2.5 mm from the disk center.

3. Results and discussion

Fig. 2 represents the stress-strain curves of the HPT-processed TWIP steels. The un-deformed ICG-TWIP had a lower yield strength (300 MPa), but higher tensile strength (1050 MPa), elongation (97%), and strain hardening; than did the un-deformed IFG-TWIP (yield strength 570 MPa, tensile strength 1000 MPa, and elongation 85%). These are the result of the difference in twinning-onset stress: ICG-TWIP has lower twinning-onset stress (80 MPa) than IFG-TWIP (130 MPa) [18]. Hence, deformation twinning was activated earlier and to a greater extent in ICG-TWIP, which resulted in greater strain hardening. After the HPT process, both ICG- and IFG-TWIPs had increased strength while tensile elongation decreased. However, the elongation of the HPT-processed ICG-TWIP steel dramatically decreased to 2.5% from 97% tensile elongation in its un-deformed state. Indeed, the HPT-processed ICG-TWIP steel exhibits brittle deformation, and this embrittlement is attributed to ε-martensitic transformation during tensile tests.

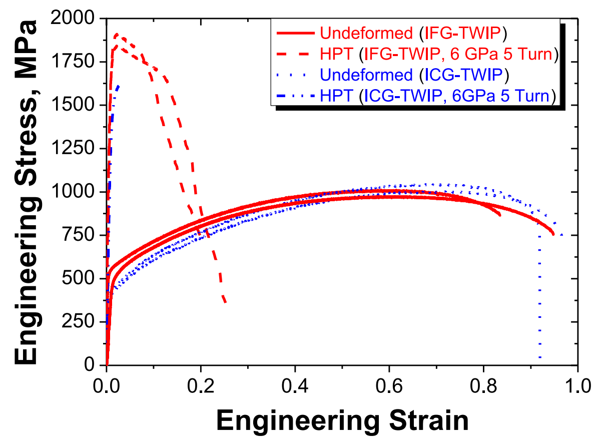

Fig. 2. Stress-strain curves of the undeformed and HPT-processed TWIP steels. (Red: IFG-TWIP, Blue: ICG-TWIP).

Fig. 3(a) and (b) represent the microstructures of the 6 GPa and 5 turns HPT-processed IFG-TWIP and ICG-TWIP steels, respectively. Nano-twins were observed in both IFG-TWIP and ICG-TWIP steels. Fig. 3(c) shows the observed nano-twins in the austenite grain of ICG-TWIP. In addition, ε-martensite SAED ring patterns existed in the HPT-processed ICG-TWIP while the HPT-processed IFG-TWIP has austenite SAED patterns only. The existence of ε-martensite not only showed in SAED patterns, but was also proved by the XRD results, as shown in Fig. 3(d). The XRD results indicate that ε-martensite transformation occurred in the HPT-processed ICG-TWIP, and that transformed ε-martensite contributes to the embrittlement of the HPT-processed ICG-TWIP, as shown in Fig. 2.

Fig. 4 plots the dislocation densities and twin boundary densities of the HPT-processed TWIP steels. Both dislocation density and twin boundary density are logarithmically increased with increasing the number of HPT turns. These increased trends are related to the initial grain size. The IFG-TWIP shows higher dislocation density than the ICG-TWIP, while the twin boundary density represents an opposite tendency. Therefore, it can be concluded that the deformation mechanisms of the HPT-processed TWIP steels depend on the initial grain size.

The grain size of a material is linked to the twin initiation stress and the stacking fault energy (SFE). The twin initiation stresses originate from the Hall-Petch-type relationship due to the reduced slip length, which makes it difficult to nucleate twins [18]. In ICG-TWIP, deformation twinning is activated due to its low twin initiation stress, and ε-martensitic transformation occurs. Both the deformation twins and ε-martensite result from the motion of partial dislocations on (111) planes in austenite, and the violation of partial dislocations during twin growth lead to ε-martensite transformation [19]. In IFG-TWIP, the formation of deformation twinning is reduced by strong twin initiation stress, and dislocation-based deformation becomes the primary deformation mechanism [14]. In the SFE scheme, the domain size of a