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Materials

Effects of annealing temperature on the microstructure and properties of the 25Mn-3Si-3Al TWIP steel

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Abstract: Microstructures and mechanical properties of the 25Mn twinning induced plasticity (TWIP) steel at different annealing temperatures were investigated. The results indicated that when the annealing temperature was 1000°C, the 25Mn steel showed excellent comprehensive mechanical properties, the tensile strength was about 640 MPa, the yield strength was higher than 255 MPa, and the elongation was above 82%. The microstructure was analyzed by optical microscopy (OM), X-ray diffraction (XRD), and transmission electron microscopy (TEM). Before deformation the microstructure was composed of austenitic matrix and annealing twins at room temperature; at the same time, a significant amount of annealing twins and stacking faults were observed by TEM. Mechanical twins played a dominant role in deformation and as a result the mechanical properties were found to be excellent.

Key words: annealing temperature; TWIP steel; annealing twins; mechanical twins

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1. Introduction

The oil crisis as well as steadily increasing safety demands forced the automotive industry to develop improved body concepts offering reduced mass and simultaneously a higher overall rigidity, therefore, recent trends in the automotive industry are improving safety standards and reducing weight as well as a more rational and cost-effective manufacturing. This generated interests amongst us to work on these high strength and “super tough” steel. The twinning induced plasticity (TWIP) steel is one of the high strength and high toughness automotive steels, which has received considerable attention by domestic and overseas researchers in last several years [1-5]. The microstructure of TWIP steel at room temperature, without loading, is stable austenite, and there are many annealing twins in the matrix. When loading, because of the strain induced mechanical twins, large non-necking extension occurred. TWIP steel shows standout plasticity and high tensile strength at room temperature. The excellent mechanical properties are because of large amount of deformation twins in the austenitic matrix during deformation [6-8].

Nowadays, the research in TWIP steel is mainly in domestic and in overseas labs, and there is no industrial production. Traditionally, the heat treatment technology of TWIP steel is the water toughening process, and the temperature of solid solution is 1000°C, which seriously limits the TWIP steel’s industrial application.

In the present work, the influence of annealing temperature on the mechanical properties and microstructure of the 25Mn TWIP steel was investigated. At the same time, the relationship between the mechanical properties and microstructure and the heat treatment process was analyzed. Furthermore, the deformation mechanics of the TWIP steel with high strength and high plasticity was discussed. The references were offered in order to get better comprehensive properties and further development of the TWIP steel. The result of the study was expected to be helpful to the future industrial production of the promising

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TWIP steel.

2. Experimental

The TWIP steel used in this experiment was prepared in lab. It was vacuum melted in an electromagnetic induction furnace protected by argon atmosphere, and then, was cast to a slab. The chemical composition (wt%) of the TWIP steel is 0.015 C, 2.89 Si, 25.00 Mn, 0.061 P, 0.0043 S, 3.02 Al, and balance Fe.

The slab was hot rolled on the 350-4H/2H mill, and then, was cold rolled on the 430-4H/2H cold rolling mill. Finally, it was annealed at different temperatures (800, 900, and 1000°C). According to GB3076–82, the tensile samples were cut using a linear cutting machine along the rolling direction. The tensile tests were conducted at a speed of 3 mm/min using an MTS-810 mechanical testing machine at room temperature. The gauge length of the TWIP samples used in the tensile tests is 50 mm.

The microstructures were optically examined by etching the mechanically polished samples with 4vol% nital. The stability of austenite of the steel during preparation and deformation was examined by X-ray diffraction (XRD, MXP21VAHF). Submicrostructures of the specimens were observed by transmission electron microscopy (TEM, H-800) operating at 200 kV. The thin foils for TEM observation were prepared by the twin-jet polishing technique using a mixture of 5vol% perchloric acid and 95vol% alcohol at −35°C with an applied potential of 20 V.

3. Results and discussion

3.1. Mechanical properties

Three kinds of samples were investigated in this experiment. The TWIP steel exhibits high strength and high plasticity, and at different annealing temperatures there are different mechanical properties (Table 1 and Fig. 1).

