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ScienceDirect

Acta Materialia 78 (2014) 181–189

Acta MATERIALIA

www.elsevier.com/locate/actamat

Novel ferrite–austenite duplex lightweight steel with 77% ductility by transformation induced plasticity and twinning induced plasticity mechanisms

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Received 11 March 2014; accepted 24 June 2014
Available online 19 July 2014

Abstract

The need for lightweight materials has been an important issue in automotive industries to reduce greenhouse gas emission and to improve fuel efficiency. In addition, automotive steels require an excellent combination of strength and ductility to sustain automotive structures and to achieve complex shapes, but the traditional approach to obtain a reduction in weight from down-gauged steels with high strength has many limitations. Here, we present a new ferrite–austenite duplex lightweight steel containing a low-density element, Al; this steel exhibits tensile elongation up to 77% as well as high tensile strength (734 MPa). The enhanced properties are attributed to the simultaneous formation of deformation-induced martensites and deformation twins and the additional plasticity due to deformation twinning in austenite grains having optimal mechanical stability. The present work gives a promise for automotive applications requiring excellent properties as well as reduced specific weight.

Keywords: Duplex lightweight steel; Annealing; Tensile properties; Transformation induced plasticity (TRIP); Twinning induced plasticity (TWIP)

1. Introduction

Recently, there has been a focus on the need to reduce vehicle weight in order to reduce exhaust emissions and improve fuel efficiency [1,2]. The most efficient method is the use of materials lighter than conventional ones. Many efforts have been directed towards applying lightweight materials such as Al alloys or Mg alloys, despite their high costs [3,4]. However, these alloys show poor formability, which restricts the application [5,6]. The development of new advanced automotive steels, namely lightweight steels, is recognized as a more realistic measure [7,8]. As a part of this study, a considerable amount of Al has been added to automotive steels to obtain a lightweight material [9–11]. It has been shown that the addition of 1 wt.% Al leads to a 1.5% weight reduction in comparison with conventional steels. However, the addition of Al reduces the ductility, and thus the method utilizing microstructures such as a full austenitic phase strengthened with κ-carbides, or a duplex phase of ferrite + austenite, has been suggested [9–19]. The full austenitic microstructure displays low work-hardening capacity, in spite of the excellent combination of strength and ductility, which results in the problem of poor formability [20]. When the austenite is utilized as a secondary phase in ferrite matrix, high-strength, high-ductility lightweight

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http://dx.doi.org/10.1016/j.actamat.2014.06.059
1359-6454/

steels having high work-hardening capacity can be developed by the austenite/martensite transformation during the deformation, namely the transformation induced plasticity (TRIP) mechanism [11–14].

According to research on an Fe–3.5Mn–5.9Al–0.4C steel [12] and an Fe–5.8Mn–3.1Al–0.12C–0.47Si steel [14], for example, the austenite was retained at room temperature when steels were annealed above 720 °C, and was transformed to α′-martensite during the deformation, which led to excellent properties of tensile strength (990 MPa) and elongation (28%). This γ/α′ transformation in (α + γ) duplex structure mainly depends on the orientation, mechanical stability and stacking fault energy (SFE) of the retained austenite [11–13,21,22]. In order to achieve the more excellent combination of strength and ductility, the utilization of another powerful deformation mechanism of twinning induced plasticity (TWIP) by properly controlling the mechanical stability or SFE of austenite is essentially needed [23–27]. In a certain stability or SFE range of austenite, deformation twins prevent the movement of dislocations as they work for the grain refinement [26,27]. This variation in deformation mechanism might affect the strength and ductility by forming complex microstructures mixed with twins and martensite. Furthermore, such a microstructural evolution occurring during the final stage of deformation might play an important role in controlling deformation mechanisms. Thus, studies on deformation mechanisms are essential for the evaluation of alloy design, microstructural evolution and process control.

