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Austenite stabilization and high strength-elongation product of a low silicon aluminum-free hot-rolled directly quenched and dynamically partitioned steel

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ABSTRACT

Microstructures composed of lath martensite and retained austenite with volume fraction between 8.0 vol.% and 12.0 vol.% were obtained in a low-C low-Si Al-free steel through hot-rolling direct quenching and dynamical partitioning (HDQ&DP) processes. The austenite stabilization mechanism in the low-C low-Si Al-free steel under the special dynamical partitioning processes is investigated by analyzing the carbon partition behavior from martensite to austenite and the carbide precipitation-coarsening behavior in martensite laths combining with the possible hot rolling deformation inheritance. Results show that the satisfying retained austenite amount in currently studied low-Si Al-free HDQ&DP steel is caused by the high-efficiency carbon enrichment in the 30–80 nm thick regions of austenite near the interfaces in the hot-rolled ultra-fast cooled structure and the avoidance of serious carbides coarsening during the continuous cooling procedures. The excellent strength-elongation product reaching up to 26,000 MPa% shows that the involved HDQ&DP process is a promising method to develop a new generation of advanced high strength steel.

1. Introduction

To meet the requirement of both light weight and safety in automobile industry, advanced high strength steels (AHSS) with adequate combination of strength and ductility have developed into the 3rd generation, one of which is currently studied famous quenched and partitioned (Q&P) steel [1]. Similar to transformation induced plasticity (TRIP) steel, the special TRIP effect of retained austenite is a determining factor for the excellent mechanical properties. The austenite stabilization in Q&P steel is especially important since martensite has particularly low ductility.

Conventional Q&P process generally contains a reheating procedure and austenite stabilization is mainly achieved in an isothermal partitioning process in which the carbon enrichment from martensite to austenite performs [2–4]. Recently, some researchers applied Q&P theory to hot-rolling process and proposed a new energy efficient concept of hot-rolling direct quenching and partitioning (HDQ&P) process, which can replace the reheating procedure by using residual deformation temperature to achieve Q&P process [5,6]. What of especial interest is the so called hot-rolling direct quenching and dynamical partitioning (HDQ&DP) process, in which retained austenite with amount of about 12.0 vol.% can be obtained with the residence time between martensite transformation start (M_s) temperature and martensite transformation finish (M_f) temperature (so-called effective partitioning time) just about 1 s [5]. The austenite stabilization mechanism under such an extreme process has not been expatiated. To stabilize austenite, conventional Q&P steel usually contains a high Si or Al content for their strong ability of inhibiting cementite formation [7]. Unfortunately, a high Si content can result in surface oxides which extremely deteriorate the practical application and a high Al content can lead to a dramatic strength decrease and smelting difficulties [8]. Thus, it must worth developing a low-C low-Si Al-free Q&P steel and achieving the stabilization of retained austenite with volume fraction above 10.0 vol.% in it.

In this paper, HDQ&DP processes were applied to a low-C low-Si Al-free steel, the austenite stabilization mechanism in the sheets was meticulously investigated by analyzing the kinetics of carbon partition from martensite to austenite and the carbide precipitation-coarsening in martensite laths combining with the microstructure evolution in conventional hot-rolled directly quenched and isothermally partitioned (HDQ&IP) sheets. Findings from the analyses about the microstructure and mechanical properties are expected to provide basic data for developing a low-Si Al-free HDQ&P steel with high strength-elongation product.

2. Experimental details

The currently studied steel, with a chemical composition of Fe–0.22C–0.52Si–1.89Mn–0.08P wt.%, was firstly melted in a vacuum

