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Tensile properties and deformation mode of Si-added Fe-18Mn-0.6C steels

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ABSTRACT

The effects of Si concentration and austenite grain size (AGS) on the tensile properties, stacking fault energy (γ), and deformation mode of Fe-18Mn-0.6C (wt.%) steel were investigated to improve the yield strength (YS) of twinning-induced plasticity (TWIP) steel. The 3% Si-added steel revealed the higher YS than previous TWIP steels at the same level of AGS. In particular when the AGS was ~6.8 μm, its YS reached ~593 MPa, which is comparable to the YS (613 MPa) of transformation-induced plasticity steel with a tensile strength of 980 MPa. The measured γ of 3% Si-added steel was exponentially decreased with grain coarsening primarily due to the reduction of micro-strain, finally reaching its intrinsic γ (γ_{int}) at the AGSs above ~70 μm. This indicates that the γ_{int} measurement by means of X-ray diffractometry must be performed using coarse-grained specimens with the AGSs above ~70 μm. Critical resolved shear stresses for twinning (τ_{twin}) and ε-martensitic transformation ($\tau_{\varepsilon\text{-}mart}$) were evaluated as a function of AGS in (0-3%) Si-added steels. Whereas the τ_{twin} value was slightly decreased with increasing AGS or Si concentration, the $\tau_{\varepsilon\text{-}mart}$ value was more significantly reduced. This indicates that ε-martensitic transformation precedes mechanical twinning with increasing AGS or Si concentration. As a result, a transition of deformation mode from mechanical twinning to ε-martensitic transformation occurred with grain coarsening in Si-added steels. A critical AGS for the transition of deformation mode was reduced from ~69 μm to ~15 μm with increasing Si concentration from 0.5 wt.% to 3.0 wt.%.

1. Introduction

Fe-high Mn twinning-induced plasticity (TWIP) steel has been spotlighted as one of advanced high strength steels (AHSSs) due to its high ultimate tensile strength (UTS) above ~800 MPa and high ductility above 60% [1–3]. However, the yield strength (YS, ~300 MPa) of TWIP steel with the average austenite grain size (AGS) of ~30 μm [4,5] is much lower than the YS (600-800 MPa) of other AHSSs, such as dual-phase (DP) steel [6] and transformation-induced plasticity (TRIP) steel [7] with the UTS of 980 MPa.

Therefore, to improve the YS of TWIP steel, grain refinement was first attempted by recrystallization occurring during annealing of a cold-rolled sheet [8–10]. For example, the YS of Fe-18Mn-0.6C-1.5Al (wt.%) TWIP steel was increased from 295 MPa to 477 MPa with decreasing AGS from 32 μm to 2.4 μm, although total elongation (TE) was decreased from 62% to 47% due to the suppression of mechanical twinning by grain refinement [8].

In recent, some of present authors [11] reported an increase of YS from 387 MPa to 452 MPa by the addition of 1.5 wt.% Si to Fe-18Mn-0.6C (wt.%) TWIP steel with an average AGS of 9 μm due to the solid solution of Si in *fcc* austenite. The UTS was also raised without a significant loss of TE due to active mechanical twinning, particularly secondary twinning caused by the reduction in stacking fault energy (SFE) [11–13]. In addition, the addition of Si reduced the serrations on the tensile stress-strain curve like the addition of Al most likely due to the suppression of dynamic strain aging (DSA) [11].

However, the 1.5 wt.% Si-added steel still exhibited the lower YS (452 MPa) compared to DP and TRIP steels and some serrations although they were weakened. These results stimulated an additional investigation on the tensile properties of TWIP steel with a higher Si concentration than 1.5 wt.%. However, an increase in Si concentration reduces SFE further so that the deformation mode may change from mechanical twinning to ε-martensitic transformation which is vulnerable to hydrogen embrittlement [14,15].

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The grain size also influences a transition of deformation mode [16] as well as the YS.

In the present study, therefore, both tensile testing and microstructural observation were performed using various specimens of Fe-18Mn-0.6C-3Si (wt.%) steel with the different levels of AGS and several specimens of Fe-18Mn-0.6C-(0 and 1.5)Si (wt.%) steels for comparison. Based on these experimental results, we comprehensively analyzed the effects of Si and AGS on the tensile properties, SFE, and deformation mode of Fe-18Mn-0.6C-(0, 1.5, and 3)Si (wt.%) steels.

2. Experimental procedures

Fe-18Mn-0.6C-(0, 1.5, and 3)Si (wt.%) steels were melted using a vacuum induction furnace and cast as three 30 kg ingots. Each ingot was reheated at 1473 K for 2 h in a protective nitrogen gas atmosphere, and hot-rolled to a 4-mm-thick plate at temperatures ranging from ~1373 K to 1173 K, followed by air cooling to room temperature. The chemical compositions of three steels were examined using the hot-rolled plates and are listed in Table 1. After surface descaling, a 3-mm-thick plate of each steel was cold-rolled to a 1.5-mm-thick sheet, corresponding to a thickness reduction of 50%. Specimens for microstructural observation were taken from the cold-rolled sheet and were annealed for 10 min at temperatures ranging from 1073 K to 1473 K to vary the AGS, followed by water quenching to room temperature.

Microstructures of the annealed specimens were observed using a field-emission scanning-electron microscope (FE-SEM; JEOL, JSM-7001F) operated at 20 kV and an electron backscattered diffractometer (EBSD; Hikari, EDAX-TSL). The step size for EBSD analysis was 0.01 μm. The EBSD specimens were prepared by mechanical polishing using SiC papers and a colloidal silica suspension, followed by electro-chemical polishing using a jet-polisher, which was performed at 288 K with an applied potential of 14 V for 2 min in a mixed solution of 90% glacial acetic acid and 10% perchloric acid. The EBSD data were post-processed using TSL-OIM Analysis 6.1 software by standardization of the confidence index (CI), followed by a single iteration of grain dilation. The mean AGSs of annealed specimens were determined excluding annealing twin boundaries.

