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Development of a high strength and ductile Nb-bearing dual phase steel by cold-rolling and intercritical annealing of the ferrite-martensite microstructures

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ABSTRACT

Dual phase (DP) steels containing different amounts of Nb microalloying element were produced by cold-rolling followed by intercritical annealing of a ferrite-martensite duplex starting structure. The effects of Nb contents (0.00, 0.06, 0.12 and 0.18 wt%) and intercritical annealing time on the microstructural evolutions and mechanical properties were studied. Results from microscopic images showed that increasing Nb content increased the volume fraction of martensite and decreased the average grain size of ferrite. Tensile results illustrated an excellent strength-elongation balance in terms of energy absorption (160 J cm^{-3}) and toughness (229 MPa). The lowest grain size of about 1.40 ± 0.37 μm was achieved in the DP steel containing 0.12 wt% Nb whose strength was about 123% higher than that of the as-received ferritic-pearlitic steel (e.g. 540 MPa), without loss of ductility. The variations of strength, elongation and fracture mechanism of the specimens with Nb contents and intercritical annealing time were correlated to the microstructural features.

1. Introduction

The optimized combination of crash safely performance and lightweight structures are driving force for the development of advanced high strength (AHSS) steels in automotive industries in order to increase the fuel efficiency and to reduce CO_2 emission [1,2]. Dual phase (DP) steels are one of the important AHSS grades whose microstructures consist of ferrite matrix with dispersed martensite. The martensite contributes with high strength and ferrite matrix provides good elongation which resulted in unique properties such as high strength, good formability, low yield ratio and high initial work hardening rates [3]. It is reported that more than 20 new types of AHSS steels that are expected to be commercially available from 2015 to 2020, above 30% of which would be DP steels with strength in the range from 500 to 1000 MPa [4].

In recent years, a great attention has been paid upon the development of the lighter and stronger DP steels with the optimized properties and reasonable production route. Grain refinement is one of the effective methods for strengthening of DP steels. Ultrafine grained (UFG) DP (UFG-DP) steels are developed either by sever plastic deformation (SPD) [5] or by thermomechanical processes (TMP). The TMP are more adaptable to large sample sizes when compared with SPD processes [6]. A variety of TMP routes have been introduced to achieve UFG-DP steels such as deformation induced ferrite transformation (DIFT) [7], warm rolling [3,8] and cold-rolling and intercritical annealing [9,10]. However, the main challenge in producing UFG-DP steels is to achieve improved mechanical properties with a cost-effective processing route. Hot-rolling and warm deformation are not very promising due to huge deformation induced at high temperatures.

Utilizing combination of microalloying elements (such as Ti, V, and Nb) and a simple processing route may activate several strengthening mechanisms in DP steels such as solid solution, grain refinement and precipitation hardening. Nb is a key microalloying element, as it is effective in very low concentrations and has a significant effect on recrystallization, grain growth and phase transformation during intercritical annealing of the DP steels [11–13]. The role of Nb can be either as solid solution strengthener, where it is thought to exhibit a strong solute drag effect, or as NbC precipitates, which are thought to be effective at pinning grain boundaries [12]. Addition of Nb could promote austenite formation during intercritical annealing [14]. Hong and Lee [7] reported that Nb and V could prevent grain growth during DIFT of the hot rolled DP steels. Niakan and Najafizadeh [15] studied the effect of Nb and rolling parameters in DP steels. They showed that specimens containing Nb had greater yield and tensile strength, and

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lower elongation and ferrite grain size. However, these researches showed the effect of Nb upon warm and hot deformations processes. Recently, Song et al. showed the effects of Nb in low concentration (0.021, 0.038 and 0.063 wt%) on the microstructural evolutions of the cold-rolled steels. They showed that the addition of Nb increased the ferrite recrystallization start temperature, but had no significant effect on the start temperature of austenite formation during heating. Nb additions accelerated austenite formation once the transformation started, and also resulted in the formation of a finer and more homogeneous microstructure after annealing [16]. However, they did not study the effect of Nb in higher concentrations. Furthermore, the application of cold rolling followed by intercritical annealing of the ferrite/martensite duplex starting structure has not been reported before for the Nb-bearing DP steels.

Therefore, in the present work, a series of UFG-DP steels containing different amounts of Nb up to 0.18 wt% were produced by the cold-rolling and intercritical annealing of the starting duplex ferrite-martensite structures. A systematic study was conducted to investigate the effects of Nb content and intercritical annealing time on microstructures, tensile behavior and fracture behavior of the UFG-DP steels.

2. Experimental details

2.1. Materials

The hot-rolled AISI 5115 steel strip with the chemical composition shown in Table 1 was used in this study. The strips were cut to several pieces and pickled by a solution of 60% Hydrochloric acid (HCl) in water for casting. Four steel specimens with the same chemical composition but different Nb content (see Table 1) were cast by a home-made copper boat vacuum induction melting furnace. The DP steels were coded as the DP00, DP06, DP12, and DP18 depending on their Nb content of 0.00, 0.06, 0.12 and 0.18 wt%, respectively. In order to prevent severe decarburization, cast iron swarfs were used to protect specimens during homogenization. The as-homogenization specimens were hot-forged at 1100 °C to a thickness of 4 mm. The samples dimensions were about $50 \times 20 \times 4$ mm^3.

