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Ensuring combination of strength, ductility and toughness in medium-manganese steel through optimization of nano-scale metastable austenite

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ABSTRACT

Medium-Mn steel was innovatively designed in terms of alloying elements for medium to heavy steel plates to obtain combination of high strength, good ductility, and excellent low temperature toughness. Martensite was the dominant microstructure in the directly quenched steel plate because of high hardenability obtained by the addition of 5.6 wt% Mn. Three intercritical annealing processes were adopted to ensure transformation-induced-plasticity (TRIP) effect through optimization of the volume fraction, morphology, and C and Mn-enriched reversed austenite. On annealing, the dislocation density of martensite plate was decreased because of recovery and recrystallization, and metastable austenite film nucleated at the interface. Both thermal and mechanical stability of austenite decreased with increase in annealing temperature. The high yield strength of 840 MPa, good elongation after fracture of 24.3%, and excellent toughness at − 60 °C of 130.3 J was obtained at intermediate annealing temperature of 650 °C, and the volume fraction of reversed austenite at room temperature and − 80 °C was 22% and 17%, respectively. The reversed austenite exhibited different stability with increased tensile strain, leading to improved ductility and delayed necking. Moreover, the crack initiation energy and crack propagation energy were increased via dynamic stress partitioning and relaxation together with the transformation of metastable austenite. Thus, significant degree of TRIP effect induced by moderate stability of austenite played an important role in governing mechanical properties.

1. Introduction

Advanced hot rolled heavy steel plates with combination of high strength, superior low-temperature toughness, and good ductility are the basic requirements for ship hull, bridges, buildings, pressure vessels, and offshore structures [1–2]. The strength-ductility trade-off has long been a dilemma in materials science. Thus, the potential of various structural materials, particularly steels, has been greatly limited [3]. At the same time, in most structural materials, the properties of strength and toughness are mutually exclusive [4], such that when a strong steel is designed, feasible strategies need to be adopted to deal with the conflicting properties, and realize the excellent combination of strength, ductility, and toughness. In comparison to lack of ductility in conventional high strength steel with tempered martensite microstructure, the good balance of strength and ductility can be obtained in transformation-induced-plasticity (TRIP) steel by introducing islands of residual austenite. It is vital to retain adequate amount of carbon in austenite during intercritical annealing and following austempering to obtain stable retained austenite [5–6], while keeping in mind that the increase of carbon in high strength steel greatly deteriorates weldability and low temperature toughness. Ni has a strong effect on stabilizing austenite in ultra-low carbon steel with 5–9 wt% [7–8], but the high alloy cost restricts industrial production.

Medium-Mn steel is defined as a steel with Mn concentration in the range of 3–10 wt%, as reported first by Miller [9]. From the perspective of improving fuel efficiency and passenger safety in the automobile industry, medium-Mn steels have drawn significant attention and actively studied for the development of 3rd generation advanced high strength steels with excellent mechanical properties and reasonable production costs. These steels consisted of only martensite in hot and cold rolled states, and the process adopted to obtain outstanding properties was to reheat the steel with original martensitic microstructure to the intercritical region ($\alpha + \gamma$ two phase region), where part of the martensite transforms to austenite. The amount, morphology, and the stability of the retained austenite was tailored through redistribution of C and Mn. These steels exhibited high strength and

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good ductility due to TRIP effect, induced by austenite volume fraction of ~0.2–0.4 [10–17]. Moreover, in comparison to the poor toughness of quenched martensite, the formation of reversed austenite during intercritical annealing played an important role in enhancing toughness [18]. To the best of our knowledge, the mechanical stability of austenite under constant tensile load and fast impact loading has not been systematically studied. Therefore, it is meaningful to study the morphology of austenite subjected to tensile straining and thermal stability of austenite at sub-zero temperature, which is important to establish the relationship between nanoscale metastable austenite and combination of strength, ductility, and toughness.

In the present study, a low carbon medium-Mn steel was subjected to controlled rolling and directly water-quenched, followed by intercritical annealing at different temperature to obtain nanoscale metastable austenite with different volume fraction, morphology, and chemical stability. Microstructural evolution was investigated by optical microscope (OM), transmission electron microscopy (TEM), and X-ray diffraction (XRD). The tensile strength and impact toughness were analyzed in combination with thermal and mechanical stability of austenite.

