Journal of Iron and Steel Research, International 24 (2017) 737-742

Contents lists available at ScienceDirect

Journal of Iron and Steel Research, International

journal homepage: www.chinamet.cn

Microstructures and mechanical properties of ferrite-based lightweight steel with different compositions

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ARTICLE INFO

Key words:
Ferrite-based lightweight steel
Microstructure
Mechanical property
Transformation induced plasticity effect
κ-carbide

ABSTRACT

The microstructures and mechanical properties of ferrite-based lightweight steel with different compositions were investigated by tensile test, scanning electron microscopy (SEM), transmission electron microscopy (TEM), X-ray diffraction (XRD) and thermodynamic calculation (TC). It was shown that the ferrite-based lightweight steels with 5 wt. % or 8 wt. % Al were basically composed of ferrite, austenite and κ-carbide. As the annealing temperature increased, the content of the austenite in the steel gradually increased, while the κ-carbide gradually decomposed and finally disappeared. The mechanical properties of the steel with 5 wt. % Al and 2 wt. % Cr, composed of ferrite and Cr_7C_3 carbide at different annealing temperatures, were significantly inferior to those of others. The steel containing 5 wt. % Al, annealed at 820 ℃ for 50 s then rapidly cooled to 400 ℃ and held for 180 s, can obtain the best product of strength and elongation (PSE) of 31242 MPa · %. The austenite stability of the steel is better, and its PSE is higher. In addition, the steel with higher PSE has a more stable instantaneous strain hardening exponent (n value), which is mainly caused by the effect of transformation induced plasticity (TRIP). When the κ-carbide or Cr_7C_3 carbide existed in the microstructure of the steel, there was an obvious yield plateau in the tensile curve, while its PSE decreased significantly.

1. Introduction

The development of lightweight steel is mainly driven by the strong need in the automotive industry because the weight reduction of transport vehicles leads to the improvement of fuel efficiency and the reduction of CO_2 exhaust. Recently, ferrite-based lightweight steel with Mn content less than 10 wt. % and Al content more than 5 wt. % has been noted. Increase in Al content, for example to 6 wt. %, could possibly lead to a reduction of 10 wt. % in automotive components. Compared with conventional high strength steel, Fe-C-Mn-Al ferrite-based lightweight steels have excellent combinations of specific strength and ductility. Frommeyer and Brüx[1] found that the ferrite-based lightweight steel can obtain excellent properties, such as a strength of over 780 MPa and an elongation of over 30%, resulting from transformation induced plasticity (TRIP) effect. However, Sohn et al.[2] pointed out that in ferrite-based lightweight steel, higher Al content would cause more formation of κ-carbide and worse mechanical properties. It was noted that in medium manganese lightweight steel, another lightweight element Cr is a strong carbide-forming element, which will promote the formation of chromium carbide, reduce the amount of κ-carbide in the steel and have benefits to mechanical properties of steels[3].

Based on the above-mentioned results, in this work, ferrite-based lightweight steel with different contents of Al and Cr were investigated by tensile test, scanning electron microscopy (SEM), transmission electron microscopy (TEM), X-ray diffraction (XRD), in-situ analysis and thermodynamic calculation (TC), aiming to study the interaction among alloying elements, microstructures, mechanical properties, and heat treatments for ferrite-based lightweight steel, and to provide theoretical reference for the research

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Received 3 October 2016; Received in revised form 26 November 2016; Accepted 27 November 2016
Available online 15 July 2017

and development of high-performance ferrite-based lightweight steel.

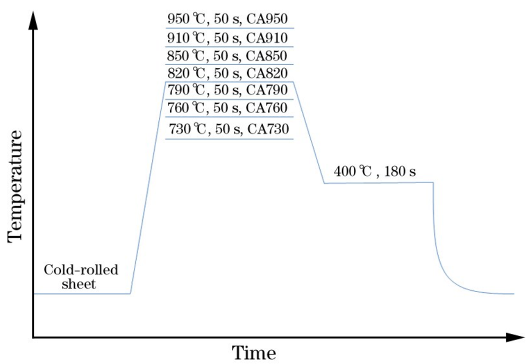
2. Experimental

The chemical compositions of experimental steels are listed in Table 1.

