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Improved ductility of a transformation-induced-plasticity steel by nanoscale austenite lamellae

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ABSTRACT

TRIP (transformation-induced-plasticity) steel with a chemical composition of 0.19C–0.30Si–1.76Mn–1.52Al (weight percentage, wt%) have been treated by intercritical annealing and austempering process. The microstructures of the obtained samples consist of the ferrite, the bainite and the retained austenite phase. The volume fractions of the bainite and the retained austenite gradually increase with increasing the temperature of the intercritical annealing. Consequently, significantly different mechanical properties have been observed. The sample annealed at 820 °C (for 120 s) and partitioned at 400 °C (for 300 s) has the best combination of ultimate tensile strength (UTS, ~682 MPa) and elongation to failure (~70%) with about 26% of bainitic ferrite plates and 17% retained austenite in its microstructure. The retained austenite has a lamella morphology with 100–300 nm in thickness and 2–5 μm in length. On the contrary, the sample annealed at the same temperature without the partitioning process yields much lower UTS and elongation to failure.

1. Introduction

Materials with good strength and excellent ductility are generally desired in many structural applications. Recently, transformation-induced-plasticity (TRIP) steel has received much attention in the automotive body construction due to their outstanding combination of strength and ductility, which makes it possible for vehicle weight reduction without compromising strength and safety. The remarkably high performance of this class of steels is closely related to both the multiphase characteristics of their microstructures and the TRIP effect, i.e., the martensitic transformation of the retained austenite induced by deformation [1]. TRIP-assisted multiphase steels typically have intercritical ferrite matrix (body-centered cubic, bcc), metastable face-centered cubic (fcc) retained austenite (RA), and bainite and martensite (bcc) as dispersed phases [2]. Good ductility results from the soft and ductile ferrite as well as the TRIP effect, while high strength originates from bainite and the freshly formed martensite induced by martensite transformation from the metastable RA [1,3–5]. Martensite transformation leads to an increase of the strain-hardening ability because the mechanical properties difference between retained austenite and martensite results in increasing strain from the shear and dilatation associated with transformation [6]. In turn, increasing work-hardening ability delays the onset of necking and ultimately leads to a higher uniform elongation. Obviously, the TRIP effect can significantly improve the formability and energy absorption of this class of materials. Jacques and co-workers [7,8] have investigated the mechanisms responsible for the work-hardening capacity and the resulting balance between strength and resistance to plastic localization at different length scales of TRIP-assisted multiphase steels. Their results support that the amount and stability of RA at room temperature is extremely important to the design of TRIP steel, which is controlled mainly by the intercritical annealing (IA) temperature. The meta-stabilization of the austenite at room temperature is mainly controlled by carbon enrichment occurring during specific heat treatments.

To obtain a microstructure with desired amount of RA, a number of processes have been proposed. Among them, quenching and partitioning (Q&P) treatment attracted much interest over the past decade [5,8], which is originally designed by Speer to produce high-strength steels with a mixed microstructure of tempered martensite and retained austenite [5,9–11]. Q&P process consists of intercritical annealing followed by rapid cooling to a bainitic transformation regime (a temperature below the start temperature of martensitic transformation (M_s) but above the finish temperature of martensitic transformation (M_f), the quenching step). At the same temperature range, a subsequent isothermal

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treatment is performed (the partitioning step), in which the amount of carbon-enriched retained austenite is controlled by the extent of carbon partitioning after initial quenching. Subsequently, many reports have demonstrated that the process is very effective in producing high strength steels with good ductility.

Chemical composition has a strong influence on the stability of the metastable retained austenite at room temperature (chemical stabilization). An increase in the concentration of C and Mn, which are strong austenite stabilizers, can result in high austenite stability at room temperature [8,9]. The excellent combination of a high strength and a ductility enhanced by the presence of a large volume fraction of retained austenite in ultrafine-grained (UFG) TRIP steel with a Mn content of 5–7 mass% has recently attracted interest [12,13]. The size effect of ultrafine austenite grain and the partitioning of Mn to austenite during intercritical annealing were the two main contributions to the austenite stability.

On the other hand, the dispersed bainite phase is beneficial for the increment of work-hardening ability of steel. Bainite is a decomposition product of austenite at a temperature below that of the austenite-to-pearlite reaction and above the M_s, and it consists of aggregates of plates of ferrite, separated by untransformed austenite, cementite or martensite. In general, bainite can be classified into upper bainite (feathery bainite formed at higher temperatures) and lower bainite (lath bainite formed at lower temperatures) depending on the variation of transformation temperature and alloy composition [14]. The island structures within the granular bainite may be martensite plus retained austenite, or bainite plus retained austenite and martensite or other metastable structures. The bainitic ferrite laths separated by film-type austenite significantly promote the excellent combination of strength and toughness [15].

