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Microstructural evolution and mechanical properties of low-carbon steel treated by a two-step quenching and partitioning process

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ABSTRACT

The quenching and partitioning (Q&P) process is studied in Ti-bearing low-carbon steel. Detailed characterization of the microstructural evolution is performed by means of optical microscopy, scanning electron microscopy (SEM), electron backscatter diffraction (EBSD), transmission electron microscopy (TEM) and X-ray diffraction (XRD). The results indicate that the investigated steel subjected to the Q&P process forms a multiphase microstructure of primarily lath martensite, with small amounts of plate-type martensite and retained austenite. The distribution and morphology of the retained austenite are observed; moreover the relationship between the phase fraction of the retained austenite, its carbon concentration, and the partitioning conditions is established. Carbides preferentially precipitate within the plate-type martensite at first, and gradually form in the martensitic laths over time during the partitioning step. Additionally, titanium precipitations contribute to both the refinement of prior austenite grains and the improvement of strength by precipitation strengthening. The results of mechanical properties testing indicate that the samples partitioned at 400 °C exhibit a superior combination of strength and elongation, with products of the two properties ranging between 19.6 and 20.9 GPa%. Based on analysis of work hardening behavior it is determined that the higher ductility is closely related to the higher phase fraction and/or stability of retained austenite.

1. Introduction

The development of advanced high strength steel (AHSS) has been of interested due to the demands of the automotive industry for lightweight components while maintaining high safety ratings. Various ideas for the development of novel alloys and thermo-mechanical treatments have been proposed to improve the comprehensive mechanical performance [1–3]. Recently, the dispersion of retained austenite has become a popular method for improving the ductility of high-strength steel [4,5]; the most representative steel grade of this trend is transformation-induced plasticity (TRIP) steel [6]. However, the strength of commercial TRIP steels is generally limited due to its microstructure that, other than retained austenite, also consists of ferrite, bainite and small amounts of martensite [7]. Therefore, the development of steels containing a combination of martensite and retained austenite seems to be one of the most promising approaches for the production of AHSS with better performance.

A typical heat treatment process that was first suggested by Speer et al. [8] in 2003 is the quenching and partitioning (Q&P) process. The Q&P process promotes martensite formation from a fully austenitic microstructure, and is followed by a partitioning step at a partitioning temperature (PT) to promote carbon diffusion from supersaturated martensite to untransformed austenite. In this way, Q&P steels contain martensite and retained austenite, with the former hard phase donating its high strength, and the latter soft phase contributing its good ductility due to the TRIP effect during deformation. Due to the redistribution of carbon between the martensite and austenite at the PT, the solid solute strengthening of carbon atoms is somewhat reduced. To compensate for this strength reduction, precipitation strengthening by the addition of microalloying elements (e.g., Nb and Mo) is generally used [9]. However, the effects of titanium precipitations on microstructure and mechanical properties in titanium-bearing steel that has been treated by the Q&P process have been seldom reported.

Herein, the mechanical properties and microstructural evolution of low carbon steel treated by two-step Q&P process are investigated. The effect of the heat treatment process parameters on the phase fraction and carbon concentration of the retained austenite is studied in detail, and the contribution of retained

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austenite to the mechanical properties of the steel is discussed. Additionally, titanium precipitations in the steel are characterized and their contribution to the refinement of prior austenite grains is assessed.

2. Experimental procedure

The chemical composition of the investigated steel is shown in Table 1. The steel was melted in a vacuum furnace forged into two bars with dimensions of 700 mm × 100 mm × 60 mm. The bar was subsequently annealed at 1200 °C for 3 h and hot rolled in 9 passes to 4 mm thickness. The final rolling temperature was about 950 °C, followed by air cooling. The martensite start temperature M_s was measured as approximately 406 °C using a push-rod Formastor-FII dilatometer. The hot-rolled sheets were cold rolled to a final thickness of 1.2 mm. The tensile specimens, with a 25 mm gauge length parallel to the rolling direction, were then machined. A schematic of the heat treatment process is presented in Fig. 1. Following the heat treatment, the tensile specimens were reheated to 950 °C for 180 s, immediately placed in a salt bath furnace at 280 °C for only 5 s, immediately placed in another salt bath and isothermally held at either 400 °C or 350 °C for 10–1000 s, and finally water quenched to room temperature. This process is referred as the two-step Q&P process, in which the partitioning temperature is different from quenching temperature.

Table 1
Chemical composition of the investigated steel (wt%).

