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Toughness and ductility improvement of heavy EH47 plate with grain refinement through inter-pass cooling

J.Y. Wu[a], B. Wang[a], B.X. Wang[a,*], R.D.K. Misra[b], Z.D. Wang[a]

[a] *State Key Laboratory of Rolling and Automation, Northeastern University, Shenyang 110819, China*

[b] *Laboratory for Excellence in Advanced Steel Research, Department of Metallurgical, Materials and Biomedical Engineering, University of Texas at El Paso, 500 W. University Avenue, El Paso, TX 79968, USA*

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A B S T R A C T

In this study, a novel inter-pass cooling technology was applied during rough rolling (R-IPC) to process a 60 mm ultra-heavy EH47 steel plate with excellent toughness and ductility. The plate was compared to a plate processed through conventional thermo-mechanical controlled processing (TMCP). The microstructure evolution at 1/4-thickness and 1/2-thickness of the plates was studied, while the relationship between microstructure and mechanical properties, through tensile and Charpy V-notch impact toughness, was established. In this study, it was reported that the R-IPC steel deformation penetration was higher compared to the TMCP steel. The ferrite fractions of the R-IPC and TMCP steels were 47% and 10% at 1/4-thickness, as well as 35% and 0.5% at 1/2-thickness, while the acicular ferrite fractions at 1/2-thickness of the R-IPC and TMCP steels were 50% and 9.5%, respectively. The granular bainite width at 1/2-thickness of the R-IPC steel (14 ± 4 μm) was significantly lower than the TMCP steel (27 ± 10 μm). The M/A island volume fraction in R-IPC steel was higher than the TMCP steel at 1/4-thickness, whereas it was reduced dramatically at 1/2-thickness. The high intensity of the desired texture $\{112\} < 110 >$ was obtained at 1/2-thickness of the R-IPC steel, while the undesired $\{411\} < 148 >$ was obtained at 1/2-thickness of the TMCP steel, which was responsible for the R-IPC steel superior toughness compared to the TMCP steel. The tensile and yield strengths of the two rolled plates were similar, while the elongation at 1/4-thickness of the R-IPC steel was higher compared to the TMCP steel. The low temperature impact energy of the R-IPC steel was significantly higher compared to the TMCP steel, resulting from finer grain size, higher ferrite fraction and higher area of the {110} texture parallel to the impact direction.

1. Introduction

Shipping containers are widely used globally for trade. To achieve high freight capacity and low cost, the container ship size increase is essential and requires strong upper steel deck for security [1,2]. As the upper steel deck thickness increases, the plane stress state is converted to plane strain state, while the yield strength of the steel is likely to be increased to a value that exceeds the brittle fracture strength, resulting in low crack resistance ability of the ultra-heavy high-strength steel deck. Therefore, the ultra-heavy high-strength steel plate with high crack-arrest ability is required [3].

The low strength crack-arrest steel microstructure is characterized by ferrite and pearlite. A ferrite matrix with low dislocation density can reduce stress concentration, originating from dislocation pile-up and the lamellar pearlite can deflect the propagation direction of cleavage cracks [4]. Through ferrite grain refinement, the cleavage crack propagation path can be frequently deflected, as it is responsible for higher crack propagation energy [5]. Along with the crack-arrest steel strength increase, both acicular ferrite and granular bainite with high dislocation density are desired in the microstructure, in order to satisfy the strength requirement. Interlaced acicular ferrite lath with misorientation exceeding 15° [6] can inhibit and deflect the propagation of brittle cracks [7,8], while granular bainite laths are bulky and lack high-angle boundaries. Also, hard and brittle M/A constituents are distributed at the boundary of acicular ferrite and at the matrix of bainite lath, including the coarse M/A islands, at which, brittle cracks initiate [9–11] as well as the fine M/A islands, at which, brittle cracking is inhibited [12]. Therefore, the crack-arrest capability becomes difficult when the microstructural constituent changes as the steel plate strength increases.

Ultra-heavy ship plates are generally produced through thermal mechanical controlled processing (TMCP), for which, the penetration of

* Corresponding author.
E-mail address: Wbxang@126.com (B.X. Wang).

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deformation is not sufficient to fully refine the austenite grains and heal the cracks at 1/2-thickness of the plate during controlled rolling. The bainite lath, usually obtained from coarse austenite during phase transformation, has inferior crack-arrest property. The inter-pass cooling (IPC) process [13–15] can improve the penetration of deformation [16] through the temperature gradient control along the thickness direction of the slab during controlled rolling. Thereby, the austenite grains inside the slab are refined.

In the present work, a 60 mm thick ultra-heavy EH47 ship plate was produced with a total reduction ratio of 62.5% through inter-pass cooling introduced during rough rolling (R-IPC). Moreover, the relationship between microstructure and mechanical properties at various plate thicknesses was studied. Compared to the TMCP steel, in which, the microstructure is composed of a high percentage of granular bainite and a low percentage of acicular ferrite, while a higher percentage of acicular ferrite and a high amount of substantially refined ferrite grains were obtained in the R-IPC steel. This improved the toughness and ductility of the plate, which was also responsible for the superior crack-arrest ability of the plate.

2. Experimental procedure

2.1. Hot rolling experiments

The experimental EH47 ship plate of 60 mm in thickness was rolled on the 750 mm experimental hot rolling mill, equipped with an inter-pass cooling device. The chemical composition was: 0.05 C, 0.12Si, 1.69Mn, 0.044 Nb, 0.015Ti, 0.15Cr, 0.48Ni, 0.2Cu and 0.03Al (wt%). The slab of 160 mm in thickness was reheated to 1200 °C for 4 h, for the microalloying elements to be dissolved. The reduction schedule of the nine passes was: 160→140→122→106→94→84→74→ 65→60 (mm), while the intermediate slab thickness was 106 mm.

