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The effects of the initial microstructure on microstructural evolution, mechanical properties and reversed austenite stability of intercritically annealed Fe-6.1Mn-1.5Si-0.12C steel

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ABSTRACT

A typical medium Mn steel with nominal chemical composition of Fe-6.1Mn-1.47Si-0.12 C (wt%) was intercritically annealed from different initial microstructures, i.e., cold-rolled martensite and as-quenched martensite (hereinafter referred as CR and AQ sample, respectively). The CR sample is mainly composed of equiaxed submicron grains owing to nearly full recrystallization of deformed martensitic matrix, while the AQ sample still presents martensite lath structure in general. Reversed austenite grains in the CR sample are almost entirely granular. In the AQ samples, there are two kinds of microscopic morphology of reversed austenite, i.e., acicular and granular austenite, and the nucleation and growth of them are analyzed individually. Additionally, Reversed austenite fraction is not affected by initial microstructure irrespective of deformed and as-quenched martensite. Tensile strength and yield strength of the CR sample are about 80 MPa and 166 MPa higher than that of the AQ sample, respectively, but the PSE value of both CR and AQ sample is a little higher than 30 GPa%. Metastable austenite in the CR sample is more sensitive to the increasing strain, i.e., lower mechanical stability, which can be attributed to the higher nucleation rate of strain-induced martensitic transformation.

1. Introduction

In recent years, the steels with 3–10 wt% Mn, referred to as medium Mn steels [1–6], have received significant attention from both industry and academia and been considered as one of the most promising advanced high strength steels (AHSS) to meet the increasing requirement for automobile lightening. In the 1970s, Miller first designed the basic concept of medium Mn steel in order to study whether the Hall-Petch relationship was still valid in ultrafine-grained microstructure [7]. In his study, the cold-rolled steel with chemical composition of Fe-5.7Mn-0.11 C was annealed at two phase region of ferrite and austenite, and finally the tensile strength and total elongation of this steel reached 878 MPa and 34%, respectively. Later researches further confirmed that medium Mn steels have superior balance of strength and ductility [8–11].

The reason why medium Mn steels exhibit such excellent property could be attributed to the tempered martensite or ferrite/metastable austenite duplex microstructure, which benefits from the distinctive design of alloy composition and heat-treating process. Metastable austenite in the microstructure can transform into martensite during deformation, i.e., TRIP effect, resulting in a localized work hardening to retard necking and improve strength and ductility simultaneously. Therefore, the mechanical stability of metastable austenite, determining the work hardening behavior to some extent, is quite important for the resulting properties. Medium Mn steels usually have an outstanding hardenability due to the relatively higher content of Mn, thus the conventional isothermal quenching process to stabilize austenite in TRIP steels [12,13] or Q&P steels [14–17] is not suitable for them. The intercritical annealing, which is widely used in medium Mn steels, promoting Mn partitioning into austenite, is also referred as austenite reverted transformation (ART) annealing. Accordingly, the metastable austenite reserved to room temperature is called reversed austenite as well. Hence, it is easy to understand that the mechanical stability of austenite in medium Mn steels is directly related to the annealing parameters, e.g., annealing temperature, holding time and heating rate etc. And actually the effect of these heating treatment parameters on microstructure and properties of medium Mn steels has been studied in some previous works [3,18–21]. In addition, we notice

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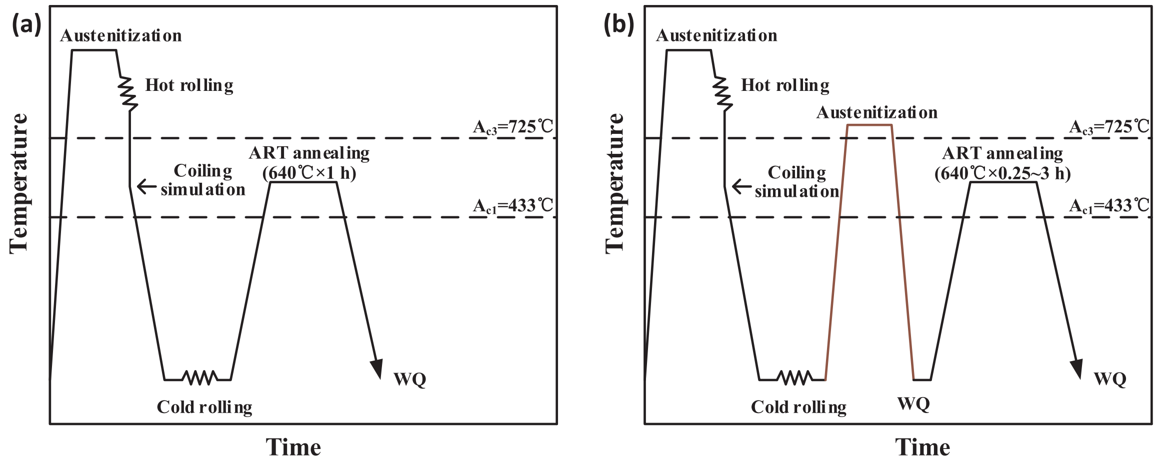

Fig. 1. Schematic illustration of the thermomechanical process used in the present study: (a) CR sample; (b) AQ samples.

