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In-situ study of the deformation-induced rotation and transformation of retained austenite in a low-carbon steel treated by the quenching and partitioning process

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ABSTRACT

We report an in-situ study of the deformation-induced rotation and transformation of austenite grains in a low-carbon steel treated by the quenching and partitioning process using electron back-scattered diffraction and uniaxial tension experiments. It was found that retained austenite could be classified into four types according to different locations in the microstructure: retained austenite at triple edges, twinned austenite, retained austenite distributed between martensite and retained austenite embedded completely in a single ferrite. The results showed that at the early stage of deformation, the retained austenite at the triple edges and twinned austenite transformed easily, while the retained austenite at the boundaries between martensite and that embedded completely in a single ferrite rotated with no transformation; and did not transform until a large deformation was provided. This phenomenon implies that the retained austenite at the boundaries between martensite and that embedded completely in a single ferrite are more capable of resisting deformation. From the observations of Schmid factor maps and the texture of retained austenite, it can be concluded that the rotation of retained austenite followed a particular slip plane and slip direction. Moreover, the rotation of retained austenite could improve the ductility of the material. In comparison with the film-like retained austenite distributed between martensite, the retained austenite embedded completely in a single ferrite could resist a larger rotation angle, i.e. the latter could contribute more to the ductility of the steel. In addition, from the analysis of kernel average misorientation that the strain distribution mainly concentrated near the $\alpha-\gamma$ phase boundaries and in the interior of martensite, and the rotation angles and dislocation density of austenite increase with increasing strain.

1. Introduction

To decrease fuel consumption and increase safety in the automotive industry, it is necessary to develop new advanced high strength steels (AHSS) with a good combination of strength and ductility. Transformation-induced plasticity (TRIP) steel, which is one type of AHSS, is mainly composed of ferrite, bainite and retained austenite [1]. The retained austenite transforms into martensite during straining and the transformation could delay the onset of necking, which suppresses the plastic instability and extends the uniform elongation of TRIP steel. This phenomenon is called the TRIP effect [2]. Because of the TRIP effect during the straining, the carbon-enriched retained austenite can be conducive to the formability and energy absorption of TRIP steel [2]. Therefore, the TRIP steel exhibits a good combination of strength and formability. Recently, a novel and promising heat treatment named quenching and partitioning (Q&P) was proposed by Speer et al. [3,4]. Q&P steel shows a better combination of strength and ductility than TRIP steel [2]. Moreover, the desired mechanical properties could be provided to Q&P steel by controlling the given ratio of martensite and austenite.

The Q&P heat treatment starts with full austenitization or partial austenitization, followed by rapid cooling to a specified quenching temperature between the martensite-start temperature (M_s) and martensite-finish temperature (M_f) to obtain the desired ratio of martensite and austenite. A subsequent partitioning treatment is employed at the same quenching temperature or a higher temperature to transfer carbon from martensite to austenite to make the austenite carbon-enriched. Finally, the specimen is cooled to room temperature using water. Therefore, carbon-enriched retained austenite can be obtained in the steel after the

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Q&P process. When starting with full austenitization, the final microstructures after the Q&P process will be composed of martensite and retained austenite. In contrast, when starting with partial austenitization, the final microstructures will consist of ferrite, marteniste and retained austenite. It is well known that different microstructures have different effects on the mechanical properties of the material. Thus, it is very important to understand the microstructural characteristics, which will be conducive to optimize the heat treatment process and the mechanical properties of the steel.

In TRIP steel, retained austenite plays a significant role by transforming into martensite during the plastic deformation [5]. The deformation behavior of retained austenite has been investigated in TRIP steel [6,7]. The findings in TRIP steel indicate that the deformation stability of retained austenite are influenced by (i) the grain size of retained austenite [8], (ii) the local carbon concentration in retained austenite [9], (iii) the crystallographic orientation of retained austenite in connection with the loading direction [10], and (iv) the constrain effect from the surrounding phase imposing on retained austenite [11,12]. These effects are also expected to have a significant influence on the deformation stability of retained austenite in Q&P steel [13]. As demonstrated through previous investigations on Q&P steel [14], film-like retained austenite is more stable than blocky retained austenite during deformation. Meanwhile, the effect of the multiphase microstructure on the mechanical behavior was studied in Q&P steel treated by the process starting with partial austenitization [15]. In addition, it has been reported [16] that fresh martensite has a negative impact on the transformation stability of retained austenite because of its constraining effect on the strain distribution.