2. Experimental

The experimental steel was melted in a vacuum induction furnace and cast as 150 kg ingot. The nominal chemical composition of the experimental steel in wt% was 0.045C, 0.2Si, 5.6Mn, 0.005P, 0.003S, 0.03Al, 0.25Cu, 0.3Ni, 0.2Mo, 0.004O, 0.003 N, and balance Fe. The 140 mm thick slab was heated to 1200 °C for 3 h. After air-cooling to 990 °C, followed by rolling via 11 passes on a laboratory rolling mill with roll diameter of 450 mm, the slab was rolled to a plate of ~30 mm thickness with total reduction of ~78.6%. The finish rolling was controlled at 930 °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 annealing temperature of 620 °C, 650 °C, and 680 °C, respectively, for 20 min, and it took ~40 min to reaching the isothermal temperature. Then, the plates were air-cooled to room temperature at a cooling rate of ~0.3 °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 0.25 °C/s to simulate the slow heating process of medium heavy plate steel and then cooled to 20 °C at 60 °C/s. The start and finish temperature of ferrite to austenite transformation (A_s and A_f) were determined by the dilatometer to be 608 °C and 764 °C, respectively, and M_s and M_f to be 427 °C and 190 °C, as shown in Fig. 1. Thus, annealing between 620 and 680 °C was within the intercritical region.

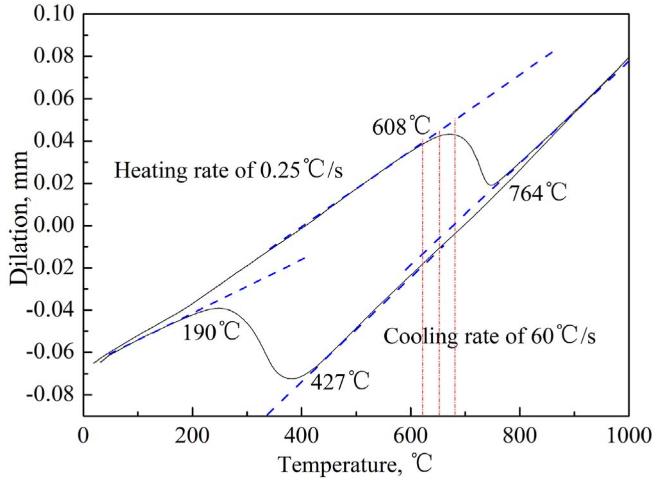

Fig. 1. Transformation temperature of ferrite to austenite at heating rate of 0.25 °C/s and austenite to martensite at cooling rate of 60 °C/s.

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 (corresponds to an initial strain rate of $1.67 \times 10^{-3} s^{-1}$) using a Shimadzu AG-X universal testing machine. The elongation after fracture was calculated by checking the gage length after the tensile test. Charpy v-notch impact tests were performed at 20 °C, −20 °C, −40 °C, −60 °C, and −80 °C, respectively, with standard specimens (dimensions: 10 × 10 × 55 mm) 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 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 Leica DMIRM OM. 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 volume fraction of austenite was determined by a D/max2400 XRD using a Cu-Kα radiation source with scanning speed of 2 deg/min. Eq. (1) was used to calculate the fraction of austenite from the intensities from diffraction, and the integrated intensities of (200)γ, (220)γ, (311)γ, (200)α, and (211)α peaks were analyzed [19–20]. The specimens were mechanically ground and electropolished to minimize the possible error originating from the mechanically-induced transformation of retained austenite during specimen preparation. The theoretical calculations concerning evolution of percent of C and Mn in austenite with temperature were studied using Thermo-Calc combined with TCFE7 database.

$$V_\gamma = 1.4I_\gamma/(I_\alpha + 1.4I_\gamma) \tag{1}$$

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.

For studying the thermal stability of metastable austenite, the experimental steel subjected to annealing temperatures of 620 °C, 650 °C, and 680 °C was kept at −40 °C and −80 °C, respectively, for 30 min, and the volume fraction of austenite was measured at room temperature by XRD. For studying the mechanical stability of metastable austenite, the experimental steel subjected to annealing temperature of 650 °C was subjected to tensile strain of 0.02, 0.04, 0.08, 0.12, and 0.16, respectively. The volume fraction of austenite in each interrupted tensile specimens was determined. Moreover, the volume fraction of austenite in the fractured specimen of room temperature Charpy impact specimen of the experimental steel annealed at 650 °C was measure to evaluate the stability of austenite under fast impact loading.

3. Results and Discussion

Fine quenched martensite packets were formed inside the prior austenite grains because of the high hardenability of medium-Mn steel. The prior austenite grain size was ~30–40 μm. Sluggish recovery occurred during annealing at 620 °C, and prior austenite grain boundaries were visible (Fig. 2a–b). Martensite plates were completely recovered at 650 °C and 680 °C, resulting in distinct grain boundaries inside prior austenite grain boundaries, and the plates were gradually coarsened with increase in annealing temperature (Fig. 2c–d).

It was proposed that the critical heating rate of diffusion and