The R-IPC schematic is depicted in Fig. 1. The dotted line demonstrated the temperature variation of the thermocouple inserted at 1/4-thickness of the slab, as measured with a midiLOGGERGL40 temperature collector. The solid line demonstrated the temperature variation at the slab surface, as measured with VF-3000 infrared radiation thermometers. During rough rolling, the initial rolling temperature was ~ 1050 °C at the slab surface, while two cooling passes of 8 s and 12 s in durations were added prior to the first and second rolling passes, respectively, which was sufficient to form large temperature gradient along the thickness direction. The holding time of the intermediate slab was 220 s, in order to ensure that the 1/4-thickness temperature would be 850 °C. During finish rolling, the initial rolling temperatures at the surface and the 1/4-thickness of the slab were ~ 780 °C and 850 °C, respectively. The finish rolling temperature was ~ 800 °C on the plate surface. After finish rolling, the hot rolled plate was cooled to 420 °C at a cooling rate of ~ 2.3 °C and then air cooled to room temperature. In the two-stage rolling of TMCP steel, as the slab was initially rolled in ~ 1050 °C during rough rolling, it was consequently for 460 s subsequently to the third rolling pass. Consequently, the finish rolling process was started at 830 °C. Following finish rolling, the plate was cooled

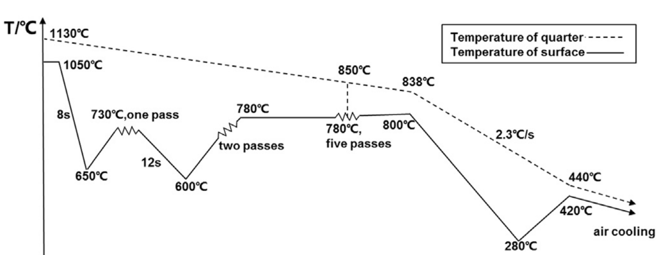

Fig. 1. Schematic diagram of R-IPC process.

from 800 °C to 400 °C at a cooling rate of ~ 2.3 °C/s and consequently air cooled to room temperature.

2.2. Microstructural characterization

Metallographic specimens were cut from the middle of the plates, polished and etched in a 4% Nital solution for observations through optical microscopy (Carl Zeiss Axio Imager Alm), scanning electron microscopy (SEM) (ZEISS ULTRA55) and electron back-scattered diffraction (EBSD) (Oxford instruments, INCA Crystal), at 1/4-thickness and 1/2-thickness of the rolled plates. The surfaces were perpendicular to the transverse direction (TD). For substructure observations, a transmission electron microscope (TEM) (JEM-2100F) with accelerating voltage of 200 kV was utilized to study the 3 mm in diameter thin foils, taken at the 1/4-thickness of the two plates. Also, electropolishing was conducted with a solution of 12% of perchloric acid and 88% of ethanol at − 30 °C.

2.3. Mechanical properties characterization

Standard Charpy V-notch specimens of 10 × 10 × 55 mm^3 in size were machined from the longitudinal direction of the rolled plates of different thicknesses and tested in the temperature range of − 100 to − 20 °C with an impact testing machine (Instron SI-IM canton MA). The impact direction was parallel to the transverse direction (TD). The tensile tests were carried out at a constant crosshead speed of 3 mm/min with an Instron machine (Instron 5585 H). Microstructure on the surface of the specimens from tensile and impact fractures, and microstructure along the cross-section near the impact fracture, were observed with SEM.

3. Results

3.1. Microstructure

Fig. 2a-d presents the microstructures of R-IPC and TMCP steels, which suggested that the microstructural constituent and grain size of the R-IPC steel differed from the TMCP steel. The microstructures at 1/4- and 1/2-thickness consisted of high volume fraction of acicular ferrite and quasi-polygonal ferrite as well as a low amount of granular bainite in the R-IPC steel, whereas in the TMCP steel, a high volume fraction of granular bainite and a low amount of acicular ferrite existed. Fig. 2e presents the volume fractions of different microstructural constituents at different thicknesses of the R-IPC and TMCP steels through multi-field statistics obtained from the optical micrographs. The volume fractions of polygonal/quasi-polygonal ferrite, acicular ferrite and granular bainite were approximately 47%, 16% and 37% at 1/4-thickness, as well as 35%, 50% and 15% at 1/2-thickness of the R-IPC steel. The corresponding volume fractions were approximately 9.6%, 14.4% and 76% at 1/4-thickness, as well as 4.5%, 9% and 86.5% at 1/2-thickness of the TMCP steel. Fig. 2f presents the grain sizes at 1/4- and 1/2-thicknesses of the R-IPC and TMCP steels, respectively. From the 1/4-thickness to the 1/2-thickness of the R-IPC steel, the diameters of ferrite grains (5–11 μm) and widths of granular bainite lath (10–18 μm) were similar, while the acicular ferrite lath width was in the range of 2–3 μm to 3–7 μm. In the case of TMCP steel, the acicular ferrite lath width was in the range of 2–4.5 μm to 3–7 μm, while the granular bainite lath width was in the range of 12–25 μm to 18–36 μm. The ferrite grain diameter range was 6.5–11.5 μm at 1/4-thickness.

The microstructures at different thicknesses of the R-IPC and TMCP steels investigated through SEM are presented in Fig. 3a-d. Regarding the R-IPC steel, quasi-polygonal ferrite grains existed at 1/4-thickness, degenerating the pearlite at 1/2-thickness. The M/A islands in the TMCP steel were distributed at the boundary of acicular ferrite and granular bainite lath, mainly in the form of strips and higher in size than the M/A islands in the R-IPC steel. Pearlite blocks surrounded by