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Structure–mechanical property relationship in a high strength low carbon alloy steel processed by two-step intercritical annealing and intercritical tempering

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ABSTRACT

The influence of annealing and tempering temperature on the microstructure and mechanical properties was investigated in a low carbon alloy steel that was processed by a two-step intercritical annealing and intercritical tempering heat treatment. In general, the microstructure of the processed steel comprises intercritical lath-like ferrite, bainitic/martensitic lath and acicular-type retained austenite. The lower intercritical annealing temperature resulted in lower fraction of intercritical ferrite with finer grain size and consequently higher strength. On the other hand, the intercritical tempering temperature significantly influenced retained austenite content and precipitation. High fraction of retained austenite was obtained at a temperature slightly above Ac_1 temperature and retained austenite content decreased with increase in tempering temperature. This behavior is attributed to the competition between the enrichment of Mn and Ni and the fraction of reversed austenite. Fine niobium carbide precipitates of size ~2–6 nm and copper precipitates of size range ~10–30 nm were obtained. The optimal intercritical annealing and tempering temperatures to obtain the product of tensile strength and elongation % of ~30 GPa% were 780 °C and 660 °C, respectively and the volume fraction of retained austenite was ~29%.

1. Introduction

It is now well recognized that the transformation-induced plasticity (TRIP) effect associated with retained austenite significantly impacts the mechanical behavior of structural steels and is an effective approach to obtain excellent strength and ductility combination. Numerous methods have been developed to obtain retained austenite and exploit the TRIP effect, such as quenching and partitioning (Q&P) [1–4], TRIP [5,6] treatment, and increasing the metastability of austenite via modification of alloy design [7–12]. In Q&P or TRIP process, the retained austenite is stabilized through diffusion of carbon from the as-quenched martensite or bainite to adjacent untransformed austenite during the partitioning or austempering process, respectively. Recently, intercritical treatment was proposed to obtain retained austenite and was intensively studied in high Mn and high Ni-steels [7–9]. A low-carbon medium manganese (5 wt%) steel with high volume fraction of retained austenite was obtained by intercritical annealing [10]. Subsequently, a relative modified 0.2C–5Mn steel with outstanding tensile strength of ~1–1.5 GPa and total elongation of ~31–44% was obtained via longer annealing time [11,12]. High volume fraction of ~30% retained austenite was obtained by enrichment of both carbon and manganese during intercritical annealing for high duration of 6–144 h.

Another route to obtain high carbon content in retained austenite is the addition of Al and Si in steel, which prevents the formation of carbides and reduces intercritical annealing time [13]. Moreover, in high Ni martensitic steels, fine microstructure with retained austenite can be created by cyclic intercritical heat treatment, where the reversed austenite is stabilized by enrichment of Ni time and again [14]. As a whole, the retained austenite is not stabilized by enrichment of carbon but primarily by Mn and Ni during the intercritical annealing process.

Lately, the authors studied a low carbon 2Mn–1Ni steel with high strength (yield strength > 700 MPa) and excellent ductility (uniform elongation > 20%) using a two-step intercritical annealing and intercritical tempering heat treatment [15]. In this steel, casting difficulties associated with high Mn content in steel were eliminated and the high cost of Ni was reduced. An important aspect considered to obtain outstanding properties was to reheat the steel to a lower intercritical region after the prior intercritical annealing. The intercritical annealing process brought about the

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first enrichment of C, Mn, and Ni in reversed austenite, which transformed to bainite/martensite because of the insufficient stability, subsequently providing nucleation sites for reversed austenite that were enriched with alloying elements again during the second intercritical step. Moreover, these enriched areas had lower Ac_1 temperature, such that reversion transformation occurred at lower temperature, when the fine precipitates were obtained. Due to the two-step enrichment of alloying elements in reversed austenite and lower temperature, stable retained austenite and nano-scale precipitates were simultaneously obtained, providing TRIP effect and precipitation strengthening.

In intercritical heat treatment, the retained austenite content is related to the volume fraction of reversed austenite and its stability, which is affected by the intercritical annealing temperature [16]. Excellent mechanical properties can be achieved by controlling the amount and stability of retained austenite [17]. Based on the above discussion, there is now a need to understand the influence of intercritical annealing and tempering temperature on reversed transformation and associated mechanical properties. In this regard, we have studied a low carbon 2Mn–1Ni steel that was intercritically annealed and intercritically tempered at different temperatures.

2. Experimental

The nominal chemical composition of steel in wt% was Fe–0.10C–2.01Mn–0.78Si–0.78Al–0.08Nb–1.01 Cu–1.0Ni–0.26Mo. The role of different alloying elements in the two-step intercritical heat treatment was discussed elsewhere [15]. To study the first step of annealing, the annealing temperature was varied from 720 to 820 °C and the tempering temperature was kept constant at 660 °C (Fig. 1a). Similarly, to study the tempering temperature, the annealing temperature was kept constant at 780 °C and the tempering temperature was changed from 620 to 720 °C (Fig. 1b).

Heat treated samples were mounted and mechanically polished to mirror finish using standard metallographic procedures. The specimens were etched with Lepera etchant [18] for optical microscopy analysis, and with 2% nital for scanning electron microscopy (SEM) observation. SEM was carried out using ZEISS ULTRA-55 field emission scanning electron microscopy operated at 20 kV. Retained austenite was quantified by X-ray diffraction (XRD) using CuKα radiation and the volume fraction was estimated by measuring the peak intensity of (200)α, (211)α, (200)γ, (211)γ and (311)γ.