2.2. Dilatomery test

Dilatational tests were carried out to determine the non-equilibrium austenite formation start and finish temperatures during heating (Ac_1 and Ac_3 temperatures, respectively), as shown in Fig. 1. The test included heating solid cylindrical specimens with the diameter of 2.4 mm and length of 10 mm to 950 °C at a rate of 1 °C/s, held at this temperature for 20 min, followed by cooling to the room temperature. The dilatation curves consisted of two main points corresponding to the two intercritical temperatures. The first and second points represent the Ac_1 and Ac_3 temperatures, respectively, characterized by the first and second peaks on the dilatation curves.

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

Steel code	Nb	C	Mn	Cr	Si	Fe
As-received	0.00	0.17	1.15	0.95	0.4	Balance
DP00	0.00	0.13	0.95	1	0.3	Balance
DP06	0.06	0.13	0.95	1	0.3	Balance
DP12	0.12	0.14	0.95	1	0.3	Balance
DP18	0.18	0.14	0.95	1	0.3	Balance

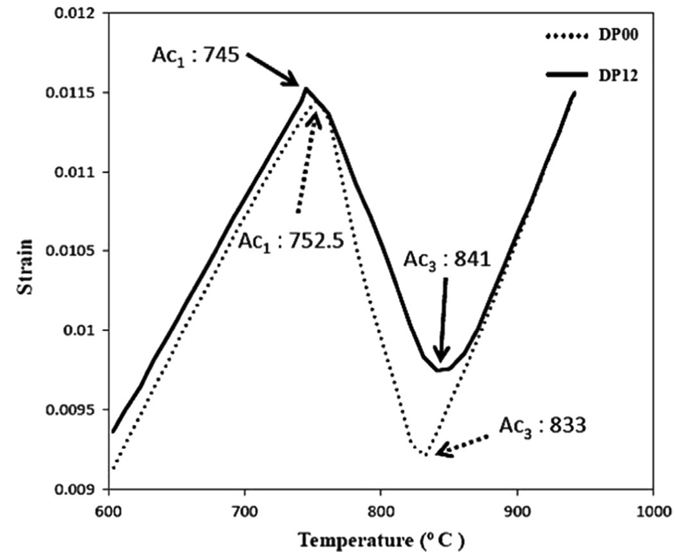

Fig. 1. Dilatometry test upon continuous heating by the rate of 1 °C/s. Ac_1 and Ac_3 are non-equilibrium austenite formation start and finish temperatures during heating, respectively.

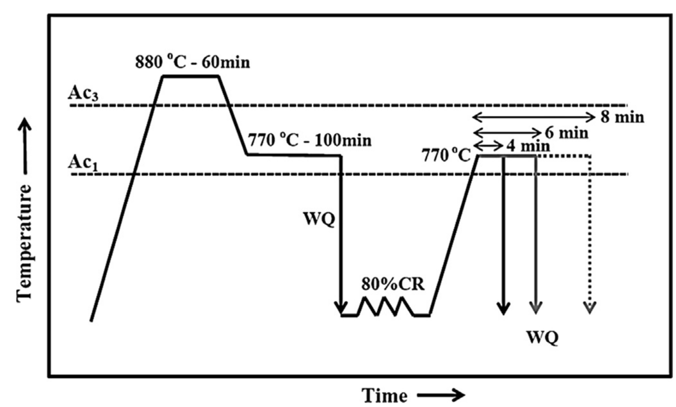

Fig. 2. Thermomechanical cycle used to produce UFG-DP steels. Ac_1 and Ac_3: austenite formation start and finish temperatures during heating, respectively; WQ: water quench; CR: cold-rolling.

2.3. Thermomechanical processing

In order to develop DP ferrite-martensite microstructures, a thermomechanical procedure based on cold-rolling and short intercritical annealing was performed on the samples. The ferrite-pearlite microstructures were first heated to the austenitization temperature of 880 °C for 60 min followed by intercritical annealing at 770 °C for 100 min and water quenching. Then, the resulting duplex ferrite-martensite structures were subsequently cold-rolled up to 80% using a laboratory mill with a reduction of about 0.05 mm at each pass. Finally the cold-rolled samples were heated to the intercritical temperature of 770 °C and held for different times followed by water quenching. The thermomechanical route was schematically presented in Fig. 2.

2.4. Characterization

Specimens for microstructural analysis were cut along the transverse direction (TD). These sectioned specimens were mounted and grounded using silicon carbide paper and polished till 4000 grit finish followed by polishing with one micrometer alumina suspension. After polishing, the specimens were etched with 2% nital solution for 3 s followed by 10% potassium metabisulfite ($K_2S_2O_5$) for about 5 s. Microstructures were characterized