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Structure–mechanical property relationship in a low-C medium-Mn ultrahigh strength heavy plate steel with austenite-martensite submicro-laminate structure

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ABSTRACT

We elucidate structure–property relationship in a 0.1C–5Mn–0.4Mo hot rolled steel that was directly water-quenched and intercritically tempered at 650 °C. Tempering in the intercritical region for optimum time was critical in obtaining elongation of 25.0% and reduction in area of 65.4%. Moreover, the tensile strength was 875 MPa and the impact energy at test temperature of −60 °C was significantly high at 165.3 J. The microstructure of water-quenched steel consisted of lath martensite, needle-shaped cementite, and about 1% retained austenite. The superior combination of strength, ductility, and toughness subjected to tempering for optimal time of 30 min is attributed to the dissolution of cementite, recovery of martensitic structure, and formation of approximately 13% reversed austenite with appropriate mechanical stability.

1. Introduction

There is a strong potential to develop advanced high strength steels (AHSS) in lieu of the conventional low strength counterpart for structural weight reduction and safety improvement. Compare to the martensitic steel characterized by high strength but low ductility due to lack of effective hardening and microcrack-assisting mechanisms [1–3], the good balance of strength and ductility can be obtained in transformation-induced-plasticity (TRIP) steel consisting of islands of hard residual austenite and carbide-free bainite dispersed in a soft ferrite matrix. The strength of conventional low carbon TRIP steel is relatively low because of high volume fraction of ferrite. It is important to retain adequate amount of carbon in austenite during intercritical annealing and following austempering to obtain stable retained austenite [4–5]. Recently, the combination of ultrahigh strength and satisfactory ductility was simultaneously achieved in several novel steels, such as nanocrystalline bainitic (NB) steel [6], quenching and partitioning (Q&P) steel [7], and 9% Ni steel [8] by taking advantage of TRIP effect. The long duration of low temperature heat treatment of NB steel [9], the precise quenching temperature between the start and finish temperature of martensitic transformation (M_s and M_f) of Q&P steel [10], and expensive alloying element, Ni, in 9% Ni steel [8] may restrict industrial production.

Compared with high-Mn steel including Hadfield steel with 10–15 wt% Mn and twin-induced plasticity steel with 15–30 wt% Mn–Al–Si, the high strength and excellent ductility medium-Mn automotive steels containing 5–8 wt% Mn, referred as third generation AHSS, have attracted increased attention due to cost-effectiveness. The improved combination of strength and ductility was obtained in the cold-rolled and annealing thin steel plate via intercritical annealing of original quenched martensitic microstructure in the ferrite–austenite region, and metastable austenite was stabilized at room temperature via enrichment of Mn in austenite during the annealing process [11,12]. A significant degree of Mn partition occurred in ferrite–austenite region of medium-Mn steel. But Mn diffusion was slow during heat treatment of Q&P steel at low temperature, and the amount and stability of austenite was attributed to the C partitioning [5,7,13].

Advanced heavy steel plates with combination of high strength, excellent ductility, and superior low-temperature toughness are frequently employed as structural materials for ship hull, bridges, buildings, pressure vessels, and offshore structures. In TMCP (thermomechanically controlled processing) and Q&T (quenching-tempering) of advanced thick steel plates, although large amount of expensive alloying elements, such as Ni, Cr, Mo, and Cu are added to increase the hardenability of austenite, unfavorable microstructures such as coarse granular bainite and Widmanstatten ferrite are generated at small

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rolling reduction and low cooling rate in the center of the heavy steel plate. Thus, ductility and toughness are low. Moreover, the high yield ratio of ~0.92–0.94 is inevitable in the Q&T thick plate steel [14,15].

In the present study, the effect of intercritical tempering time on microstructural evolution and mechanical properties of a hot-rolled and water-quenched low-carbon medium-Mn heavy plate steel of 80 mm thickness was explored. The objective was to induce TRIP effect to low carbon medium Mn heavy plate steel and obtain ultra-high strength, excellent ductility, superior toughness, and low yield ratio in the center of the plate. The microstructures were characterized by a combination of scanning electron microscope (SEM), electron back-scattered diffraction (EBSD), transmission electron microscopy (TEM), and X-ray diffraction (XRD). The impact toughness was measured, and fracture behavior was studied.

