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Precipitation behavior and mechanical properties of a hot rolled Ti-bearing dual phase steel

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ABSTRACT

We have studied here the microstructure, precipitate evolution and mechanical properties in a Fe-Mn-Cr-Ti dual phase steel processed by thermo-mechanical control processing. When the deformed austenite was treated in the temperature range of 640–760 °C, the microstructure consisted of ferrite and 7–80% martensite. Both random and interphase precipitation of nanoscale TiC particles occurred in the ferrite matrix. With decrease in temperature, the average size of precipitates was reduced from 5.4 nm to 2.2 nm, and the morphology of interphase precipitation was altered from curved to planar because of the change in the mechanism of TiC interphase precipitation. Hot rolling inhibited interphase precipitation but promoted precipitation on dislocations. Given that the ferrite matrix was significantly strengthened by nanoscale TiC particles, the hardness difference between the ferrite matrix and martensite was significantly decreased, and the strength of hot rolled Ti-bearing dual phase steels was less dependent on the martensite content compared to the conventional dual phase steels. The strength of hot rolled Ti-bearing dual phase steels was derived from a number of strengthening mechanisms, namely phase transformation, precipitation and grain refinement strengthening.

1. Introduction

High strength steels are widely used for structural applications in the automotive and mechanical sector [1]. In the last two decades, low carbon high strength low alloy (HSLA) steels with high toughness have been successfully processed to obtain strengthening through grain refinement and precipitation [2–6]. However, HSLA steels have disadvantages of high yield ratio and higher cost. Dual phase steels (DP steels) are one class of advanced high strength steels (AHSS) that have the low yield ratio, excellent combination of strength and ductility, and lower cost [7–9]. The low yield strength and good ductility of dual phase steels is associated with the soft and ductile ferrite matrix, while the high tensile strength is primarily governed by the hard martensite [8–10]. However, it is difficult to further enhance the strength of dual phase steels only via martensite phase because the volume fraction of martensite is generally limited to less than ~30% to ensure good ductility. On the other hand, the large difference in hardness between ferrite and martensite in conventional dual phase steels is responsible for low hole expansion [6,11,12].

Considering the disadvantages of low carbon HSLA steels and conventional DP steels, a class of hot rolled dual phase steels strengthened by phase transformation strengthening and precipitation strengthening is being considered [13–16]. These dual phase steels are based on the concept of strengthening the ferrite matrix through nanoscale TiC particles. The nanoscale precipitates effectively strengthen the ferrite matrix, enhance the strength of the dual phase steels and reduce the difference in hardness between ferrite and martensite phase. To develop hot rolled steels that comprise of ferrite matrix with TiC particles and dispersed martensite islands, ~0.1 wt% Ti was added and Si content was increased to ~1.5 wt% to match the nose of TiC precipitation with that of ferrite transformation and enhance the hardenability of untransformed austenite. Murakami et al. studied the effects of rolling conditions on precipitation in C-Si-Mn-Ti dual phase steel and found that the fatigue limit was maximized with the average TiC size of ~7 nm [15]. Hu et al. obtained a tensile strength of 780 MPa 0.08C-1.5Si-1.7Mn-0.1Ti dual phase steel and indicated that the yield strength of the steel was high because of the TiC precipitation and solid solution strengthening led by silicon [16].

Compared to the cold rolled-annealing process, the thermo-mechanical control processing (TMCP) does not required

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additional heat treatment after coiling. Thus, austenite-to-ferrite transformation, precipitation in the ferrite matrix, and austenite-to-martensite transformation in hot rolled dual phase steels need to be accomplished on the run-out table after hot rolling. The martensite phase can be obtained on hot rolling line through the fast cooling to below M_S before coiling [17,18]. In this regard, ferrite transformation and its relationship with the precipitation behavior are critical to develop dual phase steels strengthened by nanoscale TiC particles. On the other hand, the Ti-containing dual phase steels reported previously were characterized by high Si content, which renders poor surface quality.

In the study described here, a hot rolled Ti-bearing dual phase steel with low Si content was evaluated. A series of TMCP simulation were adopted to elucidate the effect of ferrite transformation temperature on microstructural evolution and precipitation behavior on the run-out table. TMCP was carried out with the objective of obtaining a hot rolled dual phase steel consisting of ferrite matrix with nanoscale TiC particles and dispersed martensite islands. Furthermore, the precipitation behavior and its effects on mechanical properties were discussed in detail to obtain fundamental understanding of precipitation mechanism and mechanical properties in hot rolled Ti-bearing dual phase steels with low Si content.

