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A novel route for development of ultrahigh strength dual phase steels

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ABSTRACT

Dual phase (DP) steels were produced by a new approach utilizing simple cold-rolling and subsequent intercritical annealing of a ferrite–martensite duplex starting structure. The effects of intercritical annealing temperature on the microstructural evolutions and mechanical properties were studied. It was found that the volume fraction of martensite increased by increasing the intercritical annealing temperature. Tensile testing showed a good strength–elongation balance for DP steels ($\mathrm{UTS} \times \mathrm{UE} > 100\ \mathrm{J\ cm^{-3}}$) in comparison with the commercially used high strength steels. The strength of the low carbon steel with the new ultrafine grained DP microstructure (average grain size of about 1–2 μm) was reached over 1500 MPa (about 200% higher than that of the as-received state, e.g. 540 MPa), without loss of ductility. The variations of hardness, strength, elongation, strain hardening behavior and fracture mechanism of the specimens with intercritical annealing temperature were correlated to microstructural features.

1. Introduction

Dual phase (DP) steels have been developed from conventional low carbon steel consisting of martensite and ferrite phases, in which the martensite imparts high strength and the ferrite matrix supplies good elongation. DP steels are widely used for automotive steel sheets because of their excellent mechanical properties, such as high strength, low yield ratio, high work hardening rate, continuous yielding and good formability [1–4]. According to the result of the ULSAB-AVC (Ultra Light Steel Auto Body-Advanced Vehicle Concept) partnership project, an automotive body could be constructed by utilizing approximately 85% of advanced high strength steels, achieving a weight reduction of ~25% compared with a bench-marked average base model without any increase of the manufacturing costs. In particular, DP steels occupies quite large portion, over 70%, in the materials selection of ULSAB-AVC project [5].

Although DP steels have better mechanical properties as compared to conventional high strength low alloy steels, further strengthening is required in DP steels to reduce the weight and to improve the crashworthiness of the car bodies. The main challenge in producing DP steels is to achieve grain refinement and to make them cost effective. Few studies have been done on the fabrication of fine grained DP steels with good mechanical properties using alloying additions. Terao and Cauwe [6] reported that adding high Mn content (3 wt%) to DP steels resulted in fine dispersion of martensite leading to higher tensile strength and good ductility. Adding alloying elements like Mo, Nb, Ta and B led to further improvement of the mechanical properties of the high Mn DP steels. Tsipouridis et al. [7] used C–Mn (0.1–1.5 wt%) steel with 0.8 wt% Mo and Cr additions to create fine DP structures. It is also reported that grain refinement had a positive effect on the yield strength and ultimate tensile strength values, but no conclusion was made on the hole-expansion behavior, which plays a crucial role in fracture analysis.

The conventional methods employed to strengthen the DP steels either involved adding alloying elements (increases the material cost) or increasing the carbon content (hinders weldability). Therefore, there is a great interest to design new processing techniques to reduce the material cost and simultaneously to improve the mechanical properties. Over the years new processing routes have been developed in the laboratory to increase the strength and ductility by microstructure refinement rather than adding alloying elements.

Shin et al. [8] used the equal channel angular pressing (ECAP) technique to obtain fine ferrite grains (0.2–0.3 μm) in a ferrite–pearlite structure. Park et al. [9] also combined ECAP with an intercritical annealing step to obtain ultrafine grained (UFG) DP structures in a plain C–Mn (Fe–0.15C–1.1Mn (in wt%)) steel. Tsuji [10] processed UFG DP structures by accumulative roll bonding (ARB) and subsequently intercritical annealing of a low carbon steel (JIS SM490; 490 MPa class). Mukherjee et al. [11] created fine DP structures using four different low carbon steels (Fe–0.06C–1.8Mn (in wt%)) with varying amounts of Mo and Nb. They used the deformation-induced ferrite transformation (DIFT) technique to fabricate fine DP structures. Hong and Lee [12] also produced

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a fine grained DP steel by using DIFT. Recently, Calcagnotto et al. [13,14] have developed a large strain warm deformation method to obtain fine ferrite–carbide aggregate in a plain C–Mn (Fe–0.17C–1.5Mn (in wt%)) steel. Intercritical annealing and subsequent quenching is done to obtain the final ferrite/martensite DP microstructure. Song et al. [15] have also used warm deformation to produce fine DP structure. Azizi-Alizamini et al. [16] has developed UFG DP steels by rapid intercritical annealing of fine ferrite–carbide aggregates.

According to the above-mentioned researches, grain refinement and simultaneous improvement of mechanical properties were attempted by changing starting microstructures and processing ways. However, the potential of these processing routes to be employed industrially is very slim due to the many steps involved in these individual processes. ECAP and ARB have limitation on sample size and shape; huge deformation at high temperatures is a major drawback of DIFT and warm-rolling; the drawback of the rapid intercritical annealing approach is high heating/cooling rates (300 °C/s and 1000 °C/s, respectively). Therefore, further studies could be useful for industrial production of these steels.

