Materials Science & Engineering A 614 (2014) 232–237

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

Influence of precooling and deformation temperature on microstructure and mechanical properties in a high-manganese austenitic steel

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ARTICLE INFO

Article history:
Received 31 May 2014
Received in revised form
8 July 2014
Accepted 11 July 2014
Available online 19 July 2014

Keywords:
High-manganese
Deformation
Mechanical properties
Martensite
Twin

ABSTRACT

In this work, the influence of precooling on deformation-induced α′-martensitic transformation and mechanical properties of Fe–16Mn–4Cr–0.1C (wt%) austenitic steel is investigated. It is shown that precooling in liquid nitrogen enhances the volume fraction of ε-martensite. During tensile testing, ε-martensite acts as a nucleation site for α′-martensite and promotes the strength and ductility of the steel. The precooled steel exhibits an excellent combination of mechanical properties (tensile strength of 1240 MPa, uniform elongation of 35% and total elongation of 42%). Further, it is shown that tensile strength and elongation of the steel strongly depend on the deformation temperature. This is explained by the influence of temperature on stacking fault energy (SFE) and accordingly governing deformation mechanisms of the steel.

1. Introduction

Steels with high strength and good ductility are of great importance for the automobile industry due to both energy reduction and safety requirement. Therefore, over past years extensive studies have been performed to develop next generation steels with significantly enhanced strength and ductility at a reasonable cost. Of the advanced automotive steels, high-manganese (Mn) steels have received special attention due to their superior mechanical properties. Depending on the Mn content, deformation-induced martensitic transformation or deformation twinning may occur in Mn-rich steels. These plastic deformation mechanisms are termed transformation-induced plasticity (TRIP) and twinning-induced plasticity (TWIP). In general, whereas the TRIP effect is important in Fe–Mn alloys with less than 15 wt% Mn, the TWIP effect is predominant in Fe–Mn alloys with over 25 wt% Mn. When the Mn content is in the range of 15–25 wt%, the TRIP and TWIP effects coexist [1].

Martensitic transformation can be triggered above the martensite start temperature (M_s) by deformation of the austenite. When the applied stress is below the yield strength of the austenite, the transformation is said to be stress-assisted. The applied stress may be large enough to produce dislocations and shear bands (faults, ε-martensite and twins) in the austenite, which then contribute to the nucleation of martensite. The so formed martensite is known as strain-induced martensite [2]. Many studies have been devoted to investigating the relationships between the austenite stability (including: Mn content [3], grain size [4–6], predeformation [7] and deformation temperature [8,9]), deformation mechanisms and mechanical properties in medium/high-Mn steels. The obtained results suggest that the SFE of austenite is a crucial parameter for austenite stability and affects the formation of deformation-induced martensite and deformation twin [10]. SFE values lower than 15–20 mJ m^{-2} favor austenite → ε-martensite transformation, whereas higher values (12 mJ m^{-2} < SFE < 35 mJ m^{-2}) suppress martensitic transformation, and twinning occurs during deformation [11,12].

In a recent study [13], the present authors showed that thermomechanically processed Fe–16Mn–4Cr–0.1C (wt%) austenitic steel exhibits an outstanding combination of tensile strength (about 1.4 GPa) and total elongation (about 40%). It was suggested that α′-martensitic transformation contributes effectively to the mechanical properties of this steel, being related to its low SFE of about 3 mJ m^{-2}. In continuation, this study aims to investigate the formation of ε-martensite (through precooling and deformation) and its relation with α′-martensitic transformation. Also, the

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http://dx.doi.org/10.1016/j.msea.2014.07.034
0921-5093/

influence of deformation temperature on TRIP and TWIP occurrence is discussed.

2. Material and experimental procedure

In the present study, a raw material of Fe–15.9Mn–3.9Cr–0.09C (wt%) steel was provided in the form of a sheet with a thickness of 4 mm. The sheet was hot-rolled into sheets of 1.2 mm thickness at 900 °C, followed by water quenching. These sheets were cold-rolled to a thickness of 1 mm at 298 K. Finally, the cold-rolled samples were annealed at 700 °C for 17 min, followed by quenching into water (25 °C) and liquid nitrogen (−196 °C) tanks, named WQ and NQ samples, respectively. Standard flat tensile specimens (ASTM E8) with 25 mm gage length were taken along the rolling direction from the annealed sheets using the electron discharge machining (EDM) method. Uniaxial tensile tests were carried out three times for each alloy using an Instron-type tensile machine at temperatures of 25, 100, 200 and 400 °C, with a strain rate of about 0.001 s^{-1}. The X-ray diffraction (XRD) patterns of the electropolished samples were measured at room temperature in the range of 40–100° with Cu Kα radiation. An optical microscope (OM, CX51 Olympus) was used for microstructural observations. Specimens for OM and XRD tests were first electrolytically polished at room temperature with an operating voltage of 45 V in a solution of 60 ml HNO_3, 180 g CrO, 3 ml HCl, 240 ml H_2SO_4, and 600 ml water. The OM samples were electroetched with an operating voltage of 15 V in a solution of 25 ml HNO_3, 30 g CrO, 3 ml CH_3COOH and 20 ml water. Detailed analyses of microstructures were carried out using a transmission electron microscope (TEM, JEOL, JEM-2100F) with an energy dispersive spectroscope (EDS) and an operating voltage of 200 kV. TEM specimens were prepared by mechanical polishing and electropolishing with a twin-jet electro-polisher (Struers, Tenupol-5) in a solution of 90% acetic acid glacial and 10% perchloric acid at 25 °C under 15 V. The volume fraction of α′-martensite was measured during tensile deformation using a ferritescope (model MP30).

