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Dependence of grain size on mechanical properties and microstructures of high manganese austenitic steel

Xiaoyun Yuan[a], Liqing Chen[a,]*, Yang Zhao[b], Hongshuang Di[a], Fuxian Zhu[a]

[a]*State Key Laboratory of Rolling and Automation,Northeastern University, 3-11 Wenhua Road, Shenyang 110819, China*
[b]*School of Materials and Metallurgy, Northeastern University, 3-11 Wenhua Road, Shenyang 110819, China*

Abstract

A high manganese austenitic steel Fe-25Mn-3Cr-3Al-0.3C-0.01N (in wt. pct) with grain sizes 2.2~28.7 μm was obtained by annealing the cold rolled sheet at temperature ranging from 700 °C to 1000 °C. Dependence of grain size on the mechanical properties and microstructures of this high manganese steel were studied by using scanning electron microscopy (SEM), transmission electron microscopy (TEM) and room temperature tensile test. The results show that, with the increase of grain size from 2.2 μm to 28.7 μm, the yield and ultimate tensile strengths of this steel were decreased from 410.0 MPa to 232.5 MPa and 725.0 MPa to 517.0 MPa, respectively. And the elongation of this steel was accordingly increased from 15.4% to 54.2%. Additionally, deformation twins are easy to form during tensile deformation when the initial grain size is increased.

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Keywords: High manganese steel; Twining-induced plasticity (TWIP) steel; Grain size; Microstructures; Mechanical properties

1. Introduction

It is well known that stainless steel is widely used in both industrial production and daily-life due to its anti-corrosion behavior. In view of the high-cost and shortage in Cr and Ni resources, there has been an increasing interest in developing low-cost stainless steel for several decades.

* Corresponding author. Tel.: +86-24-83681819; fax: +86-24-23906472.
E-mail address: lqchen@mail.neu.edu.cn

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High manganese TWIP steels exhibit exceptional ductility and high strength at room temperature due to the formation of extensive twins under mechanical load (Grässel et al., 2000; Brux et al., 2002). Austenitic TWIP steels are face-centered cubic (fcc) metals having low stacking fault energy (SFE) of 20~40 mJ/m^2 at room temperature (Allain et al., 2004; Vercammen et al., 2004; Ueji et al., 2008). It is now well established that the collaborative glide of intrinsic a/6 <112> Shockley partial dislocations (shear direction) on successive parallel {111} 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 behavior, make it comparable to stainless steels.

Under the frame of replacing Ni and Cr with Mn and Al, respectively, it is disclosed in a recent study that Fe-Mn-Al-C austenitic TWIP steel possesses excellent resistance to oxidation and has the potential of partially replacing austenitic stainless steel (Chen et al., 2013). In this study, a new alloy system of high-manganese low-chromium nitrogen-containing TWIP steel was proposed to develop low-cost austenitic stainless steel. As a preliminary study, the various grain sizes of this austenitic TWIP steel were obtained by annealing the cold-rolled specimen. After that, the microstructures and mechanical behavior of this high manganese austenitic steel has been characterized in dependence on grain size by microstructural observation and room temperature tensile test.

Nomenclature

σ_T	critical stress for formation of deformation twinning
σ_{T0}	lattice friction
k_T	slop
d	grain size

2. Experimental procedure

The austenitic TWIP steel in this study has a nominally chemical composition of Fe-25Mn-3Cr-3Al-0.3C-0.01N (in wt. pct). The alloy ingot was firstly melted 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 that, the slab was hot rolled to 6 mm thick in a laboratory two-roll mill and subsequently homogenized at 1100 °C for 1h. Cold rolled sheet with a thickness of 1 mm was finally obtained. The alloy sheet with various grain sizes were obtained by annealing the cold rolled sheet at temperature ranging from 700 °C to 1000 °C for 20 min and then water-cooled.

