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Effect of martensite morphology and volume fraction on strain hardening and fracture behavior of martensite–ferrite dual phase steel

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ABSTRACT

Two different morphologies of martensite in dual phase (DP) steel were obtained using two different processing routes. In one case, intermediate quenching (IQ) was adapted, where DP steel was water-quenched to obtain martensite phase, followed by inter-critical annealing. In the second case, the steel was cold rolled, followed by inter-critical annealing (CR-IA). For IQ and CR-IA steels, the inter-critical temperatures varied from 750 °C to 850 °C to obtain different volume fractions of martensite. An understanding of structure–property was obtained using a combination of scanning electron microscope (SEM), transmission electron microscope (TEM), and tensile tests. It was observed that fibrous martensite presented in IQ samples, gradually transformed to blocky martensite with increase in inter-critical temperature, resembling the CR-IA steels. The fibrous martensite encouraged martensite cracking, however, the martensite cracking was dramatically decreased in the IQ samples with increase in martensite fraction. The strain hardening behavior studied using the differential *C–J* model indicated multistage depending on the fraction of martensite. The low volume fraction of martensite in the DP steel provided high ductility–toughness combination and improved strain hardening ability due to the presence of soft ferrite phase in DP steel. Fibrous martensite in DP steel resulted in less strain hardening than blocky martensite, prior to exceeding a threshold volume fraction. The threshold value was significantly smaller for DP steel with blocky martensite.

1. Introduction

Dual phase (DP) steels are low-carbon and low-alloy steels with 10–30 vol% of martensite and a ductile ferrite matrix, widely used in the automotive industry because of the good combination of high strength and good formability at low production costs [1–4]. DP steels exhibit unique mechanical characteristics including low elastic limit, continuous yielding, low yield stress to tensile strength ratio, and high initial strain hardening rate [5–13]. These properties provide advantages over the conventional high strength low alloy steels, but also introduce certain risk factors [14], including strong stress/strain partitioning [15,16], strain localization [17,18] and damage evolution [3].

When austenite transforms to martensite, volume expansion induces plastic deformation of the adjacent ferrite [5,19,20]. During deformation, geometrically necessary dislocations (GNDs) are needed to maintain lattice continuity and statistically stored dislocations (SSDs) [21–23]. Calcagnotto [24] verified the inhomogeneous transformation and strain accommodation in ferrite and quantified overall density of GNDs by using high resolution electron backscattered diffraction (EBSD). Simulation is an effective method to study evolution of microstructure during the deformation and to predict the phenomenon that may occur. A finite element based modeling using representative volume element (RVE) approach was proposed to predict the overall stress–strain behavior of DP steel [25]. It was demonstrated that GNDs cause local hardening at the phase boundaries and the stress–strain response of these phase boundaries was governed by the local hardening mentioned above and the softening coming from the loss of back stress.

The morphology of martensite had a significant impact on the mechanical properties of DP steels [13,26–32]. DP steels with fine and fibrous martensite distributing uniformly in the ferrite matrix provided the best combination of strength and ductility compared with those that had blocky ferrite–martensite and martensite islands along the grain boundaries of polygonal ferrite grains [26]. In another study [31] related to plasticity of martensite in DP steels, it was pointed out that martensite morphology affected the strain hardening and more importantly the fracture properties. In Kyosun' study [13], chain-like networked structure of martensite led to reduction of strain

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partitioning between ferrite and martensite, thus, the strain hardening ability was greatly improved and the micro-void formation in the ferrite matrix and ferrite–martensite interface was retarded. In this situation, fracture is usually related to lower necking deformation or brittle crack propagation along the ferrite–martensite interface.

Fine microstructural constituents provide superior combination of strength, ductility, and strain hardening ability because of decrease in the stress/strain partitioning between ferrite and martensite [27, 31–34]. Saeidi [27] produced ultrafine grained DP steel by inter-critical annealing following large strain cold deformation and subsequent short time inter-critical annealing. Because of uniform strain distribution of ultrafine grained DP steel, it possessed higher ductility than the coarse-grained counterpart. Moreover, there was increase in resistance to void nucleation in the fine grained steel. Void nucleation in grain refinement DP steel was mainly caused by the increased misorientation to more than 40° in ferrite grain boundaries [35]. While in the coarse-grained DP steel, martensite was prone to cracking as the high density of dislocation pile-ups at the ferrite–martensite interface caused build-up of high stress concentration at the martensite [36]. Therefore, due to the composite microstructure, namely, the diverse nature of martensite and ferrite morphology, fraction and distribution, the mechanism of void nucleation and the main parameters controlling the ductility of DP steels, the understanding is far from complete. The objective of the study described here is to acquire an understanding of the interplay between martensite morphology and fraction and strain hardening and damage evolution behavior.