Table 1 shows that with increasing the annealing temperature, the yield stress decreases from 565 to 255 MPa. Similarly with increasing the annealing temperature, the ultimate tensile strength decreases from 840 to 640 MPa, and at the same time, the total elongation increases from 59% to 80%. The plasticity can be enhanced by increasing the annealing temperature; the elongation ratio is 80% at 1000°C, but 59% at 800°C.

Fig. 1 presents the true stress *vs*. true strain curves obtained from three different annealing temperatures. With the increase in annealing temperature, the curve changes in its curvature during the deformation process.

Table 1. Mechanical properties of the TWIP samples at different annealing temperatures

Sample No.	Yield strength / MPa	Tensile strength / MPa	Elongation / %	Annealing temperature /°C
1	255	640	80.0	1000
2	425	785	68.1	900
3	565	840	59.0	800

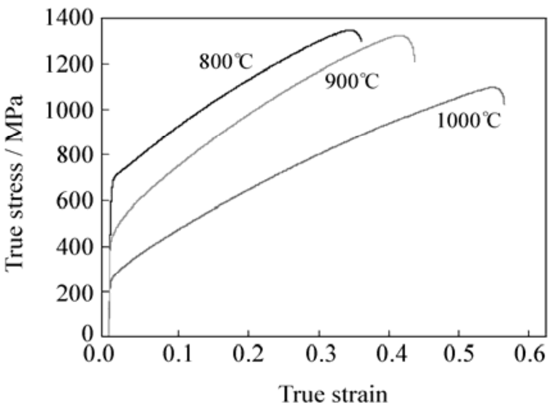

Fig. 1. True stress-strain curves at different annealing temperatures.

The true stress reaches 1300 MPa (the true strain is 0.35) at the annealing temperature of 800°C. However, when the annealing temperature reaches 1000°C, the true stress is 1100 MPa, and the true strain is above 0.55.

In the present investigation, annealing temperature has a strong effect on mechanical properties. It is concluded that, with increasing annealing temperature, the ultimate tensile strength decreases, while the elongation increases.

3.2. Microstructure

In order to find out the reason that the TWIP steel has different properties at different annealing temperatures, the investigation on the microstructures of the samples was carried out by using OM, TEM, and XRD. The OM and TEM micrographs of the three kinds of samples are given in Figs. 2-4.

Fig. 2 shows the undeformed optical microstructure of the 25Mn-3Si-3Al TWIP samples at different annealing temperatures. It shows that the grain size increases with the increase in annealing temperature, from 3-5 μm at 800°C to 20-40 μm at 1000°C. The microstructure consists of the austenite matrix and large amount of annealing twins whose two boundaries are parallel to each other, and the annealing twins are located inside the austenitic grains.

