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Austenite stability and its effect on the toughness of a high strength ultra-low carbon medium manganese steel plate

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ABSTRACT

A novel two-step intercritical annealing process was designed for an ultra-low carbon medium manganese steel plate. Excellent mechanical properties with yield strength of 590 MPa, tensile strength of 840 MPa, total elongation of 28.5% and high impact energy of 106 J at −80 °C were obtained. The microstructure comprised of ultra-fine grained ferrite and retained austenite together with a small amount of martensite after the two-step intercritical annealing. Both lath-like and blocky retained austenite with volume fraction of ~25% and relatively poor stability were obtained. The submicron-sized lath-like retained austenite exhibited Nishiyama-Wassermann (N-W) orientation relationship with the neighboring martensitic ferrite lath. The fine grain size played a crucial role in stabilizing austenite during phase transformation by significantly lowering M_s temperature and increasing the elastic strain energy. The overall stability of retained austenite during deformation was considered to be mainly governed by the chemical composition of the studied steel. The mechanism of toughening was elucidated. The superior low-temperature toughness was associated with TRIP effect of metastable retained austenite, which relieved the local stress concentration, enhanced the ability to plastic deformation and delayed the initiation and propagation of microcracks.

1. Introduction

High yield strength, superior weldability and excellent low-temperature toughness are critical mechanical properties of heavy gage plate. The methods to continuously increase the yield strength and decrease the ductile-brittle transition temperature (DBTT) are aspects of primary interest during the processing of advanced heavy steel plates [1,2]. Previous studies suggested that retained austenite can significantly enhance strength and ductility through deformation-induced transformation of metastable retained austenite to martensite, referred as "TRIP effect" [3,4]. Thus, TRIP steels consisting of ferrite, bainite and retained austenite [5,6] and Q&P steels comprising of a dual-phase microstructure of lath-martensite and film-like retained austenite [7–10] have been developed. Recently, austenite-reverted transformation (ART) annealing process of medium manganese steel has been proved to be a good method of achieving excellent combination of strength and ductility by obtaining a considerable amount of retained austenite [11–17].

However, the mechanism of retained austenite in improving toughness is inconsistent with that in improving ductility. Large volume fraction of retained austenite does not mean good impact toughness. Actually, the stability and morphology of retained austenite has a special effect on impact toughness. It is recognized that stable film-like retained austenite can remarkably improve low-temperature toughness and lower DBTT [18]. Motivated by this, a number of processes have been explored [19–25]. For example, adequate combination of high strength and good toughness in ultra-fine superbainite steels has been obtained because of the formation of stable retained austenite [22,23]. Moreover, the intercritical heat treatment has been applied to low alloyed steel plates to fabricate stable film-like retained austenite so as to enhance the low-temperature toughness [24,25]. Though the contribution of stable retained austenite on impact toughness has been widely investigated, whether the metastable retained austenite has the same effect on impact toughness is unclear to the best of our knowledge. It should be noted that the difference in stability of retained austenite will result in differences in toughening mechanisms. The stable film-like retained austenite

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improves the impact toughness primarily by suppressing crack propagation without undergoing transformation [13,21]. Different from the stable retained austenite, the metastable retained austenite with a relatively poor stability tend to transform to martensite during impact test, leading to the occurrence of TRIP effect. It is well recognized that the TRIP effect can relieve local stress concentration during deformation. Thus, we believe that the metastable retained austenite can also enhance impact toughness but through a different mechanism.

The present work is aimed at investigating the stability of retained austenite in an ultra-low carbon medium manganese steel plate and exploring the toughening mechanism of metastable retained austenite. Both one-step and two-step intercritical annealing processes were applied to the experimental steel. The role of metastable retained austenite in improving toughness is clarified through both mechanical test and microstructural characterization.

2. Experimental procedure

The nominal chemical composition of the experimental medium-manganese steel is Fe–0.01C–5.3Mn–1.53Si–0.56Ni–0.12 (Nb+V+Ti) wt%. The steel was melted in a high-frequency vacuum induction furnace and forged into billets of cross section 100 mm × 100 mm. The billets were homogenized at 1200 °C for 2 h and then hot rolled to 12 mm via two-stage controlled rolling process involving nine passes with a total reduction of 88%. The finish rolling temperature was ~900 °C and the plates were finally quenched to room temperature. Conventional one-step and novel two-step intercritical annealing processes were designed, shown in Fig. 1. The plate annealed at 640 °C for 3.5 h after hot rolling was designated as IA640 (one-step intercritical annealing process). The novel two-step intercritical annealing process consisting of intercritical annealing at 700 °C for 0.5 h and then intercritical isothermally partitioning at 640 °C for 3.5 h followed by air cooling to room temperature, was referred as IA700-640.

