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Effects of initial microstructure and thermomechanical processing parameters on microstructures and mechanical properties of ultrafine grained dual phase steels

Yousef Mazaheri *, Ahmad Kermanpur, Abbas Najafizadeh, Navid Saeidi

Department of Materials Engineering, Isfahan University of Technology, Isfahan 84156-83111, Iran

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Dual phase (DP) steels was investigated using thermomechanical processes designed to obtain ultrafine/nanoferrite-carbide aggregates and martensite–ferrite duplex starting structures prior to intercritical annealing. The effects of processing parameters such as intercritical annealing temperature and time on the microstructural evaluations, mechanical properties, strain hardening behaviors and fracture mechanisms have been studied. The ferrite grain size and martensite volume fraction were depended on the initial microstructure and thermomechanical processing parameters. Ultrafine grained DP (UFG-DP) steel with an average grain size of about 2 μm was achieved by short intercritical annealing of the 80% cold-rolled duplex microstructure. Tensile testing revealed an excellent strength–elongation balance (UTS × UE > 110 J cm^{-3}) in the DP steels. The new UFG-DP steels showed superior mechanical properties in comparison with the commercially used high strength steels. The variations of strength, elongation, strain hardening behavior and fracture mechanism of the specimens with thermomechanical parameters were correlated to microstructural features.

1. Introduction

In automotive industries, weight reduction, passenger safety, vehicle performance, fuel efficiency, cost saving and rationalizing production methods are motives for the development of advanced high strength (AHSS) and ultrahigh strength steels (UHSS) [1–3]. As a type of AHSS, DP steel contains soft ferrite with hard dispersed martensite islands, in which the martensite imparts high strength and the ferrite matrix supplies good elongation. The enhancements in formability with a very desirable combination of strength and ductility make DP steels strong candidates for structural applications [4–7].

DP steels have also other unique properties, which include low yield ratio, high strain hardening rate and continuous yielding [8]. According to the result of the Ultra Light Steel Auto Body–Advanced Vehicle Concept (ULSAB–AVC) partnership project, an automotive body could be constructed by utilizing approximately 85% of AHSS, achieving a weight reduction of ~25% compared with a benchmarked average base model without any increase of the manufacturing costs. In particular, DP steels occupy quite large portion, over 70%, in the materials selection of ULSAB–AVC project [9].

Although DP steels have better mechanical properties as compared to conventional high strength low alloy steels (HSLA), there is always the desire to improve them further. The conventional methods employed to strengthen DP steels either involved increasing the carbon content (hinders weldability) [10] or adding alloying elements (increases the material cost) [11,12]. Therefore, there is the scope 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 to increase strength and ductility by microstructure refinement rather than adding alloying elements.

Shin et al. [13] and Park et al. [14] combined equal channel angular pressing (ECAP) with an intercritical annealing step for fabrication of UFG-DP structures from ferrite–pearlite starting structures. The relatively high ECAP temperature was selected in order to minimize grain growth of retained ferrite during subsequent intercritical annealing. Tsuji [15] processed UFG-DP structures by six cycles (equivalent strain of 4.8) accumulative roll bonding (ARB) and subsequently intercritical annealing of the hot-rolled sheets with ferrite–pearlite structure. Mukherjee et al. [16] and Hong and Lee [17] produced fine grained DP steels by using the deformation induced ferrite transformation (DIFT) technique. Calcagnotto et al. [18] and Song et al. [19] used large strain warm deformation to produce fine ferrite-carbide aggregates. Intercritical annealing and subsequent quenching was done to obtain the final ferrite–martensite DP microstructures. Azizi-Alizamani et al. [20]

* Corresponding author. Tel.: +98 9173047580; fax: +98 3133912752.
E-mail address: y.mazaheri@ma.iut.ac.ir (Y. Mazaheri).

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developed UFG-DP steels by rapid intercritical annealing of fine ferrite-carbide aggregates.

According to above research, grain refinement with simultaneous improvement of mechanical properties was attempted by changing starting microstructures and processing ways. However, these processing routes are not efficient for industrial production. ECAP and ARB have sample size and shape limitation and are very cumbersome (if not impossible) to employ in a commercial steel processing line. DIFT and warm deformation are also not very promising due to huge deformation induced at higher temperatures. The major drawback of the rapid intercritical annealing approach is high heating and cooling rates (300 °C/s and 1000 °C/s, respectively). Nevertheless, further studies could be useful for industrial production of steels.

In the present study, the UFG-DP structures with simultaneous improved mechanical properties were fabricated by employing cold-rolling and intercritical annealing of a martensite–ferrite duplex starting microstructure. Short intercritical annealing treatment can be an advantage of this rather simple technique; moreover the number of processing steps is considerably reduced. A systematic study is presented to investigate the effect of initial structure and processing parameters such as intercritical annealing temperature and time on the microstructure evolutions and resulting mechanical properties.