The average grain size of all samples was obtained from online analysis of electron back-scattered diffraction (EBSD) data by HKL-Channel software. Room temperature tensile test was carried out on CMT5105 electronic universal testing machine with a strain rate of 2×10^{-3} s^{-1} and test piece has a gauge size of 25 mm×12.5 mm ×1 mm. All tensile specimens were cut along rolling direction (RD) of the sheet. The microstructural observations of this austenitic steel with different grain size 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 a solution of 9 vol.% perchloric acid and alcohol under the voltage of 40 V at –25 °C.

3. Results and discussion

The SEM microstructures of the austenitic steel annealed at different annealing temperatures are shown in Fig. 1. One can see from Fig. 1 that the grain size of this steel is increased with increasing the annealing temperature. At higher annealing temperature, there are more annealing twins within the recrystallized grains.

The variation of grain size with annealing temperature is schematically shown in Fig. 2, while the dependence of grain size on engineering stress-strain curves are presented in Fig. 3. It is obvious that annealing temperature has much effect on the grain size of this steel. Grain size changes from 2.2 μm to 28.7 μm when the steel sheet is annealed at temperature ranging from 700 °C to 1000 °C.

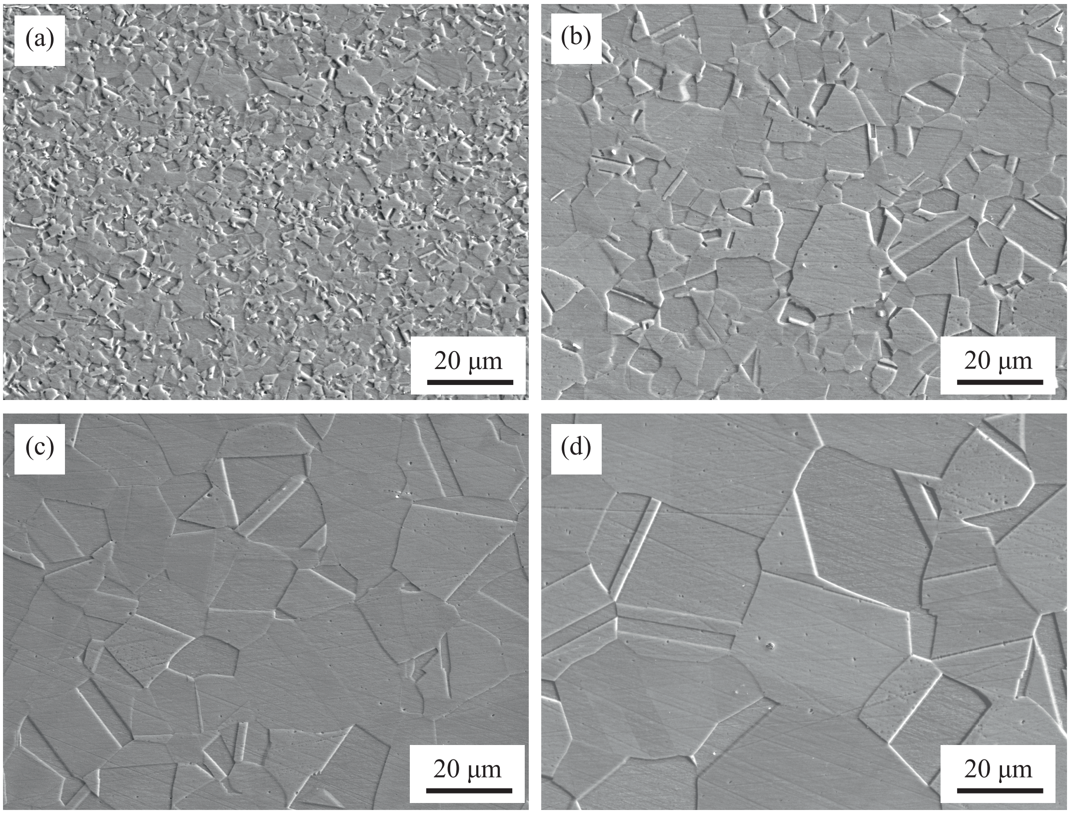

Fig. 1. SEM microstructures of the experimental steel annealed at different temperatures: (a) 700 °C; (b) 800 °C; (c) 900 °C; (d) 1000 °C.

