Materials Science & Engineering A 599 (2014) 145–149

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

Development of a new ultrafine grained dual phase steel and examination of the effect of grain size on tensile deformation behavior

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ARTICLE INFO

Article history:
Received 10 September 2013
Received in revised form
16 January 2014
Accepted 20 January 2014
Available online 27 January 2014

Keywords:
Dual phase steel
Ultrafine grained steel
Intercritical annealing

ABSTRACT

Ultrafine grained dual phase (DP) steels are among the newest grades of DP steels that incorporate the uniform distribution of fine martensite particles (in the order of 1–2 μm) within a ferrite matrix. These new grades of steels have been developed in response to the world's demand for decreasing the fuel consumption in automobiles by increasing the strength to weight ratio. In the present research, a new kind of ultrafine grained DP (UFG-DP) steel with an average grain size of about 2 μm as well as a coarse grained DP (CG-DP) steel with an average grain size of about 5.4 μm was produced by consecutive intercritical annealing and cold rolling of low carbon AISI 8620 steel. The martensite volume fraction for both microstructures was the same and about 50 percent. Scanning electron microscopy (SEM) microstructural examination and room temperature tensile deformation analyses were performed on both UFG-DP and CG-DP steels and their deformation behavior in terms of strength, elongation and strain hardening was studied and compared. Room-temperature uniaxial tensile tests revealed that for a given martensite volume fraction, yield and tensile strengths were not very sensitive to martensite morphology. However, uniform and total elongation values were noticeably affected by refining martensite particles. The higher plasticity of fine martensite particles as well as the more uniform strain distribution within the UFG-DP microstructure resulted in higher strain hardenability and, finally, the higher ductility of the UFG-DP steel.

1. Introduction

Development of present and future vehicles is driven by the need to simultaneously reduce mass and increase passenger and pedestrian safety. For this reason, the steel industries have developed many kinds of steel grades with suitable properties, as required for meeting the demands posed on the automotive manufacturers [1,2]. DP steel is one of the best-known kinds of steel in this area. Generally, conventional DP steels are produced by intercritical annealing or thermo-mechanical treatment. Intercritical annealing is associated with the annealing treatment of the steel in the two phase region (i.e., between the Ac_1 and Ac_3 temperatures), following quenching of the specimens [3]. Usually, this kind of treatment results in a coarse ferrite/martensite microstructure. On the other hand, thermo-mechanical treatment, which involves hot rolling in the intercritical region and is followed by step cooling, could produce finer microstructures [4].

Previous studies [5,6] on grain refinement in DP steels have revealed that in ultrafine grained DP steels, owing to the small size of grains, more homogeneous distribution and more spherical shape of martensite islands, formation of martensite cracks and cleavage fracture in ferrite would be suppressed, thereby encouraging ductile fracture mechanisms. Ultrafine grained DP steels can be produced [2,3] by applying a severe deformation treatment and using processes such as ECAP, cold rolling, cold swaging and large strain warm deformation to produce ultrafine grained ferrite and finely dispersed cementite or pearlite followed by a short intercritical annealing in the ferrite/austenite two phase region and subsequent quenching to transform all austenite to martensite [7]. Applying hot deformation and large strain warm deformation, which was followed by subsequent intercritical annealing, Calcagnotto et al. [8] produced ultrafine grained DP steel with grain size being between 1 and 2 μm. They showed that both yield strength and tensile strength would be increased by grain refinement; however, uniform and total elongations were not affected noticeably. Moreover, it was found that with decreasing the grain size, ductile fracture mechanism would be promoted owing to suppression of martensite cleavage cracks formation within small martensite grains. Further, using the ECAP process, which was followed by intercritical annealing in the ferrite/austenite two phase region and subsequent quenching, Park et al. [9] showed that superior mechanical properties in terms of higher strength, elongation and strain hardening exponent, as compared to those of coarse grained DP steels, could be obtained.

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0921-5093/$ - see front matter
http://dx.doi.org/10.1016/j.msea.2014.01.053

To summarize, it can be said that in commonly proposed methods used for producing ultrafine grained steels, there are a number of difficulties including complex and costly forming processes of ECAP or warm rolling, which is followed by multi-step cooling. So, the aim of the present investigation was to produce an ultrafine grained DP steel by a rather simple process consisting of intercritical annealing treatment and cold rolling of a plain low carbon steel, AISI 8620. Then, the room temperature uniaxial tensile properties of the newly developed steel were examined and compared to those of a coarse grained DP steel prepared by the intercritical annealing and subsequent quenching.

2. Materials and methods

A plain low carbon steel (AISI 8620) with the chemical composition shown in Table 1 was treated by an intercritical annealing process to produce a coarse grained DP steel. Moreover, it was treated in a two-step processing route to produce ultrafine grained DP steel. The applied production processes are presented in Table 2.

