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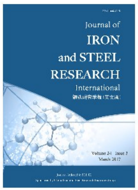

Effects of Mn and Cr contents on microstructures and mechanical properties of low temperature bainitic steel

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ABSTRACT

The effects of Mn and Cr contents on bainitic transformation kinetics, microstructures and mechanical properties of high-carbon low alloy steels after austempered at 230, 300 and 350 ℃ were determined by dilatometry, optical microscopy, scanning electron microscopy, X-ray diffraction and tensile tests. The results showed that Mn and Cr can extend bainitic incubation period and completion time, and with the increase of Mn and Cr content, the bainitic ferrite plate thickness decreased and the volume fraction of retained austenite increased. TRIP (transformation induced plasticity) effect was observed during tensile testing which improved the overall mechanical property. The increase of Mn concentration can improve the strength to a certain extent, but reduce the ductility. The increase of Cr concentration can improve the ductility of bainitic steels which transformed at a low temperature. The low temperature bainitic steel austempered at 230 ℃ exhibited excellent mechanical properties with ultimate tensile strength of (2146±11) MPa and total elongation of (12.95±0.15) %.

1. Introduction

In recent decades, in order to improve vehicle safety, realize automotive light weighting, reduce fuel consumption, increase fuel efficiency and decrease emission, the development and application of high strength steels and ultra-high strength steels have become a trend of modern automobile. In 2002, Caballero et al. [1] obtained the nano-structured bainite in high-carbon silicon-rich alloy steel with a remarkable ultimate tensile strength in excess of 2.3 GPa and a toughness of 30 MPa · $m^{1/2}$ via isothermal transformation at low temperatures. The excellent combination of mechanical properties is attributed to the fine-scaled carbide-free bainitic plates (20—40 nm) and uniform dispersion of austenite between the plates.

Developing nano-structured microstructure needs a larger undercooling and longer isothermal holding time, for instance, it takes at least 72 h to complete bainitic transformation within the temperature range of 200—300 ℃[2-5]. Therefore, the slow rate of bainitic transformation limits its development in a commercial point of view. In order to reduce the duration of isothermal transformation, the selection of rational alloy elements has been conducted to accelerate bainitic reaction. The addition of Al and/or Co can increase the chemical driving force for the transformation of austenite into ferrite; thus, the transformation can be easily accelerated[6,7]. The investigation of Huang et al. [8] showed that reducing the concentration of Mn has a much greater effect than increasing Co in terms of accelerating the bainitic reaction which can bring significant cost reduction. Goulas et al. [9] studied the effect of chemical inhomogeneity on the isothermal bainitic formation, which has shown that the growth of bainite in the high Mn and Cr concentration regions were retarded.

In this research, a novel composition of high-carbon low alloy steel has been designed, only comprising C, Si, Mn, Al and Cr, and the effects of Mn and Cr on the bainitic transformation rate, microstructures and mechanical properties were investigated.

2. Material and Methods

Three steels have been used for this work, and their chemical compositions are listed in Table 1. The addition of Al and Si in much higher quantities can

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

No.	C	Si	Mn	Cr	Al	Fe
N1	0.83	2.44	0.43	—	0.73	Balance
N2	0.83	2.54	1.01	—	0.89	Balance
N3	0.81	2.48	0.98	1.04	0.91	Balance

avoid cementite precipitation from austenite so as to form carbide-free bainite during bainitic reaction. The steels were produced as 50 kg ingots, forged to a diameter of 40 mm and then homogenized at 1200 ℃ for 24 h. Samples were firstly austenized at 950 ℃ for 30 min, subsequently treated at 230, 300 and 350 ℃ for various isothermal time to achieve a completely bainitic microstructure in salt bath furnace, respectively, and finally quenched to room temperature. The different holding time was based on the results of thermal simulation testing with cylindrical samples (ϕ4 mm×10 mm) using a DIL 805A dilatometer.