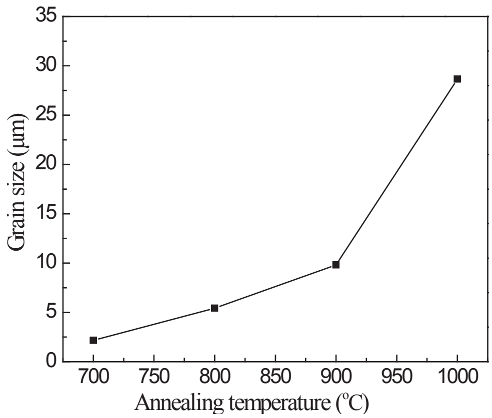

Fig. 2. Dependence of grain size on annealing temperature.

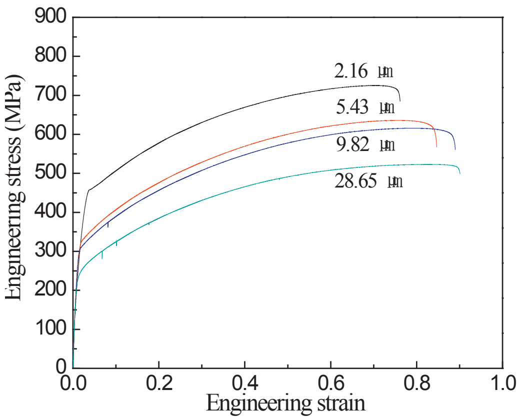

Fig. 3. Dependence of grain size on stress-strain response.

The dependence of the tensile properties on the grain size of this high manganese austenitic steel is listed in Table 1. As expected, the tensile mechanical properties of this steel changes with increasing grain size. The yield and ultimate tensile strengths decrease with the increase of grain size, while the elongation increases.

It is commonly known that the strength of polycrystalline materials can be increased by grain refinement. The dependence of strength on grain size could be examined by plotting the strength against the inverse square root of grain size (Petch, 1953; Sato et al., 1989). Fig. 4 shows the fitting curve for this steel and it indicates a linear Hall-Petch relation representing the strength and grain size.

Table 1. Tensile mechanical properties of the high manganese austenitic steel with different grain sizes.

Grain size (μm)	Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation (%)
2.2	410.0	725.0	15.4
5.4	313.3	629.3	44.3
9.8	263.3	568.3	46.5
28.7	232.5	517.0	54.2

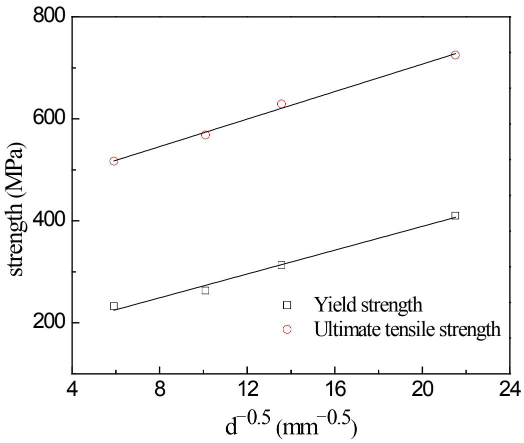

Fig. 4. Dependence of grain sizes in high manganese austenitic steel on yield and tensile strengths.

TEM photographs of the cold rolled and annealed sample is presented in Fig. 5. The microstructure was composed of polygonal and equi-axed austenite grains in the specimen as shown in Fig. 5(a). And some annealing twins can be observed within the austenite grains shown in Fig. 5(b).

