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The effects of Si on the mechanical twinning and strain hardening of Fe–18Mn–0.6C twinning-induced plasticity steel

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Abstract

The stacking-fault energy (SFE), dislocation slip, mechanical twinning, strain hardening, and yield and tensile strengths were systematically investigated in Fe–18Mn–0.6C–1.5Si twinning-induced plasticity (TWIP) steel. The results were also compared with those for Fe–18Mn–0.6C and Fe–18Mn–0.6C–1.5Al TWIP steels. The SFE decreased by 4 mJ m^{-2} per 1 wt.% Si. The addition of Si increased both the yield strength, due mainly to solid solution hardening, and the tensile strength, owing to the high strain hardening that occurred while maintaining a large elongation of over 60%. To examine this high strain hardening, especially at low strains, the volume fractions of the primary and secondary mechanical twins were quantitatively evaluated by combining the merits of electron backscattered diffractometry and transmission electron microscopy. The volume fractions of both the primary and secondary twins were the highest in the Fe–18Mn–0.6C–1.5Si TWIP steel, which had the lowest SFE of the three TWIP steels. In particular, the volume fraction of the secondary mechanical twins increased rapidly with the addition of Si. The contributions of dislocation storage, mechanical twinning and dynamic strain aging (DSA) to the strain hardening were also quantitatively evaluated in the three TWIP steels. The Si-added TWIP steel had the highest strain hardening, due mainly to the active primary and secondary twinning, and experienced negligible DSA. In contrast, the Al-added TWIP steel exhibited the lowest strain hardening due to the reductions in both the mechanical twinning and DSA.

Keywords: Twinning-induced plasticity (TWIP) steel; Stacking-fault energy; Mechanical twin; Strain hardening; Dynamic strain aging

1. Introduction

High-Mn austenitic steels have recently attracted a great deal of attention because of their high tensile strength and extraordinary ductility arising from the many mechanical twins generated during plastic deformation, which is termed twinning-induced plasticity (TWIP) [1–3]. Of the TWIP steels, the Fe–Mn–C ternary system has frequently been studied due to the easy control of both the stacking-fault energy (SFE) and austenite stability by regulating the Mn and C concentrations [4,5]. Idrissi et al. [2] investigated the relationship between high strain hardening and mechanical twinning in Fe–22Mn–1.2C TWIP steel and found that mechanical twins contain a high level of sessile dislocations and act as strong barriers to dislocation gliding, resulting in high strain hardening. Gil Sevillano [6] reported that mechanical twins contribute to the reduction of the effective grain size in Fe–22Mn–0.6C TWIP steel, which is referred to as the dynamic Hall–Petch effect.

Despite its outstanding tensile properties, Fe–Mn–C TWIP steel has some shortcomings, such as low yield strength (YS) [2,7], carbide precipitation [8] and hydrogen delayed fracture [9–11]. To solve these problems, the addition of an alloying element such as Al has been considered by different researchers [5,8,10–15]. The Al effectively suppresses the hydrogen delayed fracture [10,11,14,15] and cementite precipitation [8,12,13], and stabilizes the austenite phase against the strain-induced martensitic transformation in Fe–Mn–C TWIP steel [5]. However, the addition of Al is not effective at improving the YS in TWIP steel [15–17].

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Dyson and Holmes [18] quantitatively investigated the solid solution hardening effects of various alloying elements on the YS of Fe–16Cr–25Ni stainless steel. They found that Si causes greater improvement of the YS than Al. Ohkubo et al. [19] reported that the YS increases from 161 to 213 MPa with the addition of 1 wt.% Si to Fe–17Cr–12Ni austenitic stainless steel and found that the Si causes high dislocation densities at low strains. Furthermore, it is known that Si decreases the SFE in Fe–17Cr–14Ni austenitic stainless steel [20] and Fe–31 Mn–0.8 C shape-memory alloys [21]. The decreased SFE restrains the cross-slip of dislocations [22,23], promotes planar slip [24,25] and enhances mechanical twinning [26,27]. Therefore, Si is expected to improve both the yield and tensile strengths through solid solution hardening, dislocation hardening and mechanical twinning in high Mn TWIP steels. Nevertheless, the effects of Si on the SFE, dislocation slip, mechanical twinning, strain hardening, and yield and tensile strengths of C-bearing high-Mn TWIP steels are yet to be reported.

