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A novel multi-step intercritical heat treatment induces multi-phase microstructure with ultra-low yield ratio and high ductility in advanced high-strength steel

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ABSTRACT

A significant volume fraction of 26% retained austenite was obtained via a two-step intercritical treatment in a low carbon low alloy steel with ultra-high tensile strength of ~1200 MPa, ultra-low yield ratio of 0.32, excellent uniform elongation of ~16.4% and total elongation of ~23%. The ultra-low yield ratio and excellent uniform elongation implied high work hardening and excellent formability. The high work hardening and ultra-high tensile strength are attributed to deformation-induced twin-martensite.

Advanced high strength steels (AHSSs) have been acknowledged to be of great potential for the automobile industry. Motivated by reduced vehicle weight, increased safety and crashworthiness, AHSSs with ultra-high strength and high ductility are being developed. However, difficulties (like springback) from forming ultra-high strength steel parts at room temperature are big challenges for manufacturing. The formability is reduced because of the drop in plasticity with increase in strength of steels. To overcome such difficulties, hot-stamping processing was introduced to form parts for automobile industry. In hot-stamping process, a steel blank is reheated to a high temperature for re-austenitization, then, formed in the press, followed by the final step of quenching in the die to produce a part with ultra-high strength [1]. The hot-stamping process consumes significant energy because of reheating of steels and is less productive than traditional cold forming operations. For cold forming process, the material is required to exhibit low yield strength for easy forming and superior ductility to avoid cracking, and high tensile strength for ensuring good performance in service. In the present study, an advanced steel with high tensile strength, low yield to tensile ratio (Y/T ratio) and large uniform elongation has been processed that enables forming of high strength parts at room temperature.

Generally, dual-phase (DP) steels consisting of ferrite and martensite usually have low Y/T ratio and good uniform elongation [2, 3]. However, the formability of DP steels is not satisfactory, such as low stretch flangeability. The poor formability of DP steel is attributed to low Y/T ratio [4], which is simply caused by difference in strength between soft ferrite and hard martensite. This induces severe deformation in ferrite during early stage of deformation, such that the micro-voids at ferrite and martensite interface form and coalesce easily and form crack during cold forming [5]. Efforts have been made to improve the formability of conventional DP steels with focus on decreasing the difference in strength between the two phases. One approach is to replace martensite by bainite or tempered martensite to reduce the strength of hard martensite [6–8]. This method is not ideal because it leads to decrease in tensile strength. Another solution [9] is to enhance ferrite strength by introducing interphase-precipitated nanometer-sized carbides to ferrite in dual-phase steels. However, the improved yield strength induces forming force, which makes it hard to form parts. We propose here an alternative method to modify the yield and work hardening behavior of low alloy steels by introducing retained austenite in typical DP steels. Retained austenite is reported to be softer than ferrite so that can lower yield strength [10], and it transforms into martensite during deformation, the newly formed martensite enhances tensile strength. Moreover, ductility can be improved through transformation induced plasticity (TRIP) effect of retained austenite. In this study, a novel approach involving multi-step intercritical heat treatment was

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adopted to obtain multi-phase microstructure consisting of ferrite, martensite and retained austenite, with the aim to develop low carbon low alloy steel grades that exhibit high strength and formability, which enables cold forming. The underlying microstructural development and the relationship with tensile properties are elucidated.

The chemical composition of steel in weight percent (wt%) was 0.21 C, 2.00 Mn, 0.77 Si, 0.76 Al, 0.08 Nb, 1.05 Cu, 1.02 Ni and 0.26 Mo. Heat treatment samples of dimensions 8 × 10 × 90 were cut along the rolling direction. Samples were reheated to 1000 °C for 10 min for complete austenitization and water quenched to obtain fully lath-like martensitic microstructure. Then, the quenched samples were firstly intercritically annealed at 760 °C for 30 min and air cooled to room temperature (samples are designated as FIA). Next, the annealed sample was intercritically annealed for the second time at 720 °C for 30 min followed by air cooling to room temperature (samples are designated as SIA). Standard tensile tests with a diameter of 5 mm and gauge length of 25 mm were conducted at room temperature on longitudinal samples. After metallographic polishing, the specimens were etched with 2% nital for scanning electron microscopy (SEM) using a ZEISS ULTRA-55 field emission scanning electron microscope (FE-SEM) operated at 20 kV. Electron back scattered diffraction (EBSD) analysis was carried out after mechanical and electrolytic polishing using ZEISS ULTRA-55 FE-SEM at an acceleration voltage of 20 kV and step size of 0.1 μm. Quantitative assessments of retained austenite were carried out by X-ray diffraction (XRD) using Cu Kα radiation. The volume fraction of retained austenite was estimated by measuring the peak intensity of (200)α, (211)α, (200)γ, (211)γ and (311)γ. Microstructures after tensile test were observed in a FEI Tecnai G2 F20 transmission electron microscope (TEM) operated at 200 kV.