The dilatometer experiments were carried out using cylindrical specimens of 3 mm diameter and 10 mm length on a Formastor-FII full-automatic thermal dilatometer. Standard round tensile samples with the gauge length of 40 mm and diameter of 8 mm were machined from the plates along the rolling direction. Tensile properties, namely strength and elongation were measured using a CMT5105-SANS machine at a crosshead speed of 3 mm/min at room temperature. Full-size (10 mm × 10 mm × 55 mm) Charpy v-notch impact specimens were prepared along the rolling direction and tested using Instron drop weight impact tester in the temperature range of −80 °C to 20 °C. Considering the rise of temperature during the test, the specimens were cooled to −3 °C below the test temperature. Three tests were conducted for each condition and the average value was calculated as the final data.

The JXA-8530F electron probe microanalyzer (EPMA) and Zeiss Ultra-55 field emission scanning electron microscope (SEM) equipped with electron backscattered diffraction (EBSD) were employed for microstructural studies. Specimens with typical microstructure were observed on TECNAI G220 transmission electron microscope (TEM) at an accelerating voltage of 200 kV. The elements content in retained austenite were measured using TEM-EDS and theoretically calculated by Thermo-calc software combined with TCFE6 database. The fracture morphology of the impact specimens was studied by Leica DMIRM optical microscope (OM). The D/max2400 X-ray diffractometer (XRD) was applied and the integrated intensities of the $(200)_\alpha$, $(211)_\alpha$, $(200)_\gamma$, $(220)_\gamma$ and $(311)_\gamma$ diffraction peaks were calculated to quantitatively measure the volume fraction of retained austenite. The specimens for OM and EPMA observation were metallographically polished and etched by 4 vol% nital solution for about 10 s. Specimens for the EBSD observation and XRD measurement were mechanically ground and electro-polished with an electrolyte consisting of 650 ml alcohol, 100 ml perchloric acid and 50 ml distilled water to remove the residual stress. The TEM specimens were first ground to a thickness of 50 μm and then punched to disks with diameter of 3 mm, which were finally electro-polished using twin-jet machine under a voltage of ~29 V and a temperature of ~−10 °C.

3. Results

3.1. Microstructural characterization

Fig. 2 shows secondary electron micrographs of as-hot-rolled steel plate subjected to different intercritical annealing processes. The one-step intercritical annealing sample (IA640) possessed microstructure composed of retained austenite (RA) and ferrite (F). Both blocky and lath-like retained austenite was observed. Microstructure of two-step intercritical annealing sample (IA700-640) consisted of ultrafine-grained lath-like retained austenite and ferrite, with the presence of a small amount of martensite (M). During the first step intercritical annealing at 700 °C, a higher density of austenite grains nucleated along the original martensite laths, which divided the martensite lath and lead to the reduction of average width of ferrite laths in the final microstructure of

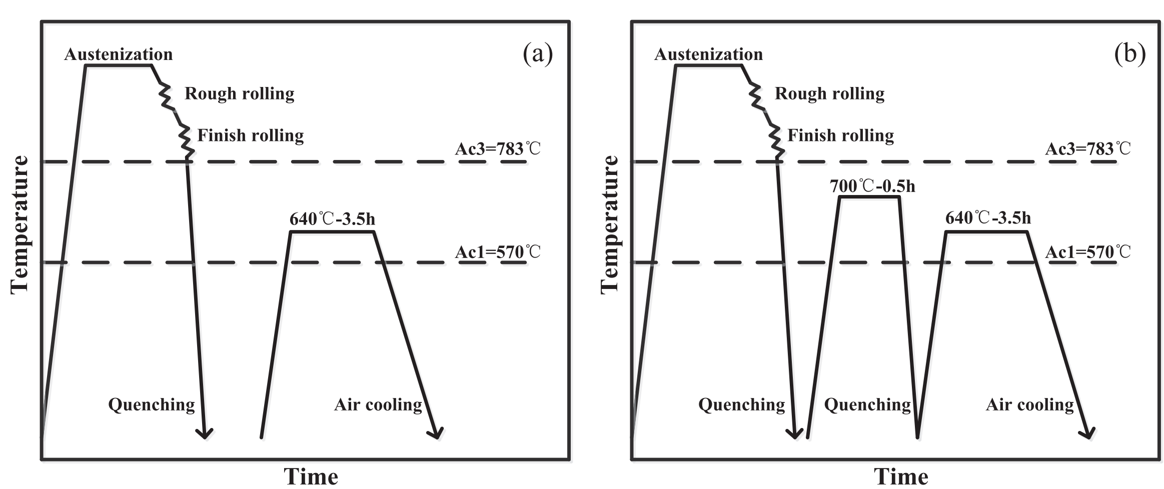

Fig. 1. Schematic diagram of the hot rolling and intercritical annealing process: (a) IA640; (b) IA700-640.