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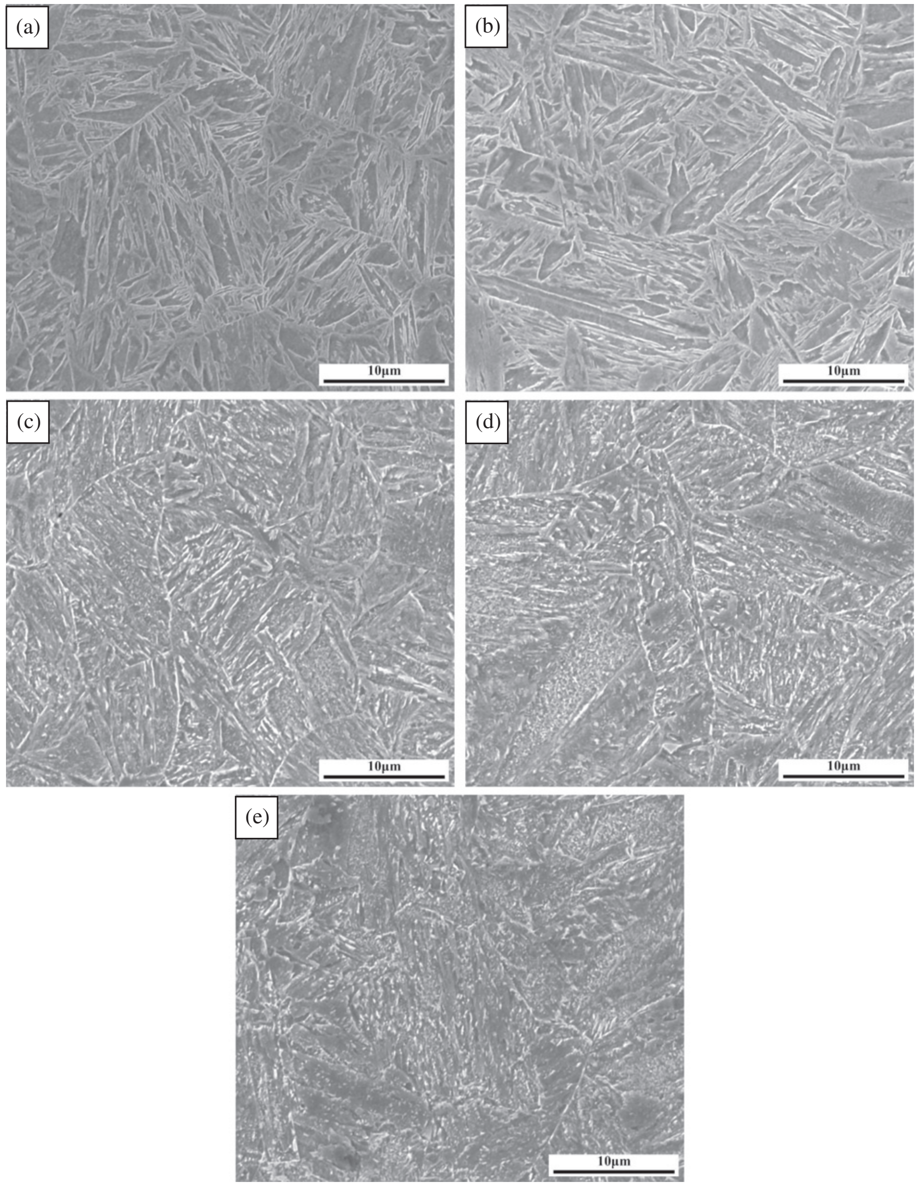

Fig. 1. Secondary electron images of the tested specimens: (a) No. 1; (b) No. 2; (c) No. 3; (d) No. 4; and (e) No. 5.

induction furnace and then cast into a 150 kg ingot. The ingot was forged into slabs with thickness of 60 mm. The A_{c1}, A_{c3}, A_{r1}, A_{r3}, M_s, and M_f temperatures were determined by a formastor-FII(FTF-340) dilatometer and the corresponding values are 670 °C, 816 °C, 521 °C, 705 °C, 398 °C and 171 °C, respectively (the possible measuring error is about 15 °C). Both HDQ&DP and HDQ&IP processes were applied to the steel based on self-developed ultra-fast cooling equipment. The 60 mm thick slabs were fully austenized at 1200 °C for 2 h followed by hot-rolling to 4 mm after seven passes on a Φ450 mm rolling mill and the finish rolling temperatures are around 900 °C. Subsequently, for HDQ&DP processes, one sheet (No. 1) was directly ultra-fast quenched to room temperature with average cooling rate of about 200 °C/s and another sheet (No. 2) was directly ultra-fast quenched to 255 °C and then air cooled to room temperature. The residence time between the M_s temperature and the M_f temperature for No. 1 sheet is just about 1–2 s while the time for No. 2 sheet to air cool from 255 °C to the M_f temperature is about 220 s, which was obtained by measuring the air cooling curve. For HDQ&IP processes, three sheets (Nos. 3, 4 and 5) were directly ultra-fast quenched to about 280 °C (the values of No. 3, No. 4 and No. 5 sheets are 268 °C, 282 °C and 290 °C, respectively) then isothermally partitioned in a resistance heating furnace at 400 °C for 1 min (No. 3), 5 min (No. 4) and 20 min (No. 5), and finally cooled to room temperature by air cooling.

The tensile tests were conducted at room temperature using a CMT5105-SANS machine. The dog-bone shaped tensile specimens were machined with their longitudinal axes parallel to the rolling direction and cut into the gage length of 25 mm, width of 5 mm and thickness of 4 mm, and the crosshead speed is 1 mm/min.

The amounts and carbon concentrations of retained austenite in both undeformed and deformed specimens were measured by X-ray diffraction (XRD) at room temperature with Cu Kα radiation, and the specimens were first mechanically ground and finally electro-polished for stress relieving. To avoid the decarburized layer, the XRD specimens were ground from the as-rolled surface to one quarter of the thickness of the sheets before the electrolytic polishing procedure. Each specimen was step-scanned over a 2θ range from 40° to 100° with a scanning speed of 2°/min. The average amount and carbon concentration of each sheet were calculated based on three specimens. Austenite peaks