2. Experimental

2.1. Material

The steel used in the present study was a commercial DP590 steel with an initial thickness of 1.5 mm. The chemical composition is listed in Table 1.

2.2. Heat treatment

In order to develop the DP microstructure with different martensite morphologies and fractions, the steel was subjected to two different processing schedules:

(a) *Cold rolling-inter-critical annealing*: The steel was cold rolled to 54.7% reduction and then heated to various inter-critical temperatures (750 °C, 775 °C, 800 °C, 825 °C, 850 °C) in a furnace for 2 min, before water quenching to the ambient temperature. This treatment is referred as cold rolling-inter-critical annealing and abbreviated as CR-IA.
(b) *Intermediate-quenching*: In order to obtain near complete martensite, the steel was heated to 900 °C for 10 min followed by water quenching. Subsequently, it was inter-critically annealed, at temperatures identical to those listed in (a) above. This treatment was referred as intermediate-quenching and abbreviated as IQ.

2.3. Tensile tests

After inter-critical annealing, tensile samples according to GB T228-2002 standard were cut from the heated-treated steel. Tensile samples with a nominal gauge length of 50 mm and nominal width of 12.5 mm were used. The tensile test was carried out at a cross head speed of 2 mm min^{-1} using a 100 kN Instron tensile machine. All specimens were tested to failure. During the tensile experiments, force and displacement plots were recorded, from which stress and strain data was obtained.

Table 1
The chemical composition of DP590 steel (in wt%).

C	Si	Mn	P	S	N	Cr
0.08	0.42	1.83	0.16	0.002	0.0035	0.18

2.4. Microstructure characterization

To characterize the microstructure, the samples were grounded using silicon carbide paper with a grit size of 240, 400, 600, 1000, 1200 and 1500 in sequence, and then polished with diamond abrasion paste. After polishing, the samples were etched with a 4% nital solution for 10 s. The etched samples were used for observing the microstructure by means of scanning electron microscope (SEM) on a FEI Quanta 600. The transmission electron microscopy (TEM) was carried out using FEI Tecnai G2F20S-TWIN microscope. Thin foils were electro polished to perforation using a twin-jet electro-polishing device with an electrolyte consisting of 4% perchloric acid and 96% ethanol. The fraction of martensite was obtained using the image processing software, Image Pro Plus. The fracture surfaces were studied by SEM to determine the mode of fracture. The sub-surfaces were prepared by sectioning the tensile samples through thickness along the mid-width in longitudinal direction. The SEM micrographs of sub-surfaces in the necked region, just beneath fracture surface were used to study the micro-voids and micro-cracking.

3. Results and discussion

3.1. Microstructure analysis

The SEM micrographs of steels processed by IQ and CR-IA treatments are presented in Figs. 1 and 2, respectively. It is evident that the both treatments resulted into ferrite–martensite DP microstructure, but the morphology, size and distribution of martensite phase varied significantly with the heat-treatment schedules. The IQ sample inter-critically annealed at 750 °C (Fig. 1a) yielded fine and fibrous martensite together with ferrite grain boundaries and uniform distribution of martensite laths. Additionally, some small polygonal martensite particles were present at the triple points of ferrite grains. With increase in the inter-critical annealing temperature, martensite grew gradually into block and there was significant increase in their content (Table 2).

CR-IA steels (Fig. 2) indicated martensite islands along the grain boundaries while a small number of the islands with small size were present in grains and their fraction (Table 3) increased with increase in temperature. Note that, in Fig. 2a and b, ferrite grains have bimodal size distribution. Given that we can obtain superior contrast of martensite phase than ferrite in TEM, and can be clearly distinguished, TEM studies were carried out. The martensite morphology in the two samples had distinct features. The fibrous martensite in IQ sample exhibited feather-like microstructure (Fig. 3a) along the ferrite grain boundaries, while blocky martensite in CR-IA sample (Fig. 3b) was distributed along the ferrite grain boundaries. In particular, the feather-like martensite in IQ sample possessed twin substructure which was confirmed by the selected area electron diffraction pattern (Fig. 3c).

The differences in microstructure of sample before inter-critical treatment may be responsible for the observed differences in the martensite morphology. In IQ samples, before inter-critical annealing, the microstructure consisted of lath martensite transformed from original austenite. Thus, the original austenite grain boundaries and martensite lath provided numerous sites for nucleation