However, the deformation mechanism of retained austenite in Q&P steel is still not completely understood. Therefore, the main objective of this paper is to achieve the complete in-situ characterization of the transformation behavior of retained austenite in Q&P steel through electron back-scattered diffraction (EBSD) and uniaxial tensile tests and to attain a complete understanding of the interaction between the deformation, the transformation of retained austenite, and its rotation. In addition, we attempt to determine the relationship between the deformation behavior of retained austenite and the ductility of the steel.

2. Experimental procedure

The chemical composition of the investigated steel is given in Table 1. The steel was melted in a vacuum induction furnace at 1200 °C for 2 h, following which it was then hot rolled to a final thickness of 6 mm. The A_{c1}, A_{c3} and M_s of the steel estimated using Thermo-Calc [17] with the TCFE5 database, are 728 °C, 872 °C, and 382 °C, respectively. The specimen was subjected to the Q&P process starting with partial austenizatition at 825 °C for 5 min, followed by quenching to 240 °C for 15 s in a salt bath; subsequently, the specimen was partitioned at 420 °C for 1000 s in another salt bath and finally quenched to room temperature with water. Silicon and aluminum were added to suppress carbide precipitation during the partitioning process.

All the specimens were cut from hot-rolled sheet steel. The specimen for the uniaxial tensile test was prepared using an electric discharge machine and was cut into a shape with a gauge length of 6 mm and thickness of 1 mm, as shown in Fig. 1. The long axis of the tensile specimen was selected to be parallel to the rolling direction of the sheet steel, and the center point of the tensile specimen was marked by a small Vickers hardness to act as the reference point for the EBSD patterns. Two EBSD areas, marked as area 1 and area 2, were measured before and after the deformation of the specimen. Furthermore, the two areas were separated by the marked point and were approximately 0.5 mm away from the marked point.

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

C	Si	Mn	Al	Cr	Fe
0.176	1.31	1.58	0.26	0.30	Bal.

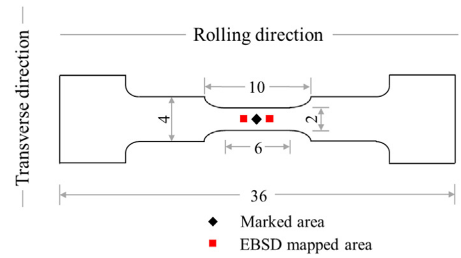

Fig. 1. Schematic of the specimen used for tensile test and EBSD (dimensions are in mm).

The uniaxial tension experiment was performed using an Ultra 55 Zeiss field emission scanning electron microscope (SEM) equipped with a tensile tester. The extension speed was set at 5 μm/s for the uniaxial tensile test. The specimen for the EBSD analysis was ground and polished according to the conventional technique, following which it was etched using 4% nital for releasing the surface stress; finally it was polished using a colloidal silica suspension with a particle diameter of 50 nm. The working conditions of EBSD are as follows: accelerating voltage of 20 kV, working distance of 8 mm, aperture size of 120 μm, tilt angle of 70° and step size of 0.1 μm. The obtained orientation data were post-processed with OIM 6 software.

3. Results and discussion

3.1. Macroscopic stress–train responses

Fig. 2 shows the macroscopic stress–strain curves of the specimen recorded step-wise during the in-situ (interrupted) EBSD experiment in the strain control mode. As shown in Fig. 2, the

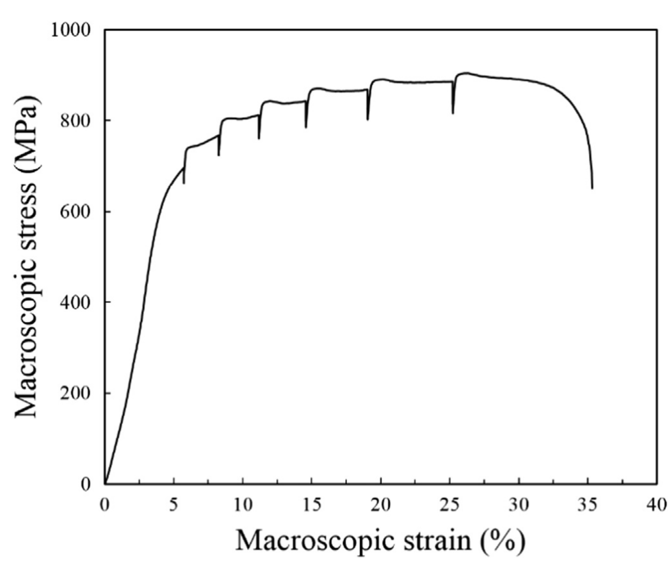

Fig. 2. Macroscopic stress–strain curves of the specimen recorded during the in-situ EBSD experiment.