Specimens for microstructural analysis were mounted, ground and polished to 2000 grit finish and then polished with 0.1 μm alumina suspension. This was followed by etching with distilled water–10 percent potassium metabisulfite ($K_2S_2O_5$) reagent.

Tensile specimens were prepared by machining heat-treated steels through electro discharge machining (EDM), according to ASTM A370 standard [10]. The thickness of the specimens was 1.2 mm and their gage length was 15 mm. The finished surfaces of machined specimens were polished to remove any effect of the machining process. For each kind of steel, three specimens were prepared and tensile tested by an Instron machine at an initial strain rate of 1 mm/min. Fracture surfaces as well as initial microstructures were examined by electron scanning microscopy (SEM) and optical microscopy (OM). The volume fractions of the different phases in the studied DP steels were measured by image analysis of the several OM micrographs using ImageJ software [11]. Also grain size measurements were performed by the linear intercept method [12]. Moreover, the hardness measurements were carried out using a Vickers indenter with an applied load of 20 kg.

3. Results and discussions

3.1. Microstructural analysis and tensile properties

Considering the microstructures of the steels studied obtained by SEM analysis (Fig. 1), it is quite obvious that in the CG-DP steel, martensite particles are much coarser than the UFG-DP steel. Moreover, martensite particles are less uniform in size and distribution in the former than in the latter. Another distinguishable difference between the two steels is the more rounded edges of martensite particles in the UFG-DP steel rather than the CG-DP steel. Moreover, martensite particles in the UFG-DP steel are rather connected or banded. Image analysis of OM micrographs revealed that both steels consisted of a similar martensite volume fraction, 50 ± 4 percent. Moreover, using the linear intercept method [12], grain sizes of the CG-DP and UFG-DP steels were obtained to be equal to 5.4 ± 0.4 and 2 ± 0.5 μm, respectively. The engineering and true stress–strain curves as well as important mechanical properties obtained during room temperature uniaxial tensile tests are presented in Fig. 2 and Table 3, respectively. The obtained mechanical properties data were compared with a commercial modern high strength automobile steel, DP980 [13]. It was revealed that in the two steels developed, including the same martensite volume faction, tensile strength was nearly the same, while total elongation as well as uniform elongation value in the UFG-DP steel was about 34 and 25 percent, respectively, higher than the CG-DP steel. Also, it is noticeable that in the UFG-DP steel fracture strain is about 0.45 percent higher than in CG-DP steel. This is nearly consistent with the 32 percent higher value of toughness in UFG-DP than in CG-DP steel (Table 3). The toughness values were obtained by measurement of the area under the engineering strain–stress curves, which is an indication of the required energy to break the material. On the other hand it was obtained that (Table 3) the hardness of UFG-DP steel is about 17 percent lower than CG-DP steel. Comparison of yield strengths showed the same trend as hardness, such that the CG-DP steel showed a higher yield strength value of 850 MPa compared to the UFG-DP steel with 820 MPa. Comparing these results with the mentioned DP980 steel seemed to show that although the newly developed UFG-DP steel had nearly the same tensile strength as DP980, its total and uniform elongation values were about 10 and 36 percent, respectively, higher than DP980 steel. The mentioned mechanical properties of the newly developed UFG-DP steel along with the commercially used high strength DP980 steel, which is one of the highest strength automobile steels, clearly indicated the good potential of the new UFG-DP steel for application in automobile body structure.

As presented in the previous paragraph, one of the main differences between the two studied microstructures was the difference in grain size, such that in the UFG-DP steel grain size was about 45 percent smaller than in the CG-DP steel. It was showed [5] that with decreasing martensite particle size, its ductility was increased. This could be due to the fact that the higher plastic constraint in ferrite grain, and within the UFG-DP microstructure, forced martensite to deform plastically earlier during straining; due to the existence of higher ferrite–martensite interfaces in a fine microstructure than in a coarser one, load transfer to the hard martensite particles would be more efficient [14]. Moreover, in the UFG-DP steel, martensite particles had more rounded edges than CG-DP steel, showing that less stress concentration acted on martensite particles and so the probability of martensite cracking would be lower than that of CG-DP steel.

Table 1
Chemical composition of the used AISI 8620 steel (wt%).

Element	C	Mn	Ni	Cr	Si	P	S	Mo	Fe
wt%	0.19	0.79	0.50	0.54	0.20	0.14	0.02	0.17	Bal.

Table 2
Applied treatment processes.

Designation	Microstructure	Applied heat treatment cycle
CG-DP	Coarse grained DP steel	Austenitization at 850 °C for 20 min, followed by intercritical annealing at 740 °C for 60 min and water quenching
UFG-DP	Ultrafine grained DP steel	Austenitization at 850 °C for 20 min, followed by intercritical annealing at 740 °C for 60 min, 90 percent cold rolling to 1 mm thickness, a short intercritical annealing at 740 °C for 3 min followed by water quenching