that deformed martensite changed into equiaxed grains after the intercritical annealing [7,22], but the ordinary martensite decomposed to lath-shaped ferrite and austenite [2,20]. That is, the initial microstructure strongly affects the microstructure and properties of intercritically annealed medium Mn steels. Therefore, performing this present work, we use the cold-rolled sheet of Fe–6.1Mn–1.5Si-0.12 C steel as raw material and make a direct comparison on microstructure, mechanical properties and austenite stability of this steel intercritically annealed from different initial microstructures, i.e., cold-rolled martensite and as-quenched martensite (hereinafter referred as CR and AQ sample, respectively). The objective of the present work is to clarify the effect of initial microstructure, microstructure evolution during intercritical annealing and difference in deformation behavior. Specifically, we focus on the difference in mechanical stability of metastable austenite in different combination of microstructural structures.

2. Experimental procedure

The experimental material is a typical medium Mn steel with actually nominal chemical composition of Fe-6.1Mn-1.5Si-0.12 C (wt%). The reason for addition of Si element in this steel is to suppress carbide precipitates [23]. Based on the calculation using Thermo-Calc software with the TCFE6 database, the A_{c1} and A_{c3} temperatures are respectively about 433 ℃ and 725 ℃. The steel was melted in a vacuum furnace and forged into rectangular bars with dimensions of 700 mm × 100 mm × 60 mm. The thermomechanical processes used in the present study is illustrated in Fig. 1. After solution treatment at 1200 °C for 3 h, the bar was hot-rolled in 9 passes to form a 4.3 mm thick plate, held at 600 ℃ for 1 h, and then furnace-cooled to room temperature for the coiling simulation. The hot-rolled sheets were further rolled at room temperature to the cold-rolled sheet of 1.1 mm thickness, from which the tensile specimens, with a 25 mm gauge length parallel to the rolling direction, were then machined. Subsequently, these tensile specimens were treated by different heat treatment processes. In one case, as shown in Fig. 1a, the tensile specimens were directly annealed at 640 °C for 1 h in a tube furnace, which is referred as the CR samples. In the other case, the specimens were first water-quenched after an austenitization at 850 ℃ for 3 min, and then annealed at 640 °C for 0.25–3 h, referred as the AQ samples. That is, the initial microstructure before the ART annealing for CR and AQ sample is respectively deformed martensite and as-quenched martensite, as shown in Fig. 2a and b.

The multiphase microstructures of the samples were revealed using a 4% nital etch after mechanical polishing. The second electron micrographs were obtained using JEOL JXA-8530F electro probe microanalyzer (EPMA). Electron backscatter diffraction (EBSD) techniques were also employed to characterize different microstructural constituents. The specimens for EBSD were mechanically ground and then electro-polished using a 700 mL CH_3COOH + 200 mL $HClO_4$ solution at 16 °C and 31 V. EBSD measurements were performed on a Zeiss Ultra 55 analyzer at 20 kV by a spatial step size of 0.03 µm. Channel 5 software was used to collect and index the Kikuchi band patterns.

X-ray diffraction (XRD) analysis was performed on a D/max2400 analyzer using Cu K_α radiation operating at 50 kV and 150 mA. Spectra were taken in the 2θ range from 40° to 120° with a (2θ) scanning speed of 5°/min. The integrated intensities of the (200) γ, (220) γ, (311) γ, (200) α, and (211) α peaks were calculated to quantify the amount of reversed austenite by the following equation [24]:

$$V_\gamma = 1.4I_\gamma/(I_\alpha + 1.4I_\gamma) \quad (1)$$

where V_γ is the volume fraction of retained austenite, I_γ is the integrated intensity of the austenite peaks, and I_α is the integrated intensity of the ferrite peaks.

Mechanical performance testing and interrupted tensile tests were carried out on a CMT-5105 tensile machine with a crosshead

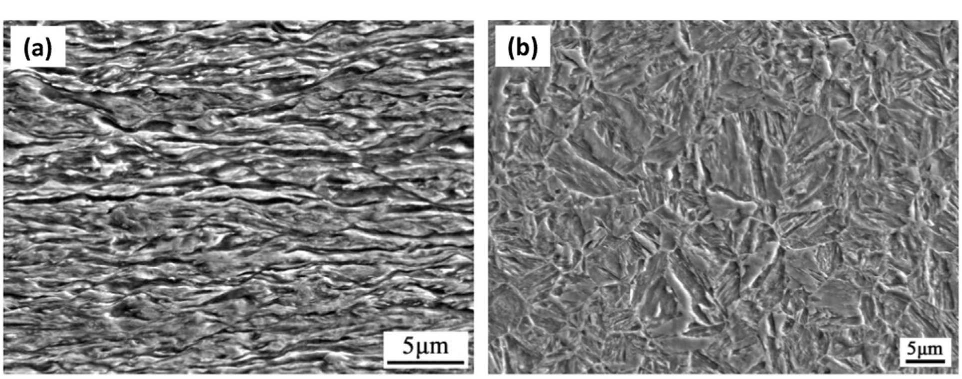

Fig. 2. SEM micrographs of the initial microstructure before the inter-critical annealing: (a) deformed martensite, and (b) as-quenched martensite.