Tensile specimens were machined along the rolling direction from the cold-rolled sheets as ASTM E-8M-04 sub-size specimens [17] with a gauge portion measuring 6 mm in width, 25 mm in length and 1.5 mm in thickness. Tensile specimens were also annealed at the same condition employed for the specimens for microstructural observation, and then polished mechanically and electrochemically. Tensile testing was performed at room temperature at an initial strain rate of 1×10^{-4}/s using a servo hydraulic universal tensile testing machine (Instron, 3382). Fractured surfaces of tensile specimens were observed using a FE-SEM operated at 20 kV.

To investigate the behaviors of mechanical twinning and ε-martensitic transformation with tensile strain and AGS, some annealed tensile specimens were strained by 0.1, 0.15, and 0.25, and their microstructures were observed using the FE-SEM equipped with the EBSD. The step size for EBSD analysis was 0.01 μm.

Table 1
Chemical compositions of three steels used in the present study (in wt.%).

TWIP steel	Mn	C	Si	Fe
0Si	17.65	0.62	0.01	Bal.
1.5Si	17.70	0.59	1.59	Bal.
3Si	17.80	0.55	2.96	Bal.

The phase constituents in the strained and fractured tensile specimens of 3Si steel were also examined using an X-ray diffractometer (XRD, RIGAKU, D/MAX-RINT 2500) with a Cu target (λ = 1.5405 Å) operated at 30 kV. The scanning range, rate, and step size were 40°–100°, 2°/min, and 0.02°, respectively.

The SFE (γ) values of 3Si steel specimens with various AGSs were experimentally measured based on the following equation suggested by Schramm and Reed [18].

$$\gamma = \frac{K_{111}\omega_0 G_{(111)} a_0 A^{-0.37}}{\pi\sqrt{3}} \frac{\langle \varepsilon_{50}^2 \rangle_{111}}{\alpha} \quad (1)$$

where $K_{111}\omega_0$ is a proportionality constant with a value of 6.6 [18,19], a_0 was the lattice parameter measured from five XRD peaks of an austenite phase, and then the five measured values were averaged (~0.36 nm). A is the Zener anisotropy of 3.43 [18]. $G_{(111)}$ is the shear modulus of 61 GPa in the (111) fault plane of Fe-18Mn-0.6C-1.5Al (wt.%) TWIP steel [20,21].

The micro-strain ($<\varepsilon_{50}^2>_{111}$) was determined using a Williamson-Hall plot [22] obtained from the XRD results. The stacking-fault probability (α) was obtained using the following equation for both strain-free (0%) and 5%-strained specimens [18]:

$$\Delta 2\theta = (2\theta_{200} - 2\theta_{111})_{5\%} - (2\theta_{200} - 2\theta_{111})_{0\%} = -\frac{45\sqrt{3}}{\pi^2}\left(\tan\theta_{200} + \frac{1}{2}\tan\theta_{111}\right)\alpha \quad (2)$$

where $2\theta_{hkl}$ is the XRD peak position of a {hkl} plane.

The intrinsic SFE (γ_{int}) values of 0, 1.5, and 3Si steels were thermodynamically calculated using a sublattice model [12]:

$$\gamma_{\text{int}}\left(\text{mJ/m}^2\right) = 2\rho\left(\Delta G_{ch}^{\gamma\to\varepsilon} + \Delta G_{mag}^{\gamma\to\varepsilon}\right) + 2\sigma \quad (3)$$

where ρ (mol/m^2) is the molar surface density along the atomic plane of (111). $\Delta G_{ch}^{\gamma\to\varepsilon}$ (J/mol) and $\Delta G_{mag}^{\gamma\to\varepsilon}$ (J/mol) are the changes of chemical and magnetic Gibbs free energies between the γ and ε phases, respectively. σ (mJ/m^2) is the γ/ε interfacial energy. The ρ value was determined from the measured a_0 of γ austenite, and both $\Delta G_{ch}^{\gamma\to\varepsilon}$ and $\Delta G_{mag}^{\gamma\to\varepsilon}$ were calculated using thermodynamic properties adopted for the previous study carried out by Pierce et al. [12]. A constant value of 10 mJ/m^2 was employed for the σ value [23,24].

The shear moduli (G) of 0, 1.5, and 3Si steels were measured with the samples of $10 \times 10 \times 1.5$ mm^3 at room temperature using an ultrasonic measuring system (HKLAB CO., HKL-01-UEMT) and a pulse-echo method [25]. The G value of each steel was repetitively measured five times. The specimens for the measurement of the G values were annealed at 1073 K for 10 min, and then polished mechanically and electrochemically.

3. Results and discussion

3.1. Tensile properties of Si-added TWIP steels

0Si, 1.5Si, and 3Si steels annealed at 1073 K for 10 min possessed an austenite single phase with the similar grain sizes of 6.8–8.5 μm and a random texture (Supplementary Fig. 1). Shen et al. [26] and Barrales et al. [27] have also observed random texture in Fe-20Mn-0.6C (wt.%) TWIP steel annealed at 1173 K and in Fe-22Mn-0.6C (wt.%) TWIP steel recrystallized at 973 K, respectively. Fig. 1a shows room-temperature engineering stress-strain curves of annealed three steels. The YS was increased from ~387 MPa for 0Si steel to ~593 MPa for 3Si steel, which corresponds to an increase of ~69 MPa per 1 wt.% Si. The increase in YS is most likely due to the