2. Material and experimental procedure

2.1. Material

The steel used in this investigation was AISI 5115 with the chemical composition presented in Table 1. The material was received as a hot forged plate with the thickness of 6 mm. Hot forged sheets were cut to several specimens with $50 \times 30 \times 6\ mm^3$ dimensions.

2.2. Thermomechanical processing

Processing routes performed on low carbon steel to develop ferrite–martensite DP steels are shown in Fig. 1. At first, the ferrite–pearlite structure was austenitized at 880 °C for 60 min in an electric furnace. In order to prevent severe decarburization, cast iron swarfs were used to protect samples during heating. The intercritical annealing at 770 °C for 100 min and subsequently water quenching were introduced prior to cold-rolling to obtain a duplex martensite–ferrite structure. This process makes it easier to perform cold reduction. This annealing temperature (770 °C) laid between the lower (A_1) and upper (A_3) temperatures of the two-phase ferrite and austenite region of the investigated steel. Therefore, the samples just had an austenitic–ferritic structure.

In this study, the A_1 and A_3 temperatures were determined by a dilatometry experiment, as shown in Fig. 2. The resulting duplex structures were subsequently cold-rolled up to 80% using a laboratory mill with a reduction of about 0.05 mm at each pass. Further annealing of the cold-rolled sheet at 600 °C for 20 min resulted in an ultrafine/nanoferrite-carbide aggregate which was chosen as one of the initial structures prior to final intercritical annealing (Fig. 1a, DP_I). For comparison, the 80% cold-rolled duplex structure which could be produced by less processing steps was

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

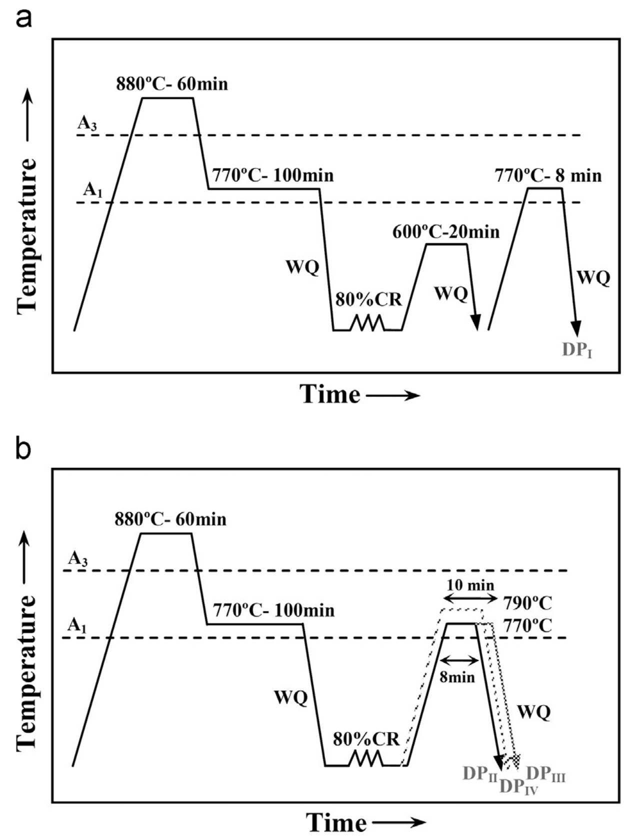

Fig. 1. Thermomechanical treatments developed to produce UFG-DP steels. A_1: start and A_3: finish temperature of austenite formation during heating; WQ: water quench; CR: cold-rolling.

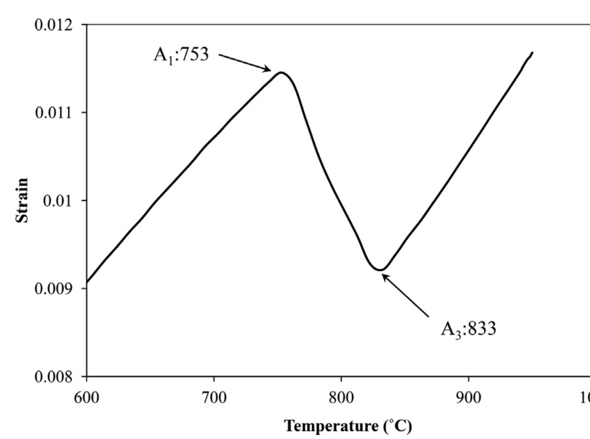

Fig. 2. Dilatometry test experiment upon continuous heating by the rate of 1 °C/s. A_1 and A_3 are austenite formation start and finish temperatures during heating, respectively.

selected as the other initial structure (Fig. 1b, DP_{II}). The final processing step for both treatments involved heating to the intercritical annealing region and holding for 8 min at 770 °C followed by water quenching. In addition, to investigate the effects of intercritical annealing time and temperature on the microstructure evolutions and mechanical properties, the 80% cold-rolled duplex sheets were annealed at 770 °C for 10 min (DP_{III}) and 790 °C for 8 min (DP_{IV}).

2.3. Characterization

Microstructural analysis was carried out along the transverse direction (TD), i.e. the plane perpendicular to both the rolling