In the present study, therefore, the (α + γ) duplex lightweight steel showing the operation of both TRIP and TWIP mechanisms was developed by varying annealing conditions of an Fe–0.3C–8.5Mn–5.6Al steel, and tensile properties were evaluated. Detailed deformation mechanisms were investigated in relation to microstructural evolution by electron back-scatter diffraction (EBSD) and transmission electron microscopy (TEM) analyses, and the correlation between microstructural evolution process and tensile ductility was verified.

2. Experimental

2.1. Lightweight steels

The lightweight steel used in this study was fabricated by a vacuum induction melting method, and its nominal composition is Fe–0.3C–8.5Mn–5.6Al–(<0.02)(P + S) (wt.%). After thick plates of 60 mm in thickness were homogenized at 1200 °C for 1 h, they were hot-rolled between 1100 and 900 °C. They were then cooled in a furnace from 650 °C after holding at this temperature for 1 h in order to simulate a coiling procedure. The hot-rolled steel sheets of 3 mm in thickness were rolled at room temperature to make 1 mm thick steel sheets. The sheets were annealed at 800 °C for 1 min or 30 min and at 900 °C for 30 min in a continuous annealing simulator (model; CAS-AY-II, Ulvac-RIKO, Inc., Japan) to form a mixture of ferrite and austenite, and were cooled in the air. For convenience, the steel sheets annealed at 800 °C for 1 min, at 800 °C 30 min and at 900 °C for 30 min are referred to as "A81", "A83" and "A93", respectively.

The effects of Al addition on weight reduction are attributed to the lattice expansion and the low atomic weight of substitutional solution [3]. The density of the present steel was measured to be 7.2 g cm^{-3}, by a densitometry (Mettler-Toledo XP205, Mettler-Toledo AG, Switzerland) on the basis of the Archimedes principle, which shows an apparent reduction of 8.5% in comparison to pure Fe.

2.2. Microstructural analysis

Phases present in the specimens were identified by X-ray diffraction (XRD; Cu K_α radiation; scan rate, 2° min^{-1}; scan step size, 0.02°) and TEM. Their volume fractions were measured by the direct comparison method using XRD analysis [14]. Integrated intensities of $(200)_\alpha$ and $(211)_\alpha$ peaks and $(220)_\gamma$ and $(311)_\gamma$ peaks were used for this XRD method. For the TEM observation, specimens were mechanically polished to a thickness of 50 μm, punched to prepare disk specimens (diameter: 3 mm) by a disk cutter and then electro-polished by a twin-jet polisher (model; Tenupol-5, Struers, Denmark) in a solution of CH_3COOH (90%) and $HClO_4$ (10%) to prepare thin foil specimens. The thin foils were observed in a TEM (model 2100, JEOL, Japan) operated at an acceleration voltage of 200 kV. EBSD analysis (step size, 50 nm) was conducted by a field emission scanning electron microscope (FE-SEM, Quanta 3D FEG, FEI Company, USA). The data were then interpreted by orientation imaging microscopy (OIM) analysis software provided by TexSEM Laboratories, Inc. Electron probe microanalysis (EPMA) measurements employing wavelength-dispersive spectrometry (WDS) were also performed by an EPMA microprobe (model; JXA 8530F microprobe, JEOL, Japan) at an electron beam voltage of 15 keV. Since the precise measurement of C content was difficult by EPMA, the C content was measured by the XRD method using the following equation [28]:

$$\alpha_\gamma = 3.578 + 0.0330X_C + 0.0056X_{Al} + 0.00095X_{Mn} \quad (1)$$

where α_γ is austenite lattice parameter, in Å, and X_C, X_{Mn} and X_{Al} are concentrations of C, Mn and Al, respectively, in wt.%. The austenite lattice parameter (α_γ) was determined from a d-spacing of $(220)_\gamma$ position.

2.3. Tensile test

Plate-type tensile specimens having gage length of 25 mm, gage width of 6 mm and gage thickness of 1 mm were prepared in the longitudinal direction. They were