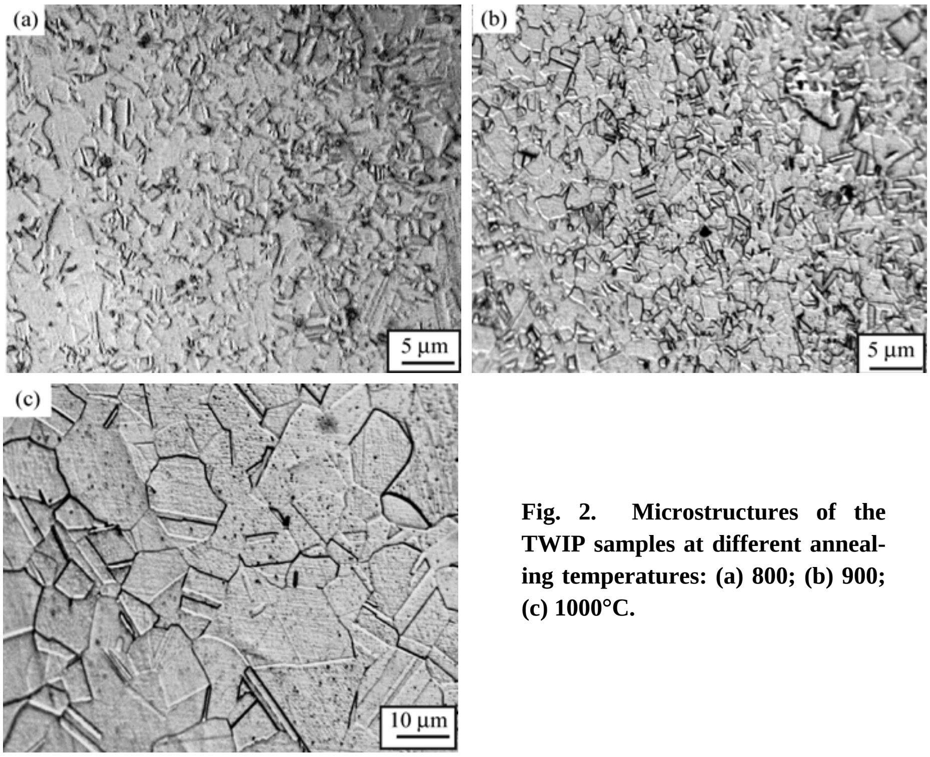

Fig. 2. Microstructures of the TWIP samples at different annealing temperatures: (a) 800; (b) 900; (c) 1000°C.

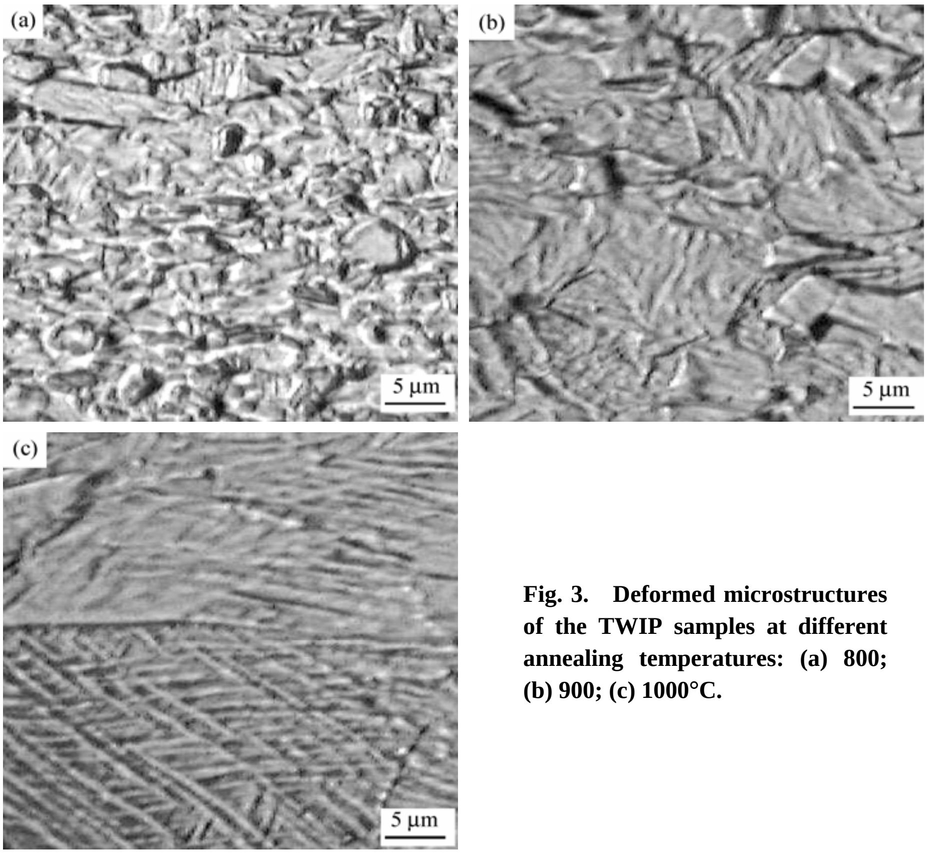

Fig. 3. Deformed microstructures of the TWIP samples at different annealing temperatures: (a) 800; (b) 900; (c) 1000°C.