2. Experimental procedure

2.1. TMCP simulation

The chemical composition of the experimental steel in wt% was 0.06 C, 0.25 Si, 1.50 Mn, 0.50 Cr, 0.10 Ti, 0.02 Al, 0.0028 P, 0.0016 S and 0.004 N. The steel was melted in a 160 kg vacuum induction furnace and cast into ingots. The ingots were subsequently forged into square billets of 70 mm × 90 mm × 100 mm. The billets were heated to 1250 °C for 2 h and then hot rolled to 12 mm thickness on Φ450 mm two-high rolling. Cylindrical samples of Φ8 mm × 15 mm for thermal simulation experiments were machined from the hot rolled plates along the rolling direction. MMS-300 thermo-mechanical simulator was used to simulate the TMCP, and the schematic diagram is presented in Fig. 1a. The specimens were heated to 1250 °C (above α-γ complete transformation temperature) for 180 s to obtain the full austenite with abundant dissolved alloying elements. Next, the specimens were cooled to 880 °C at a cooling rate of 10 °C/s, held for 20 s to eliminate the temperature gradient, and deformed in compression to ~50% strain at a strain rate of 5/s. The austenite-ferrite start transformation temperature (A_{r3}) of the experimental steel was estimated at ~762 °C by $A_{r3} = 910–310C – 80Mn – 20Cu – 55Ni – 80Mo – 0.35(h – 8)$ [19], where h is the plate thickness (mm), and in our case is the specimen diameter of 8 mm. Therefore, after deformation, the specimens were cooled at a rate of 30 °C/s to 760, 740, 720, 700, 680, 660 and 640 °C, respectively, and held for 300 s in order to obtain ferrite. Finally, the specimens were rapidly cooled to room temperature at a cooling rate of 80 °C/s to promote martensitic transformation.

2.2. TMCP practice

The TMCP practice was carried out on two-high Φ450 mm experimental hot rolling mill equipped with water cooling system developed in our laboratory, and the schematic diagram is presented in Fig. 1b. The plates of 70 mm thickness were reheated to 1250 °C for 1 h and hot rolled to 5 mm thick strips via nine passes. The hot rolling was initiated at 1150 °C and finished at 880 °C and 850 °C, respectively. After hot rolling, the strips were cooled to 690–700 °C by water, followed by air cooling for 20 s, and cooled by water again to 150 °C on the run-out table, and then placed in the coil box to simulate the industrial coiling process.

2.3. Microstructure and mechanical properties

Specimens for optical microscopy were prepared from thermally simulated samples and hot rolled strips using regular grinding, polishing, and etching in 4% nital solution for 10 s. To accurately measure the volume fraction of martensite, another set of metallographic specimens were etched with LaPera etchant for 60 s [20]. The microstructure was observed by Leica-DMIRM optical microscope. Transmission electron microscopy specimens with diameter of 3 mm and thickness of 50 μm were twin-jet electropolished in a solution containing 9% perchloric acid and 91% ethylalcohol at −30 °C, at a voltage of 30 V. They were examined by field-emission transmission electron microscopy (FEI Tecnai G^2 F20), operated at 200 kV. The energy dispersive X-ray spectroscopy (EDS) was used to characterize the chemistry of precipitates.

Microhardness measurements were carried out in individual ferrite grains and martensite islands/blocks using FM-700 Vickers hardness testing machine at a load of 10 g. Macrohardness was also determined by universal-hardness testing machine (KB 3000 BVRZ) at a load of 10 kg. The tensile samples with gauge of 50 mm and width of 12.5 mm were machined from the strips parallel to the rolling direction. The tensile tests were conducted at room temperature using CMT5105-SANS electron universal testing machine at cross-head speed of 3 mm/min.

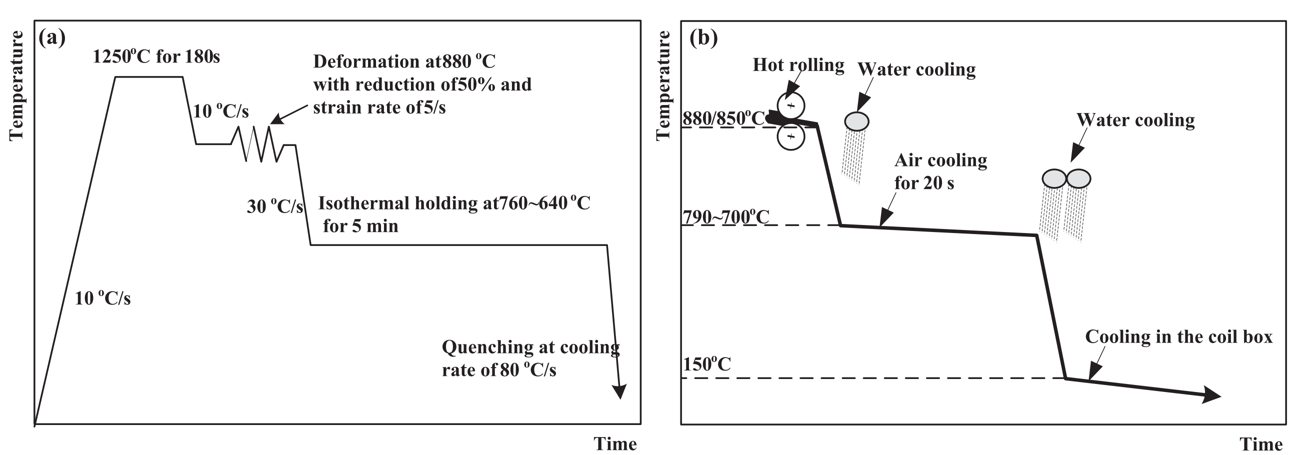

Fig. 1. Schematic diagrams of the experimental process: (a) TMCP simulation and (b) TMCP practice.