In this study, the as-received cold-rolled TRIP steel with a chemical composition of 0.19C–0.30Si–1.76Mn–1.52Al (weight percentage, wt%) is investigated with two heat treatment processes: intercritical annealing and intercritical annealing plus bainite partitioning. In intercritical annealing, the steel is reheated to a temperature just above the start temperature of austenitic transformation (A_{c1}) but below the finish temperature of austenitic transformation (A_{c3}), in the upper part of the ferrite/austenite two-phase region, resulting in a high volume fraction of austenite. The microstructure of TRIP-assisted multiphase steels obtained from a two-step heat treatment after cold-rolling typically has multiphase microstructures composed of ferrite, bainite, retained austenite and martensite. The first intercritical annealing step results in a ferrite and austenite mixture. The ratio between the two phases depends on the chemical composition and holding temperature. The second step consists of a bainite holding conducted at a temperature between 380 and 450 °C with different duration from 150 to 400 s. After the second isothermal holding and subsequent cooling to room temperature, part of the austenite transforms into bainite. The motivation of this study is to establish the relationships between heat treatment processes, corresponding microstructure features, and the resulting mechanical properties for a commercially produced low alloy Mn-containing TRIP steel, and to establish an economical and effective set of heat treatment parameters in obtaining the best combination of strength and ductility through a proper amount of nanometer-thick RA lamella in the microstructure.

2. Experimental

2.1. Heat treatments

Commercially produced 0.19C–0.30Si–1.76Mn–1.52Al (wt%) TRIP steel sheet was used in this study with chemical composition listed in Table 1. As a starting point for determining the processing parameters, continuous cooling transformation (CCT) curves have been determined using dilatometry. Cylindrical dilatometric samples of diameter 3 mm and length 10 mm were performed with a push-rod L78-RITA dilatometer (Linseis Messgeraete, Germany). The sample temperature is measured by a thermocouple welded to its surface using a precision welder and the jig supplied by the dilatometer manufacturer. The heating and austenitization treatments were carried out under a vacuum of 5×10^{-4} MBar, and the cooling was achieved using argon gas.

Isothermal IA tests have been performed with a continuous annealing machine (CAS30011, China). The steel sheet was quickly heated to 820 °C (in the intercritical region) with a heating rate of 150 °C/s and holding for 120 s. Then the specimen was quenched to RT with a cooling rate of −40 °C/s. Q&P treatments were carried out with salt-bath furnaces. The process consists of the following procedures: starting with intercritical annealing at a temperature of 750, 800, 820, 850 and 880 °C and holding for 120 s, followed by rapid cooling at a rate of −120 °C/s to a partitioning temperature (bainite region: 380–450 °C), isothermal holding at that temperature for 150–400 s before cooling to RT.

2.2. Mechanical property tests

To examine the effects of different heat treatments on the mechanical properties of the steel, microhardness measurements were performed on a MVK-H300 hardness testing machine with a load of 30 g and a loading time of 10 s.

The as-treated steel sheets were cut into the dog-bone shaped specimens with a gauge length of 20 mm and a width of 6 mm, and the final thickness of 1.2 mm after polishing. Uniaxial tensile tests were performed on a SANS micro-force testing system at a constant strain rate of 5×10^{-3} S^{-1} under RT. A contactless MTS LX300 laser extensometer was used to calibrate and measure the sample strain upon loading. Metallurgical cross sections were cut from the gauge of the deformed samples and evaluated for martensite volume fraction, using X-ray diffraction and electron-backscatter-diffraction (EBSD) analysis.

2.3. Microstructure characterization

Specimens were cut from the heat-treated sheet and the gauge of the deformed samples to evaluate RA volume fractions, using X-ray diffraction (XRD) and electron-backscatter-diffraction (EBSD) analysis. Samples for XRD analysis were chemically cleaned using a mixture of 70 vol% HCl and 30 vol% HNO_3, further swabbing by few drops of C_2H_5OH to improve precision of analysis. The X-ray diffraction measurement was performed on X'Pert PRO diffractometer (PW3040/60, Panalytical B.V., Netherlands) with a sample stage for Co anode (wavelength λ=0.1789 nm) and X-Celebrator detector. Samples were scanned at a step size of 0.02 deg/s in the 2θ range from 40° to 80°. The penetration depth of

Table 1
Chemical composition of the TRIP steel used in this study (wt%).

C	Si	Mn	P	S	Al	Mo	Cu	Ni	Ti	N	Fe
0.194	0.293	1.764	0.012	0.004	1.516	0.003	0.007	0.007	0.002	0.003	Bal.