Elements	C	Si	Mn	Ni	Mo	Cu	Ti	B	Al
Composition	0.2	1.52	1.51	0.33	0.27	0.64	0.03	0.0032	0.025

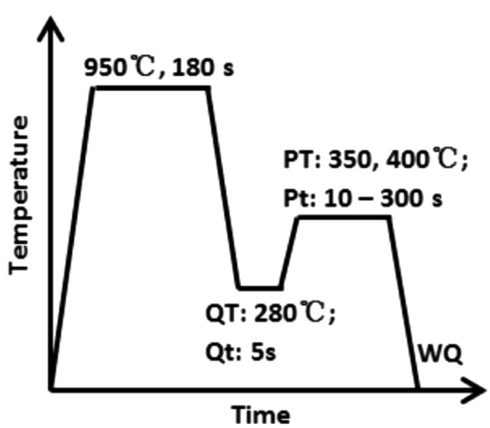

Fig. 1. Schematic of Q&P heat treatment process, where *QT* is the quenching temperature, *Qt* is the quenching time, *PT* is the partitioning temperature and *Pt* is the partitioning time.

The multiphase microstructures of the samples were revealed using a 4% nital etch. The microstructures were characterized by scanning electron microscopy (SEM) on a FEI Quanta 600 analyzer. A supersaturated picric acid solution at about 70 °C was used to corrode the as-quenched samples, and then prior austenite grains were observed using an optical microscope (OM). Electron backscatter diffraction (EBSD) techniques were also used to characterize different microstructural constituents (i.e., martenite and austenite). The samples for EBSD were mechanically ground and then electro-polished using a 700 mL CH_3COOH+200 mL $HClO_4$ solution at 16 °C and 31 V. EBSD measurements were carried out on a Zeiss Ultra 55 analyzer at 20 kV using a spatial step size of 0.02 μm. Channel 5 software was used to collect and index the Kikuchi band patterns. Disc-shaped transmission electron microscopy (TEM) foils 3 mm in diameter and 0.05 mm thick were electro-polished to perforation using a twin-jet electro-polishing device at 253 K with an electrolyte consisting of 4 vol% perchloric acid and 96 vol% ethanol. TEM observation on a FEI Tecnai G2F20S–TWIN microscope was also used for determining overall microstructural features (various phases, precipitates etc.) and carbon extraction replica technique was used for precipitation study.

X-ray diffraction (XRD) analysis was performed on a D/max2400 analyzer using Cu K_α radiation operating at 50 kV and 150 mA to calculate the amount of retained austenite. Spectra were taken in the 2θ range from 40° to 120° with a (2θ) scanning speed of 5°/min. The integrated intensities of the (200) γ, (220) γ, (311) γ, (200) α, and (211) α peaks were used to quantify the amount of retained austenite by the following equation [10]

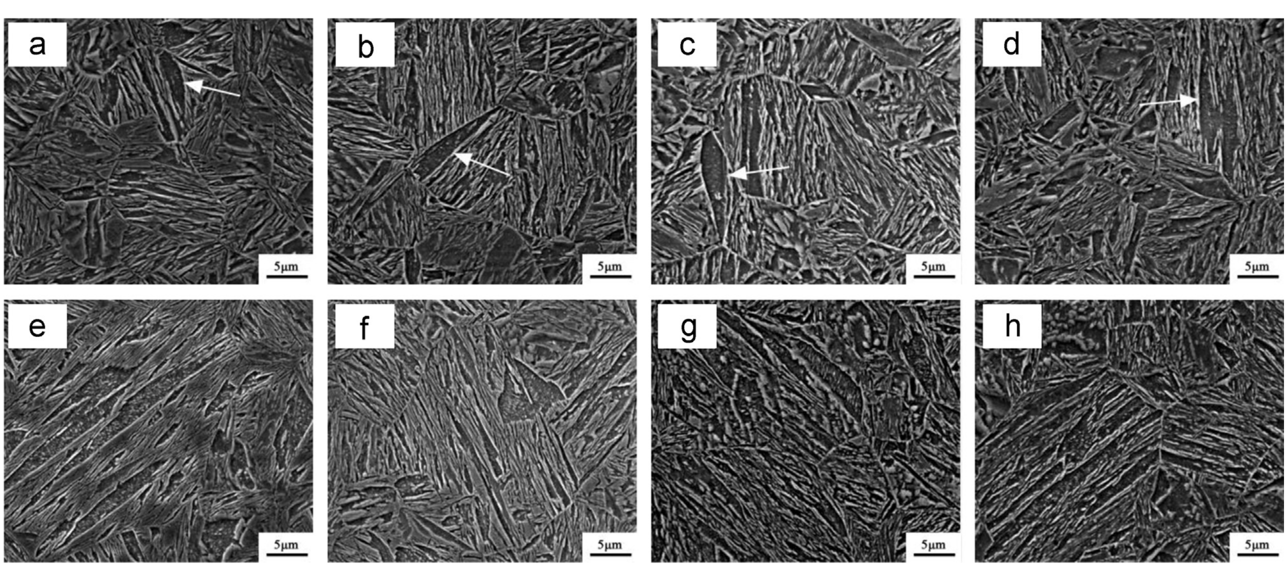

Fig. 2. SEM micrographs of the samples treated by different Q&P processes: the first set of samples had *PT*=400 °C, and *Pt*=(a) 10, (b) 30, (c) 100 and (d) 1000 s; the second samples had *PT*=350 °C, and *Pt*=(e) 10, (f) 30, (g) 100 and (h) 1000 s.