2. Experimental

The experimental steel was melted in a vacuum induction furnace and cast as 150 kg ingot. The nominal chemical composition of the steel in wt% was 0.1C, 0.2Si, 5.0Mn, 0.003P, 0.0015S, 0.015Al, 0.4Mo, and balance Fe. A small amount of Mo (0.4 wt%) was added to enhance resistance to temper embrittlement. The role of Mo in the tempered martensite matrix is to tie-up P atoms because of high interaction energy between the two elements and prevent segregation of P to the grain boundaries and hence temper embrittlement [16]. The 140 mm thick slab was heated to 1200 °C for 3 h. After air-cooling to 960 °C, followed by rolling via 5 passes on a trial rolling mill with roll diameter of 450 mm, the slab was rolled to a plate of ~80 mm thickness with total reduction of ~43%. The finish rolling was controlled at 900 °C. Subsequently, the plate was directly water-quenched to room temperature using an accelerated cooling system. Next, the water-quenched plates were reheated to the tempering temperature of 650 °C for 10 min and 30 min, respectively, and it took ~50 min to reaching the isothermal temperature. Then, the plates were air-cooled to room temperature at a cooling rate of ~0.125 °C/s. The Formastor-FII dilatometer was used to measure the phase transformation temperature. The tested specimens were cut from the hot-rolled and water-quenched steel plate, and machined to cylindrical specimens of dimensions 10 mm long and 3 mm diameter. The samples were heated to 1000 °C at a linear rate of 0.2 °C/s to simulate the slow heating process of heavy plate steel and then cooled to 20 °C at 100 °C/s. The start and finish temperature of ferrite to austenite transformation (A_s and A_f) were determined by the dilatometer to be 582.2 °C and 769.5 °C, respectively, and M_s and M_f to be 365.3 °C and 128.5 °C, as shown in Fig. 1.

The tensile specimens of dimensions 6 mm diameter and 30 mm length were machined from the plates parallel to the rolling direction. The tensile tests were conducted at room temperature with a crosshead speed of 3 mm/min using a Shimadzu AG-X universal testing machine. Charpy v-notch impact tests were performed at 20 °C, 0 °C, −20 °C, −40 °C, −60 °C, respectively, with standard specimens (dimensions: 10 × 10 × 55 mm^3) with a v-notch parallel to the rolling direction using Instron Dynatup 9200 series instrumented drop weight impact tester, consistent with ASTM E23 specification. The samples were cooled to −5 °C below the test temperature to take into consideration the rise in temperature during transfer of cooled sample to the Charpy v-notch impact tester. The toughness data presented is an average of five measurements for each test condition, and strength data is an average of three measurements.

The specimens for microstructural studies were polished using standard metallographic procedure and etched with a 4 vol% nital solution and observed using a Zeiss Ultra 55 SEM. For EBSD, the sample was electrolytically polished in a solution consisting of 650 ml ethyl alcohol, 100 ml perchloric acid, and 50 ml distilled water at room temperature. TEM studies were conducted using 3 mm diameter thin foils, ground to a thickness of 40 μm and electropolished using a solution of 8% perchloric acid and alcohol at −20 °C in a twin-jet machine, and examined by FEI Tecnai G^2 F20 TEM at an accelerating voltage of 200 kV. The fracture surface of impact specimens was studied by a FEI Quanta 600 SEM. The volume fraction of austenite was determined by a D/ma × 2400 XRD using a Cu-Kα radiation source with the scanning speed of 2 °/min, and the integrated intensities of (200)γ, (220)γ, (311)γ, (200)α, and (211)α peaks were used to quantify the content of austenite using Eq. (1) [17]. The specimens were mechanically ground and electropolished to minimize the possible error originating from the mechanically induced transformation of retained austenite during the specimen preparation. The theoretical calculations concerning evolution of various phases with temperature, such as FCC, BCC, and cementite, were studied using Thermocalc combined with TCFE6 database for thermodynamic calculation in equilibrium.

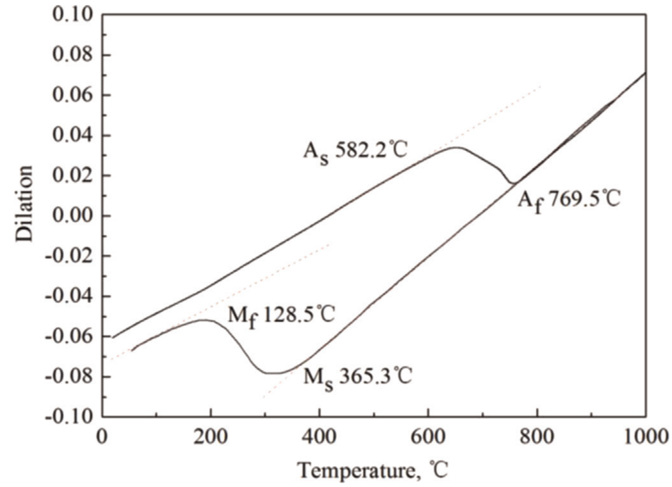

Fig. 1. Transformation temperature of ferrite to austenite at heating rate of 0.2 °C/s and austenite to martensite at cooling rate of 100 °C/s.

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

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.

3. Results and discussion

3.1. Microstructural evolution

The calculated volume fraction of phase for the experimental steel and weight percent of element in FCC are presented in Fig. 2. The temperature range of FCC and BCC two phases zone was between 430 °C and 740 °C. The volume fraction of FCC at 650 °C was 37.8%. The volume fraction of cementite between 20 °C and 525 °C was ~1.5%, and decreased gradually with increase in temperature and disappeared at temperatures greater than 600 °C. The Mn content in wt% in FCC was 9.23 at 650 °C.

The SEM micrographs of experimental steels are presented in Fig. 3. The water-quenched steel of 1/4 thickness and 1/2 thickness consisted of lath martensite, needle-shaped cementite, and a small amount of retained austenite. The width of martensite lath was 0.3–0.5 μm and film-type austenite was present between the laths (Fig. 3a and b). In steel of 1/4 thickness tempered for 10 min, the