As shown in Fig. 3, the tensile specimen annealed at different temperatures has much strain striation in the deformed optical microstructure. The striations are deformed twins. These deformed twins are dense and clear especially in Fig. 3(c). It is believed that the increasing elongation at room temperature is attributed to the strain-induced twinning, which is the TWIP-effect [6]. These fine twins induce plasticity and excellent elongation. X-ray diffraction reveals that no phase transformation occurs.

TEM photographs of the samples annealed at 800°C are shown in Fig. 4. Fig. 4(a) shows that the microstructure is composed of polygon austenite. A small amount of annealing twins and stacking faults can be seen in the austenitic grains (Fig. 4(b)). From the Fe-Mn-C phase diagram, we can find the nonequilibrium microstructure and that the annealing twins consist of growing grains. Its migrating steps are associated with a moving grain boundary [9]. After being annealed at 1000°C, TEM observation is shown in Figs. 5-6. There is a single austenitic phase, a large volume of annealing twins, and stacking faults in the austenite matrix. The region marked A is twins. The region marked B, symmetrical to A, is the dense stacking fault in Fig. 5. The length between the annealing twins is small; it is only 0.3 μm in Fig. 5(a). Fig. 5(b) is the magnification of the annealing twins of region A (Fig. 5(a)). Fig. 5(c) shows the pattern of the stacking faults with fine and layer stripes. The stacking faults are enclosed by Shockley partial dislocations [7], perfect dislocation dissociates two partial dislocations. A set of pairs of partial dislocations makes up the stacking faults. This behavior is related to the low stacking fault energy (SFE) of the Mn-Al-Si TWIP steel (20 mJ/m^2).

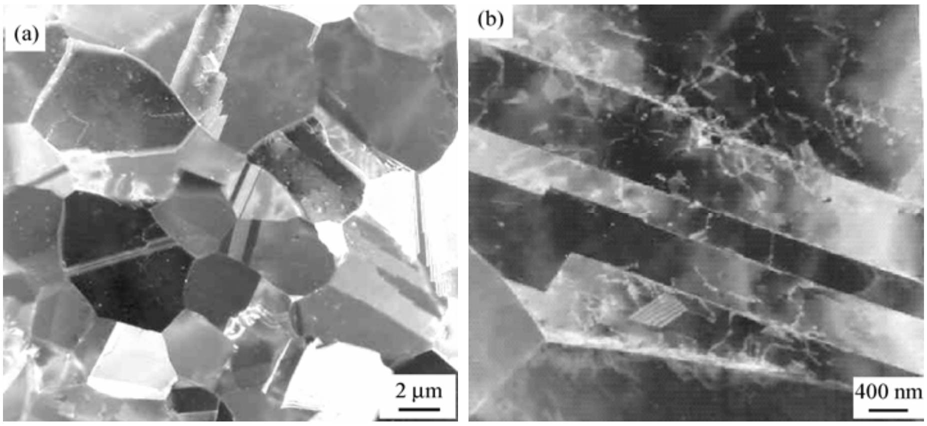

Fig. 4. TEM photographs of the steel at the annealing temperature of 800°C: (a) annealing microstructure; (b) annealing twins and stacking faults.