In the present study, ultrahigh strength DP steels with simultaneous good elongation were fabricated by employing cold-rolling and intercritical annealing. On one hand, UFG DP structures were fabricated by employing lower heating (~1 °C/s) and cooling (~300 °C/s) rates. On the other hand, UFG microstructures were obtained by relatively low plastic strain through conventional cold-rolling compared to an extremely high equivalent strain of over 4 or 5 which is required to produce the UFG microstructures through ECAP and ARB. The short intercritical annealing treatment can be an advantage of this rather simple technique; moreover the number of processing steps is considerably reduced. So definitely, duplex starting structures seem to be a potential processing route to produce UFG DP steels. However industrial implementation can be challenging with the existing production lines for steel sheets. The process was characterized by the starting microstructure before intercritical annealing, which was a ferrite–martensite duplex structure. In addition, the obtained microstructures were introduced and the tensile properties of processed specimens were studied. For a given chemical composition, temperature of the intercritical annealing is the critical factor determining the microstructural and mechanical characteristics of constituent phases and so whole mechanical properties of ferrite–martensite DP steel. Therefore, the effect of intercritical annealing temperature on microstructural evolution and mechanical properties was determined to evaluate the processing window for the proposed intercritical annealing stage.

2. Materials and experimental procedures

2.1. Materials

The steel used in this investigation was AISI 5115 with the chemical composition presented in Table 1. The chemistry of the DP steels typically contain about 0.05–0.2 wt% carbon and 1–2 wt% manganese [17,18]. In addition, they may contain small amounts of silicon, niobium, molybdenum and chromium. A chemical composition similar to that of the commercial DP600 and DP800 steels [19] was selected for the purpose of comparison and possibility of practical production. Carbon enhances both grain refinement and grain size stability [20]. Indeed, the mechanical behavior of DP steel is to a large extent controlled by the carbon concentration through its effect on the volume fraction and strength of the martensite phase. At the same time, the carbon content has to be low enough to ensure good weldability, which is fulfilled for carbon contents below 0.2 wt%. Silicon is useful in preventing pearlite and carbide formation and also results in solid solution hardening of the ferrite phase [21,22]. Manganese content also plays a key role in the processing of DP steels as it substantially enhances the grain size stability during intercritical annealing and the ability of austenite to undergo martensitic phase transformation [23]. This implies that a critical amount of Mn content has to be present in steels otherwise high heating rates (to promote grain size stability) and high cooling rates (to promote austenite to martensite transformation) have to be employed to achieve UFG DP steels. This explains the reason behind the high heating and cooling rates employed by Azizi-Alizamini et al. [16], because the Mn content in their steel was only 0.74 wt% as compared to the other UFG DP steels, which have at least 1.5 wt% Mn. Chromium improve hardenability, suppress pearlite formation and promote martensite formation. The material was received as a hot forged plate with the thickness of 6 mm. Hot forged sheets were cut to several specimens with $50 \times 30 \times 6\ \mathrm{mm}^3$ dimensions.

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

Element	C	Si	Mn	Cr	S	P
Composition	0.17	0.4	1.15	0.95	0.035	0.025

2.2. Thermomechanical processing

Processing route performed on low carbon steel to develop ferrite–martensite DP steels is shown in Fig. 1. At first, the ferrite–pearlite structure was austenitized at 880 °C for 30 min in an electrical furnace. In order to prevent severe decarburization, cast iron swarfs were used to protect samples during heating. Okitsu et al. [24] fabricated fully annealed UFG ferrite grains and homogenously dispersed cementite particles in low-carbon steel by 91% cold-rolling of an initial martensite–ferrite duplex microstructure and short time annealing. They have conducted the annealing below austenite formation start temperature; whereas this work uses the phase transformation after cold rolling. Similarly, it is thought that martensite–ferrite duplex microstructure would have also a potential as a starting structure to form UFG DP structure. A series of preliminary tests revealed that after 100 min intercritical annealing at 770 °C followed by water quenching, a ferrite–martensite duplex microstructure containing almost equal amounts of martensite and ferrite phases could be produced. Therefore, the intercritical annealing at 770 °C for 100 min

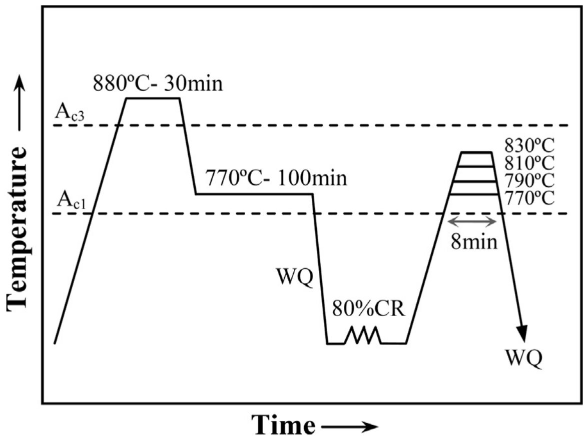

Fig. 1. Thermomechanical treatment developed to produce ultrahigh strength DP steels. A_{c1}: start and A_{c3}: finish temperature of austenite formation during heating; WQ: water quenching; CR: cold-rolling.