Table 1
Chemical compositions of investigated steels (wt. %)

Specimen	C	Mn	Al	Cr	Fe
1	0.24	3.57	4.99	—	Balance
2	0.28	3.67	7.70	—	Balance
3	0.24	3.46	5.17	2.08	Balance

Three 150 kg ingots with the designed composition were produced in a vacuum induction furnace filled with argon, hot rolled to 3.5 mm, and subsequently cold rolled to 1.2 mm. The investigated steels were continuously annealed in a salt bath furnace, and corresponding heat treatment processes are shown in Fig. 1.



CA—Continuous annealing.

Fig. 1. Schematic diagram of heat treatment processes.

The steel specimens were polished and etched in a 4 vol. % nital solution, and the microstructures were observed using an optical microscope (Nikon MA100) and scanning electron microscope (Hitachi S-570). A D/MAX-2500 X-ray diffractometer (CuKα radiation, scan rate 2(°)/min, scan step size 0.02°) operating at 40 kV and 40 mA was used to determine the type of phases.

The carbon content was measured by XRD using the following equation[4].

$$\alpha_{\gamma}=0.3578+0.0033X_{C}+0.00056X_{Al}+0.000095X_{Mn} \quad (1)$$

where, α_{γ} is the austenite lattice parameter, nm; and X_{C}, X_{Mn}, and X_{Al} are the concentrations of carbon, manganese, and aluminum, respectively, wt. %.

The microstructure and phase composition were analyzed with a transmission electron microscope (JEM-2010F) operated at an acceleration voltage of 200 kV. Thin foils for TEM observation were sliced from bulk specimens and ground to around 50 μm discs with diameters of 3 mm. Electropolishing was conducted using 5 vol. % perchloric acid in ethanol at −30 ℃ in a twin jet electropolisher, with the electrical potential set at 40 V.

Carbide particles in Steel 3 were chemically extracted in phosphoric acid (2 : 1)[5] at room temperature and filtered using a micro-porous membrane with 20 nm aperture and dried. The dried powder was analyzed by XRD with accelerating voltage of 40 kV, current of 40 mA, scanning range of 40°−90°, and scan rate of 4 (°)/min. Tensile samples were designed according to the standard of GB/T228-2010, with a gauge length of 30 mm. The tensile test was operated on a WANCE ETM504C tester at room temperature and a strain rate of $1\times10^{-3}\ s^{-1}$.

The change of the volume fraction of retained austenite (VF-RA) as a function of tensile strain was measured using an X-ray stress apparatus (X-350) aided by a micro-electronic universal testing machine. Tensile specimens in flat dog-bone shape with gauge length of 30 mm and gauge width of 1.2 mm were stretched with crosshead speed of 0.5 mm/min by using a micro-electronic universal testing machine, and VF-RA in the tensile zone of the specimen was measured with intervals of a certain strain by X-ray stress apparatus to observe the change of VF-RA during tensile testing.

3. Results

3.1. Microstructure

Fig. 2 shows the SEM micrographs of the three steels after different heat treatment processes. It is found that the sunken and dark gray structure is ferrite and the bright grey relief structure is austenite and carbide. Combined with the result of XRD analysis (Fig. 3), the microstructure of Steel 1 is composed of ferrite, austenite and κ-carbide when the annealing temperature is lower than 760 ℃. As the annealing temperature increases, the κ-carbides dissolve, even disappear at 790 ℃. The microstructure of Steel 2 is composed of ferrite and κ-carbide when the annealing temperature is lower than 820 ℃. When the annealing temperature exceeds 820 ℃, austenite forms and κ-carbide dissolves. When the temperature increases to 910 ℃, the steel is composed of ferrite and austenite. The microstructure of Steel 3 is composed of ferrite and Cr_7C_3 carbide when the annealing temperature is lower than 820 ℃.

3.2. Mechanical properties

The stress-strain curves and comparison of mechanical properties of three steels are presented in Figs. 4 and 5, respectively. For Steel 1, there is a yield plateau observed on the curve for the sample heat treated after annealed below 790 ℃. As the an-