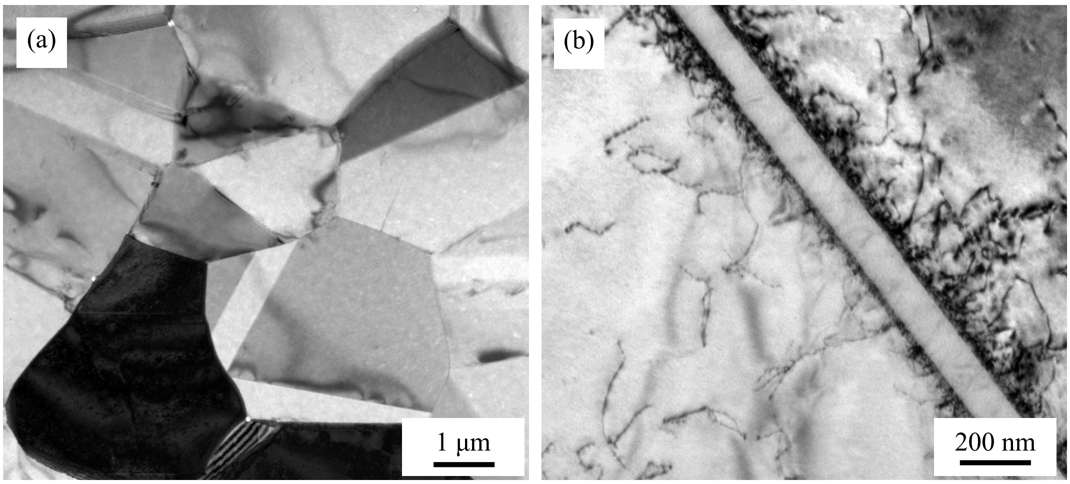

Fig. 5. TEM micrographs showing the microstructures (a) and annealing twins (b) for the austenitic steel annealed at 800 °C.