Tensile properties were measured at room temperature using standard tensile samples machined to 5 mm diameter and 25 mm gauge length. To characterize the fine-scale microstructure, transmission electron microscopy (TEM) was carried out using 3 mm disks that were twin-jet electropolished in an electrolyte of 10% perchloric acid and 90% ethanol. TEM was carried out using Hitachi H7600 and JEOL JEM-2100 FS microscopes equipped with energy dispersive X-ray spectrometer (EDS) operated at 120 kV and 200 kV, respectively.

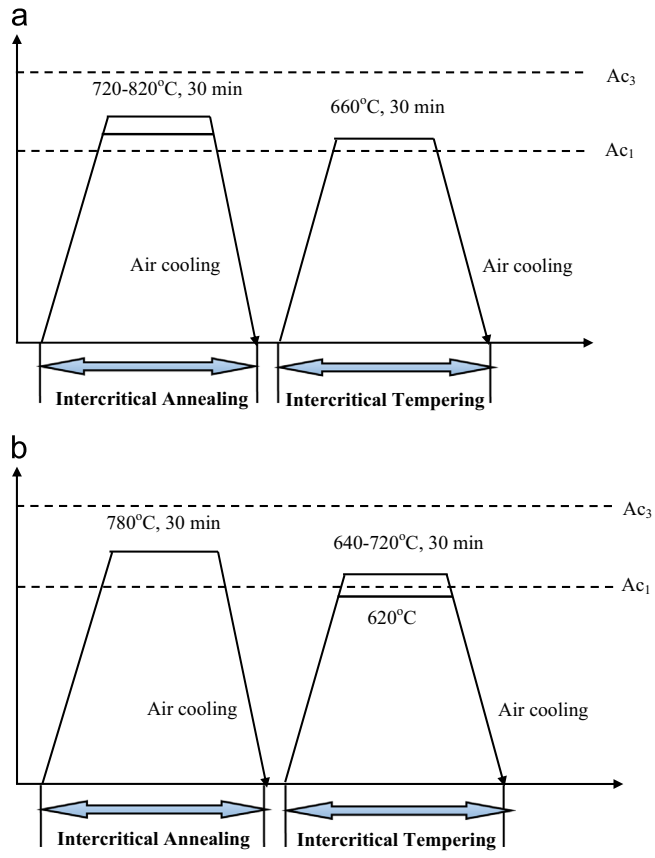

Fig. 1. Schematic diagram of heat treatments: (a) influence of intercritical annealing temperature at constant tempering temperature of 660 °C; (b) influence of intercritical tempering temperature at a constant annealing temperature of 780 °C.

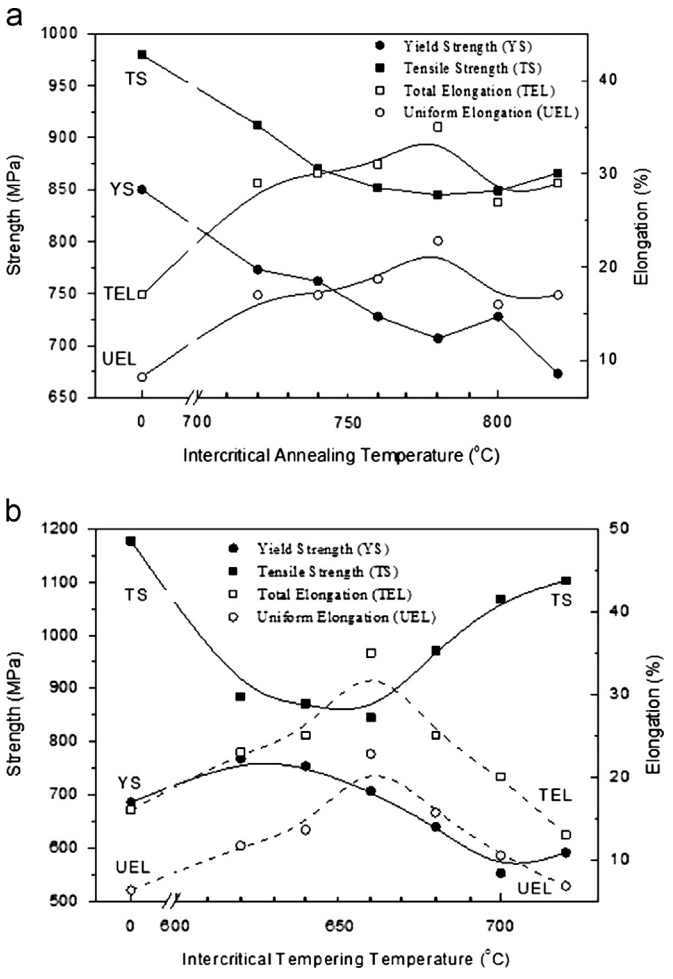

Fig. 2. Yield strength, tensile strength, total elongation, and uniform elongation as a function of (a) intercritical annealing temperature (constant tempering temperature at 660 °C); (b) intercritical tempering temperature (constant annealing temperature at 780 °C).