3. Results and discussion

Fig. 1a–c shows microstructures of the samples taken from the raw material, hot-rolled (HR) and WQ steel, indicating a dual phase microstructure composed of austenite and ε-martensite. Average grain sizes (AGS) of the austenite in these samples is 65, 17 and 20 μm. ε-Martensite appears like thin plates in OM micrographs, as shown in Fig. 1a and b [14–16]. Fig. 1d shows bright field (BF) image and corresponding selected area diffraction (SAD) pattern taken from the WQ sample. Characteristic deformation bands consisting of many overlapping bands of thin plates are observed (from right side to left side direction in the figure). In the corresponding SAD pattern, circles indicate diffraction spots from ε-martensite plates whose intersections are potential sites for the formation of deformation-induced α′-martensite (DIM) [17].

Fig. 2 represents the XRD patterns of the raw material, hot-rolled (HR) and WQ steel. It can be seen that the raw material and HR steel have a definitive preferred orientation along $\{111\}_\gamma$ planes; however, WQ steel acquires a random orientation. Fig. 3 shows OM micrograph and XRD pattern of NQ steel. It is readily observed that in contrast to WQ steel, NQ steel possesses distinctive peak of ε-martensite (Fig. 3b). OM and XRD studies revealed that the fraction of thermal ε-martensite increases with decrease in the precooling temperature without the formation of α′-martensite, being in agreement with the results of previous works [18,19].

Fig. 4 shows the curve of change in volume fraction of α′-martensite as a function of true strain for WQ and NQ steels. It is observed that α′-martensite fraction is higher for NQ steel, especially at small strains. This can be related to the higher fraction of thermal ε-martensite in NQ steel. In an earlier investigation, Lee et al. [19] studied the effects of ε-martensite, carbon content and cold working on the damping capacity of an Fe–17 wt % Mn alloy. It was found that the volume fraction of ε-martensite (82 vol% before deformation) increases with deformation up to 10% reduction in thickness (up to about 90 vol%) and decreases with further deformation. Simultaneously, the volume fraction of

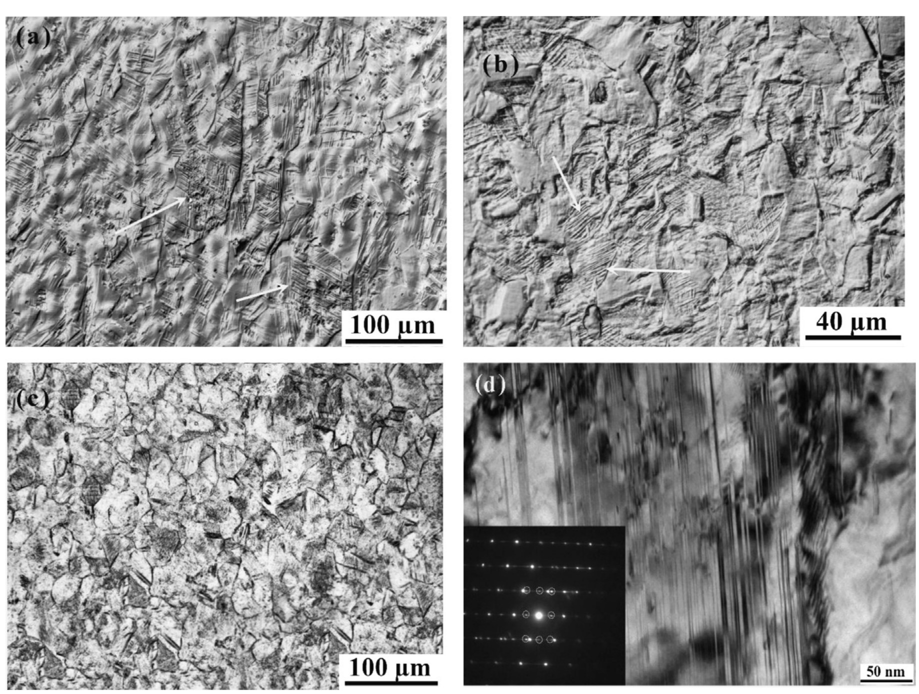

Fig. 1. OM micrographs of the (a) raw material (DIC mode), (b) hot-rolled steel (DIC mode), (c) WQ steel and (d) a typical TEM micrograph of ε-martensite in WQ steel.