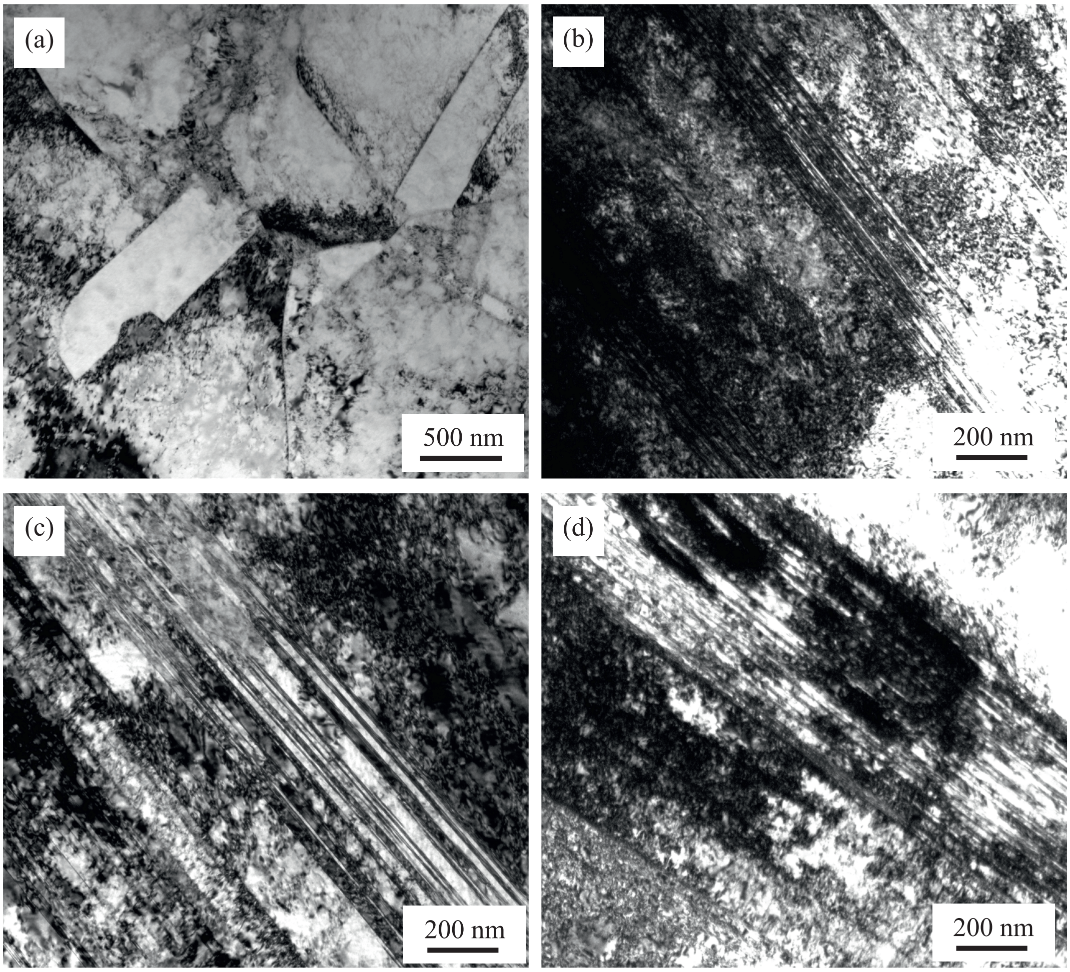

Fig. 6. TEM microstructure of deformed TWIP steel with different grain sizes: (a) 2.16 μm; (b) 5.43 μm; (c) 9.82 μm; (d) 28.65 μm.

TEM microstructures of this high manganese austenitic steel after tensile deformation are shown in Fig.6. The tensile deformed microstructure with originally fine grain size (Fig. 6(a)) is distinctly different from that with coarse grain (Fig. 6(b)~(d)). The twins in the specimen of 2.2 μm grain size are mainly annealing twins, while deformation twins were produced in the specimens with coarse grains (5.4 ~28.7 μm). Additionally, the amount of deformation twins in austenite matrix is increased with the increase of grain size.

The formation of deformation twins needs to overcome the critical stress, which was caused by moving of dislocation. Any factors that hinder the dislocation motion will lead to the increase in critical stress (Sato et al., 1989). Therefore, the critical stress for the formation of deformation twins depends strongly on grain size. The relationship between grain size and critical stress for formation of deformation twins is usually described by Hall-Petch relation (Meyers et al., 2001; Sevillano et al., 2008; Danaf et al., 1999).

$$\sigma_T = \sigma_{T0} + k_T d^{-1/2}, \tag{1}$$

where σ_T is critical stress for formation of deformation twinning, σ_{T0} is lattice friction, k_T is slop and d is grain size.

According to Eq. (1), critical stress for the formation of deformation twins decrease with increasing grain size. That is to say, the deformation twins are easy to form within coarse grains. It is believed that deformation twins coordinate with a relatively large plastic strain and thus with an extensive increase in the formation of deformation twins, the contribution from strain of twinning to the total elongation will be increased (Dini et al., 2010). This explains the increase in elongation with the grain size, as showed in Table 1.

4. Conclusions

The dependence of grain size on mechanical properties and microstructures of austenitic TWIP steel Fe-25Mn-3Cr-3Al-0.3C-0.01N has been studied. The following conclusions can be drawn.

(1) The tensile mechanical properties of this steel depend largely on the grain size. When the grain size was increased from 2.2 μm to 28.7 μm, yield and ultimate tensile strengths were decreased from 410.0 MPa and 725.0 MPa to 232.5 MPa and 517.0 MPa, respectively, while the elongation was increased from 15.4% to 54.2%.

(2) Grain size of this austenitic steel has great influence on the formation and morphology of deformation twins. With the increase of grain size, deformation twins become easy to form. In tensile deformed samples with grain size of 2.16 μm, there are almost no deformation twins. However, in samples with grain size of 5.4~28.7 μm, deformation twins are easy to be found.

Acknowledgements

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