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Influence of annealing temperature on mechanical properties and microstructures of a high manganese austenitic steel

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ABSTRACT

By using scanning electron microscope (SEM) equipped with electron back-scattered diffraction (EBSD), transmission electron microscope (TEM) and room temperature tensile deformation test, the mechanical properties and microstructure evolution of a high manganese austenitic twinning-induced plasticity (TWIP) steel 25Mn–3Cr–3Al–0.3C–0.01N were investigated for the cold-rolled sheets annealed at different temperatures. The results show that annealing temperature has a tremendous effect on grain size and mechanical properties of the cold rolled high manganese austenitic TWIP steel. The features of the annealed grain microstructures of this steel can be characterized by coincidence site lattice (CSL) $\Sigma3$ at grain boundary. The occurrence frequency of $\Sigma3$ grain boundary and deformation twins in this steel has a close relation to annealing temperature. The microstructure evolution at different strain levels was finally described for the annealed and tensile deformed high manganese austenitic steel.

1. Introduction

Stainless steels are widely used in both industrial production and daily-life due to their anti-corrosion ability. Owing to high-cost and shortage in Cr and Ni resources, there has been an increasing interest in developing low-cost stainless steels for decades.

One more decade ago, Grässel et al. (2000) reported that steels with 25Mn (in wt.%) exhibit exceptional ductility and high strength. After that, Brüx et al. (2002) suggested that the excellent mechanical properties of the high manganese twinning-induced plasticity (TWIP) steels at room temperature were attributed to the formation of deformation twins. Frommeyer et al. (2003) also found that deformation twins formed under mechanical load. Most austenitic steels, such as high manganese Hadfield steels (Adler et al., 1986) and austenitic stainless steels (Donadille et al., 1989) are face-centered cubic (fcc) metals and have low stacking-fault energy (SFE) of 20–40 mJ/m^2 at room temperature (Ueji et al., 2008). It is now well established that the collaborative glide of intrinsic $a/6\langle 1\,1\,2\rangle$ Shockley partial dislocations (shear direction) on successive parallel $\{1\,1\,1\}$ planes determining the twinning habit plane leads to the formation of deformation twins in low SFE fcc alloys. Such features of TWIP steel, e.g. formability and mechanical behaviors, make it comparable to stainless steels.

It has been recognized that deformation mechanisms in steels depend on strain rate (Krüger et al., 2010), deformation temperature (Martin et al., 2011) and their chemical compositions (Jahn et al., 2011), for each of the factors can affect the SFE and stability of austenite strongly. Regarding the grain size, it has been reported that fine grain size can inhibit the formation of twins in low SFE materials (Asgari, 2004). Furthermore, another investigation (Danaf et al., 1999) indicated that the initiation of twins requires a critical dislocation density, i.e. the twin formed after a given plastic strain. And before the onset of twinning, slip occurs initially, caused by dislocations gliding.

Under the frame of replacing Ni and Cr with Mn and Al, respectively, a recent study disclosed that Fe–Mn–Al–C austenitic TWIP steel possesses excellent resistance to oxidation and has potential of partially replacing austenitic stainless steels (Chen et al., 2013). As well known, carbon and manganese are added to stabilize the austenitic structure in Fe–Mn–Al–C alloys. Moreover, carbon plays an important role in promoting precipitation strengthening and manganese enhances the mechanical properties at high temperature (Chen et al., 2010). Aluminum is used to improve the anti-corrosion behavior by forming a protective Al$_2$O$_3$ layer on the surface (Wang and Chang, 2002).

As a viable alternative to low-cost austenitic stainless steel, the new alloy system of high-manganese low-chromium nitrogen-containing TWIP steel was developed in this study. Nitrogen is added, because it is a strong austenite stabilizer that can reduce the tendency to form ferrite and deformation-induced α′- and

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Table 1
Chemical composition of the high manganese austenitic TWIP steel (in wt.%).

C	Mn	Cr	Al	N	Si	P	S	Fe
0.33	25.9	2.96	2.83	0.01	0.27	0.005	0.008	Balance

ε-martensites, thereby reducing the amount of nickel required in austenitic stainless steel. Furthermore, nitrogen is beneficial for pitting corrosion resistance (Simmons, 1996). Considering its corrosion resistance, the alloy is not completely free of chromium, yet the content is relatively low (Yuan et al., 2014). As a preliminary study, the influence of annealing temperature on microstructures and mechanical behaviors of this high manganese austenitic steel has been characterized by microstructural observation and room temperature tensile test. The microstructure evolution at various deformation stages was also investigated during room temperature tensile deformation for this TWIP steel.

2. Experimental

The high manganese austenitic steel used in this study was firstly smelted in a vacuum induction furnace and cast to an ingot. The ingot was then forged at 1200 °C to a slab of 35 mm × 100 mm × 120 mm in size. After being heated to 1200 °C for 120 min, the slab was hot rolled to sheet at 1100 °C in a laboratory two-roll mill and cooled in air. The thickness of the hot rolled sheet was 6 mm. The hot rolled sheet was homogenized at 1100 °C for 1 h prior to cold rolling with a final thickness of 1 mm. The chemical composition of this austenitic TWIP steel is shown in Table 1.