Microstructure development during two-step intercritical annealing is presented in Fig. 1. Fig. 1a and b are the SEM micrographs for the FIA and SIA samples, respectively. After the first-step incterctritical annealing (FIA), a lamellar duplex microstructure consisting of intercritical ferrite (tempered martensite formed during annealing) and martensite was obtained (Fig. 1a). Previous studies [11–13] revealed that, during intercritical annealing at 760 °C in the two-phase region, reverted austenite is formed uniformly along the prior grain boundaries and the martensite laths, alloying elements were redistributed in austenite and ferrite during holding in the intercritical region. Therefore, a duplex microstructure consisting of reverted austenite enriched with austenite stabilizers such as C, Mn, Ni, etc., and intercritical ferrite depleted with them was created. The enrichment of alloying elements in austenite led to high hardenability of the reverted austenite. Hence, fresh martenite was obtained on subsequent air cooling of FIA sample. SEM image for SIA sample was similar to the FIA sample (Fig. 1b). It exhibited a duplex microstructure consisting of intercritical ferrite and martensite. The difference from the SEM micrographs was that volume fraction of intercritical ferrite in SIA sample was higher than in FIA sample. Moreover, some smooth region, corresponding to retained austenite, can be observed together with martensite. Fig. 1c presents the band contrast (BC) map from EBSD analysis for SIA sample, in which red areas are retained austenite. Retained austenite exhibited mostly film-like morphology dispersed among matrix laths. It may be noted that dark area with low BC value, which is martensite, was observed next

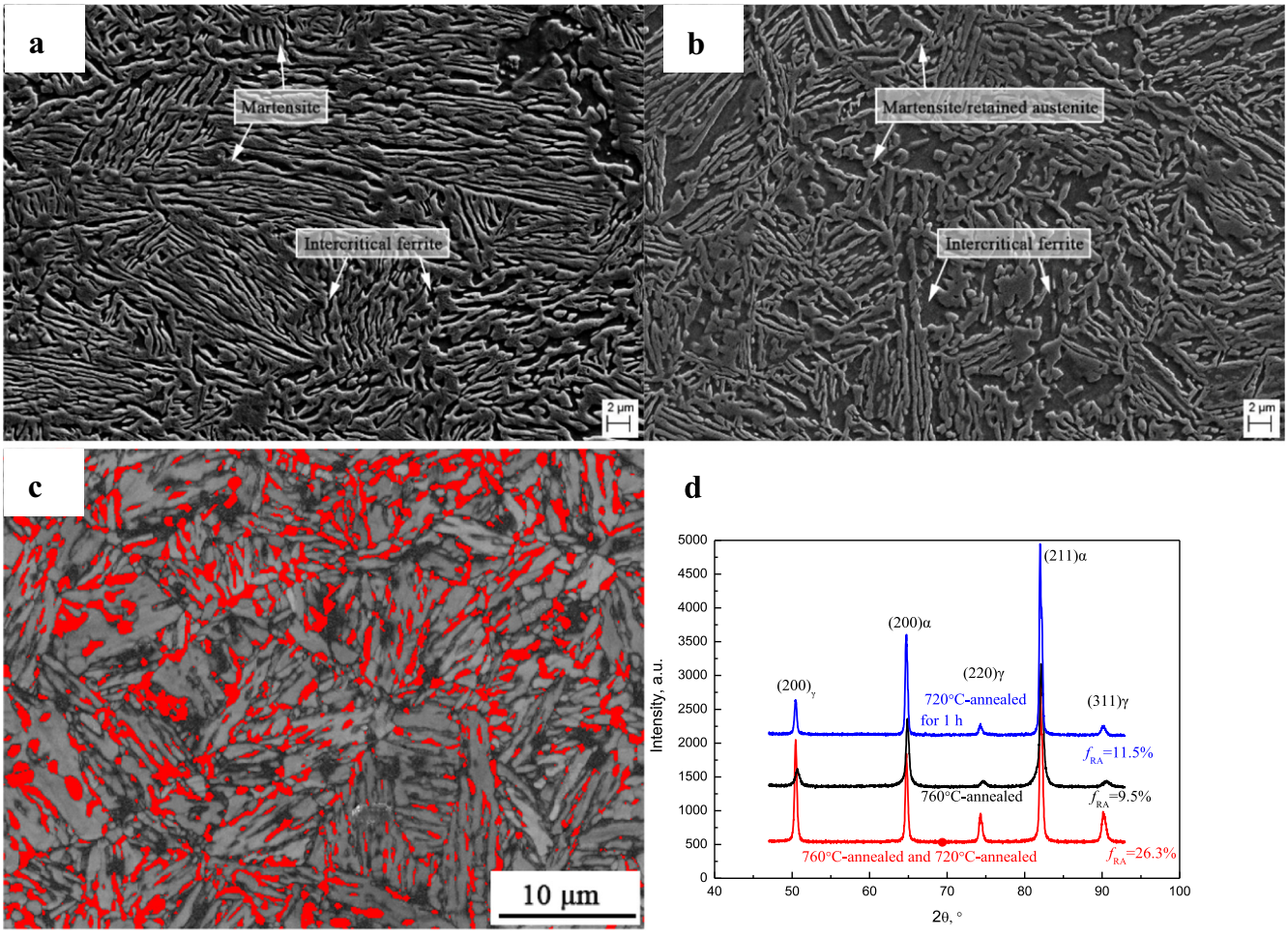

Fig. 1. SEM images for samples after first step intercritical annealing at 760 °C (a) and second step intercritical annealing at 720 °C (b); (c) EBSD images for sample after second step intercritical annealing at 720 °C; (d) XRD spectra for samples after different treatment steps.