Meanwhile, both the dislocation storage and mechanical twinning contribute to strain hardening in TWIP steels with low SFE [3,7,28–30]. Dini et al. [29] investigated the change in dislocation density with strain in Fe–31Mn–3Si–3Al TWIP steel using an X-ray diffractometer (XRD) and evaluated the contribution of dislocation storage to strain hardening. Allain et al. [7] analyzed the contribution of mechanical twinning to the strain hardening in terms of a dislocation mean free path (MFP) in Fe–22Mn–0.6C TWIP steel. However, the detailed experimental method for measuring the twin fractions, which are an essential parameter for determining the MFP, has not been introduced in the literature. Therefore, the quantitative analysis of mechanical twins, such as the area fraction of twinned grains, twin density and twin volume fraction, must still be performed to examine the relationship between strain hardening and mechanical twinning.

Shun et al. [31] attempted to measure the area fraction of twinned grains, defined as the ratio of the number of grains containing mechanical twins to the total observed grains in Fe–30Mn–1.0C–(0 and 3)Al austenitic steels using an optical microscope (OM). However, the measured area fraction of the twinned grains seems to be inaccurate because there has been no evidence that all of the etched regions are twins and that all twins are etched.

Li et al. [32] investigated the twin density, defined as the total length of the twin boundaries in the area observed in a nanostructured Cu–Zn alloy using a transmission electron microscope (TEM). Mechanical twins have been confirmed by means of selected area electron diffraction (SAED), and fine twins have also been observed. However, due to the limitations of the observed area, TEM observation is not suitable for the quantitative analysis of mechanical twins in high-Mn TWIP steel.

McCabe et al. [33] measured the twin volume fraction in highly purified Zr from electron backscattered diffractometer (EBSD) images, defined as the ratio between the total area of mechanical twins and the observed area. Although EBSD provides a larger observable area than TEM, the spatial resolution is not high enough to observe extremely thin mechanical twins [34,35].

Recently, Gutierrez-Urrutia and Raabe [36] succeeded in more clearly observing mechanical twins in Fe–22Mn–0.6C TWIP steels using an electron channeling contrast imaging (ECCI) method, compared with the EBSD method, and quantitatively evaluated the area fraction of the twinned grains. However, the ECCI still has a lower spatial resolution than that of TEM [34,35] and has yet to become a conventional electron microscopic technique like TEM and EBSD. Therefore, no qualified experimental methods have been performed to measure the twin fraction.

As a result, the following three subjects were investigated in the present study. First, the effects of Si on the SFE, dislocation slip, mechanical twinning, strain hardening and yield and tensile strengths in Fe–18Mn–0.6C–1.5Si TWIP steel were examined and compared with those in Fe–18 Mn–0.6C and Fe–18Mn–0.6C–1.5Al TWIP steels. Second, the twin volume fractions of the three TWIP steels were quantitatively measured using both EBSD and TEM to compensate for the shortcomings of each method and obtain more accurate analysis of the mechanical twinning. Finally, using the measurements of the dislocation density and twin volume fraction, the contributions of dislocation storage, mechanical twinning and dynamic strain aging (DSA) to the strain hardening of each TWIP steel were quantitatively evaluated to identify a predominant hardening mechanism.

2. Experimental procedure

Three ingots, weighing 30 kgf each, with the chemical compositions listed in Table 1, were prepared by vacuum induction melting. The ingots were homogenized at 1200 °C for 12 h in a protective nitrogen gas atmosphere and hot-rolled at temperatures between 1000 and 1100 °C into a plate 5 mm thick. To eliminate the decarburized layers of the plate, surface grinding was performed that removed ∼1 mm from each side of the plate. The surface-ground plate was cold-rolled at room temperature to make sheets ∼1.4 mm thick, corresponding to a thickness reduction of ∼55%. The cold-rolled sheets were annealed at 900 °C for 5 min using a vacuum tube furnace, followed by oil quenching to prevent carbide precipitation.

The microstructures of the annealed specimens were observed using an electron backscattered diffractometer

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

TWIP steel	Mn	C	Si	Al	Fe
T618	17.65	0.62	0.01	0.01	Bal.
T618–Al	17.51	0.58	0.05	1.54	Bal.
T618–Si	17.70	0.59	1.59	0.03	Bal.