In order to obtain steel sheets with various grain sizes, the cold rolled sheets were annealed at temperature ranging from 700 °C to 1000 °C for 20 min and then cooled in water. The mechanical properties were measured by conducting room temperature tensile test on CMT5105 electronic universal testing machine with a strain rate of 2×10^{-3} s^{-1}. All tensile specimens were cut along the rolling direction (RD) of the sheets and Fig. 1 shows the dimension of the tensile specimens. For the specimens annealed at 800 °C for 20 min, room temperature tensile tests were performed and stopped at strains of 5%, 10% and 30% in order to reveal the deformed microstructures and tensile deformation mechanisms.

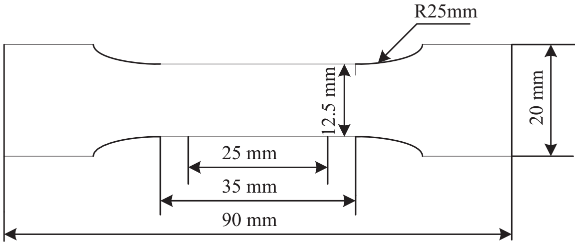
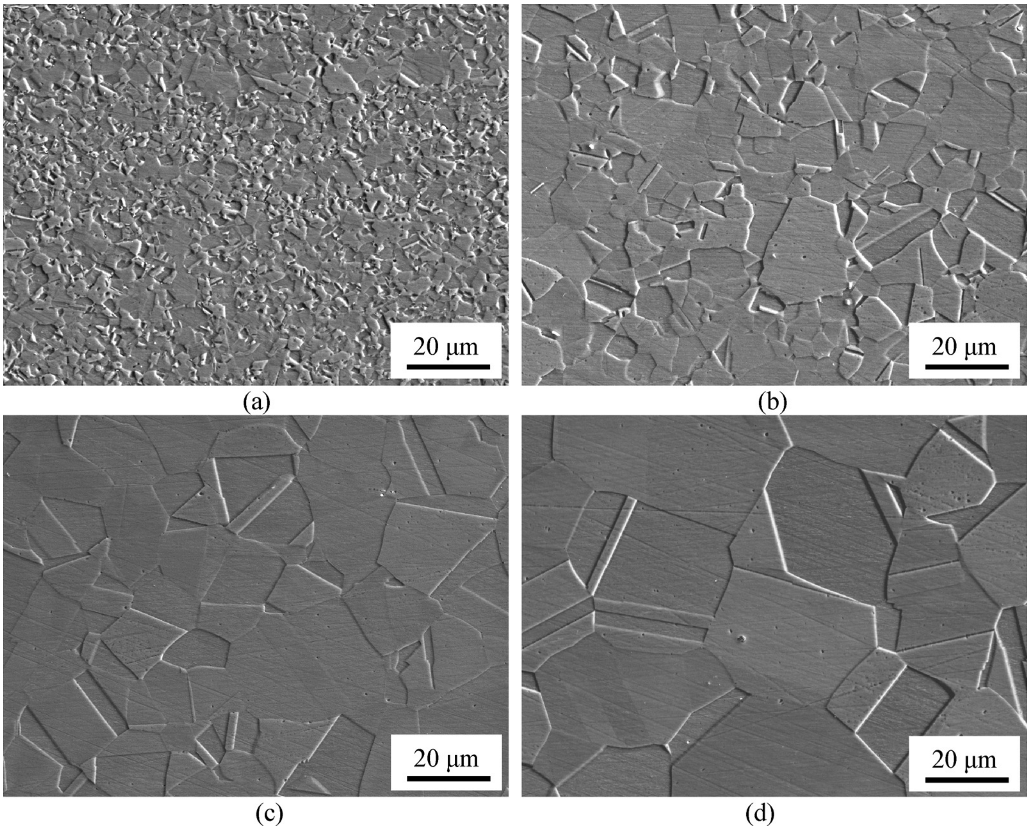


Fig. 1. Dimension of the tensile test specimen.

The microstructural observations of this high manganese austenitic TWIP steel were performed by using scanning electron microscope (SEM, FEI Quanta 600) and transmission electron microscope (TEM, FEI Tecnai G^2 F20). After mechanically ground to a thickness of ~50 μm, thin foils for TEM observation were prepared by twin-jet polishing in the solution of 9 vol.% perchloric acid and alcohol under the voltage of 40 V at −25 °C. The average grain size and misorientation between grains for all samples were obtained from the online analysis of electron back-scattered diffraction (EBSD) data by HKL-Channel software.



(a) (b) (c) (d)

Fig. 2. SEM microstructures of the sheets annealed at 700 °C (a), 800 °C (b), 900 °C (c) and 1000 °C (d).