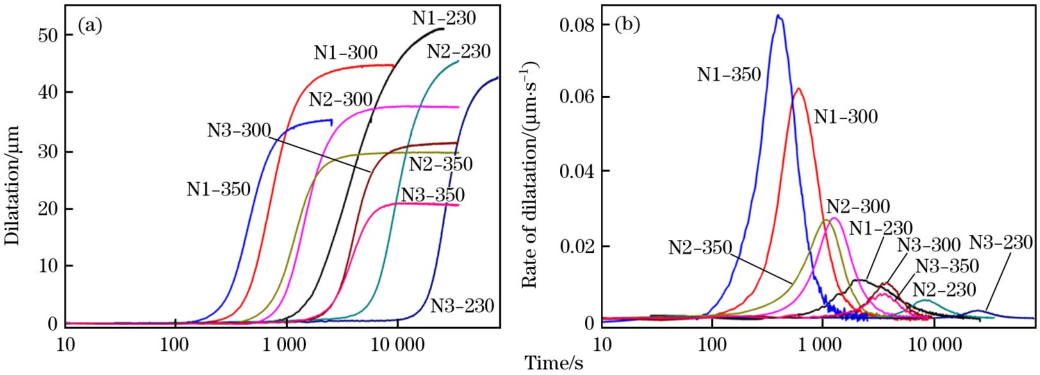
Tensile tests were carried out on a MTS 810 tensile testing machine at room temperature according to Chinese standard GB/T228-2002. The specimens were 12 mm in diameter and 25 mm in gauge length. The cross-head speed was 1 mm · min^{-1}. The engineering stress-strain curves measured during uniaxial tensile tests were converted into the true stress-strain curve, and strain hardening was characterized by the work hardening index that was calculated from the true stress-strain curve.

The microstructure morphology and phase distribution were characterized with a ZEISS AX10 optical microscope (OM) and ZEISS ULTRA 55-type field emission scanning electron microscope (SEM). Metallographic samples for OM and SEM were ground, mechanically polished and etched with 2 vol.% nital. The determination of phase components and relative volume fraction change of retained austenite before and after tensile test were achieved by X-ray diffraction (XRD) analysis using Cu-Kα radiation with a voltage of 40 kV and a current of 150 mA. The hardness of the samples was measured by a Rockwell hardness tester.

3. Results and Discussion

3.1. Bainitic transformation kinetics

Fig. 1 presents the phase transformation kinetic of tested steels under the influence of isothermal treatment at different temperatures. Fig. 1(b) displays the corresponding transformation rate of Fig. 1(a). The time at which 1%−3% and 95%−98% volume fraction of bainite is generated is considered as the start and completion time of isothermal bainitic transformation, and the relative results at different temperatures are listed in Table 2. It can be seen that lower transformation temperature and higher concentration of Mn (N2 steel) and Cr (N3 steel) are accompanied by longer transformation incubation time and lower transformation rate, and the bainitic transformations are retarded. As the concentration of Mn increases, the bainite start time of N2 steel is nearly twice as much as the bainite terminal time of N1 steel. With further increasing the Cr content, the time needed for bainite start transformation of N3 steel is almost the same as the bainite terminal time of N1 steel. The transformation rate rapidly decreases with the increase of Mn and Cr contents, and the maximum transformation rate of N1 steel austempered at 230 ℃ is



(a) Dilatation-time curves; (b) Transformation rate.

Fig. 1. Transformation kinetic of tested steels under influence of isothermal treatment at different temperatures.

Table 2
Bainitic transformation time and maximum transformation rate

No.	Temperature/℃	t_s/s	t_f/s	ε_{max}/(μm · s^{-1})
N1	230	1180	14428	0.010
	300	313	1954	0.062
	350	194	1069	0.082
N2	230	3816	24444	0.005
	300	732	3816	0.027
	350	495	2916	0.027
N3	230	13607	46656	0.002
	300	1800	8496	0.010
	350	1439	6156	0.007

Note: t_s, t_f and ε_{max} stand for start time, completion time and maximum rate of bainitic transformation, respectively.

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