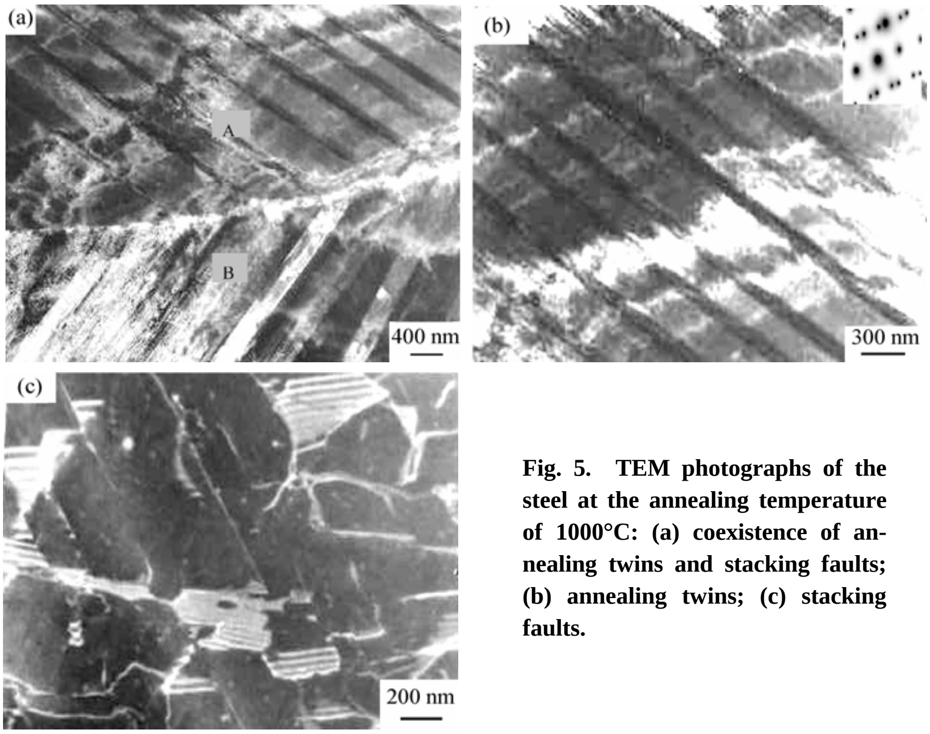

Fig. 5. TEM photographs of the steel at the annealing temperature of 1000°C: (a) coexistence of annealing twins and stacking faults; (b) annealing twins; (c) stacking faults.

The sample of the Fe-25Mn-3Si-3Al TWIP steel has low SFE ($\gamma_{\mathrm{fcc}} \leq 20$ mJ/m^2) [2], which is decided by its chemical elements. Therefore, the annealing twins with straight boundaries and stacking faults are observed in the samples. The mechanical properties of austenitic steels depend primarily on the SFE, which controls the ability of a perfect 60° dislocation to dissociate into two partial Shockley dislocations. The SFE thus determines the main deformation mechanism among gliding and cross slipping of perfect dislocations, gliding of dissociated partial dislocations, deformation twinning and strain-induced martensitic transformations [10]. Because the SFE of the Fe-25Mn-3Si-3Al TWIP steel sample is about 20 mJ/m^2, its deformation mechanism is mainly deformation twins.

Both OM and TEM observations show the evolution of different deformation mechanisms, which is active at different annealing temperatures. When the annealing temperature is 800°C, the annealing twins are very small (4-5 μm), wherein the twin boundaries are acting as strong barriers to subsequent dislocation motion [11-14]. However, when the sample is annealed at 1000°C, the annealing twins are up to 20-40 μm. The annealing twins can change the crystal orientation, which leads to slip, and then, the deformation can develop. As a consequence, it becomes the main accommodation mechanism [15]. It is believed that twinning acts as the primary deformation mechanism in this low SFE austenitic TWIP-steel. It results in extremely good mechanical properties.

4. Conclusions

(1) When the annealing temperature was 1000°C, the 25Mn-3Si-3Al TWIP steel had comprehensive mechanical properties. Its tensile strength, yield strength, and elongation were 640 MPa, 255 MPa, and 80%, respectively.

(2) During the annealing and deformation, there was no occurrence of phase transformation in the 25Mn-3Si-3Al TWIP steel. After annealing, there were large amounts of annealing twins in the austenitic matrix. During deformation the strain induced deformation twins, and then, the twinning induced plasticity (TWIP) effect. Therefore, excellent mechanical properties were because of the TWIP effect.

(3) When the grains size was up to 20-40 μm in the 25Mn-3Si-3Al TWIP steel samples, the twinning-induced plasticity (TWIP) effect could fully develop and resulted in above 80% elongation.

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