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Effects of Nb on microstructure and continuous cooling transformation of coarse grain heat-affected zone in 610 MPa class high-strength low-alloy structural steels

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ABSTRACT

Continuous cooling transformation diagrams of the coarse grain heat-affected zone and microstructure after continuous cooling were investigated for 610 MPa class high-strength low-alloy (HSLA) structural steels with and without niobium. For the steel without Nb, grain boundary ferrite, degenerate pearlite and acicular ferrite are produced at slower cooling rates. Bainite phase is formed at faster cooling rates. However, for the steel with Nb, granular bainite is dominant at a large range of cooling rates. At cooling rates <32 K/s, transformation start temperature is decreased by 20 K approximately in the steel with Nb compared with that without Nb. Ferrite nucleation at prior austenite grain boundaries is suppressed and the cooling rate region for granular bainite transformation is broadened. At cooling rates >32 K/s, Nb addition has no obvious influence on transformation start temperature, but it influences microstructure transformation significantly. Martensite is observed in steel with Nb at faster cooling rates, but not produced in steel without Nb.

1. Introduction

High-strength low-alloy (HSLA) steels have been widely used to manufacture large engineering structures such as large oil tanks. In the manufacture of these tanks, welding methods with high heat input must be adopted. However, after such processing, impact toughness in the coarse-grain heat-affected zone (CGHAZ) could be deteriorated. In order to achieve good match of strength, toughness and weldability, steel chemistry and processing techniques have to be designed carefully.

Nb is thought to be an element that can raise the strength of HSLA steels by precipitation of second phase. However, there is still considerable disagreement as to the effect of Nb on toughness. Especially under welding condition, the effect of Nb on CGHAZ toughness relies heavily on heat input [1,2]. Generally, Nb addition could promote the formation of more low temperature transformation product, such as granular bainite, through decreasing the transformation start temperatures in the continuous cooling transformation (CCT) diagram [3–5]. But little is known on the effect of Nb on CGHAZ-CCT diagrams.

Through simulation of welding thermal cycles and observation of microstructures in the CGHAZ, the effect of Nb on continuous cooling transformation of CGHAZ in HSLA structural steels was investigated, and CGHAZ-CCT diagrams of the tested steels with and without Nb were determined.

2. Experimental procedure

The chemical compositions of investigated steels are given in Table 1. Steel plates were given a heat treatment of reheat quenching and tempering after controlled rolling. Cylindrical samples 6 mm in diameter × 55 mm were machined from the surface portion of 21.5 base steels, The CGHAZ simulations were carried out in a Gleeble-3800 thermo/mechanical simulator using the Rykalin-2D thermal cycle model [6]. The formula used for simulation is:

$$T = \frac{E/\delta}{2\sqrt{\pi\lambda c\rho t}} \exp\left(-\frac{r^2}{4\alpha t}\right)$$

where T is the temperature of the thermal cycle at time t, E is the heat input, δ is the plate thickness, λ is the thermal conductivity, c is the specific heat, ρ is the density of the steel, α is the thermal diffusivity and r is the vertical distance to from the welding heat source axes.

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Table 1
Composition of HSLA steels (wt. %)

No.	C	Si	Mn	S	P	Ni + Cr + Mo	V	Nb	Ti	N (ppm)
Steel A	0.073	0.21	1.34	0.0016	0.004	0.37	0.042	–	0.012	36
Steel B	0.074	0.23	1.41	0.0025	0.005	0.36	0.044	0.026	0.010	42

Table 2
Cooling time (CT) and mean cooling rate (CR) from 1623 K to 1073 K

Thermal cycle feature	Cooling rate from 1073 K to 773 K (K/s)									
	1	2	4	8	16	32	50	65	80	125
Heat input (kJ/cm)	155	110	78	55	39	27	22	17	14	9
CT from 1623 K to 1073 K (s)	134	67.5	34.6	16.9	8.4	4.2	2.8	3.5	2	1.1
CR from 1623 K to 1073 K (K/s)	4.1	8.1	15.9	32.6	65.3	131	202.2	159	273.6	509.3

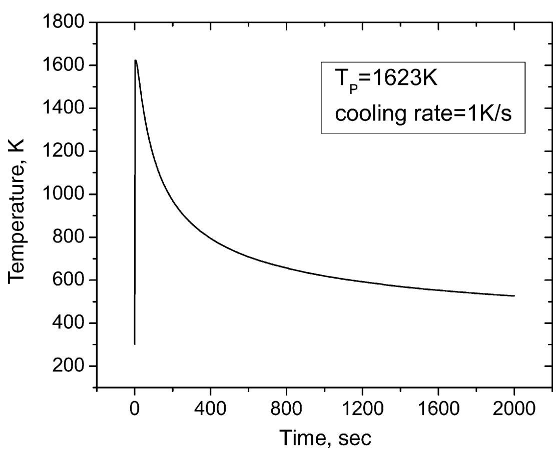

Fig. 1. Welding thermal cycle profile of the CGHAZ simulation at a cooling rate of 1 K/s.

A Pt-10% Rh thermocouple and a quartz dilatometer were used to record temperature and diametric strains, respectively. The specimens were uniformly heated at a rate of 500 K/s to peak temperature 1623 K and held for 2 s. The cooling course followed the Rykalin-2D heat flow equation. The cooling rates of simulated thermal cycles were determined by the cooling time from 1073 K to 773 K, and the range of cooling rate was from 1 K/s to 125 K/s. A typical CGHAZ thermal cycle is shown in Fig. 1.

Microstructure examinations were conducted by optical microscopy, scanning (SEM) and transmission electron microscopy (TEM). Cylindrical specimens were split in the vertical direction, and the sections were mechanically polished and etched with 2% Nital solutions, and then examined by optical microscopy and SEM. For TEM studies, samples were sliced from the center with 500 μm thickness and mechanically polished to 100 μm, and then electrically thinned by a twin-jet polished (GATAN) in an 8% perchloric acid + 92% acetic acid solution. Vickers hardness measurements were carried out using a tester under 5 kg load.

3. Results and discussion

The cooling time and cooling rate from peak temperature 1623 K to 1073 K and from 1073 K to 773 K and corresponding heat input are shown in Table 2. The cooling rate from 1623 K to 1073 K is significant as it influences the dwelling time of above austenite temperature, which determines grain growth [7]. On the other hand, the cooling rate from 1073 K to 773 K has been found to significantly influence the phase transformation temperatures, type of phase formed, and the morphology of the microstructures [8].

3.1. Microstructure

3.1.1. Steel A without Nb

The morphologies of the ferrite, pearlite, bainite and martensite in the CGHAZ vary with the changes of temperature and time in the cooling process. The morphologies and terminologies of these microstructures are still not clearly identified and defined [9,10].

For the steel A without niobium, microstructures of CGHAZ at slow cooling rate are identified as grain boundary ferrite (GBF), degenerate pearlite, and acicular ferrite as shown in Fig. 2. Grain boundary ferrite nucleated first on prior austenite grain boundary, and lengthened along the boundaries and thickened into the grain interiors to form equiaxed or near-equiaxed ferrite grains. Degenerate pearlite was normally formed between grain boundaries of GBF, the cementite existed in the form of small pieces or granular. Fig. 2(b and c) shows the morphology of degenerate pearlite at the cool-

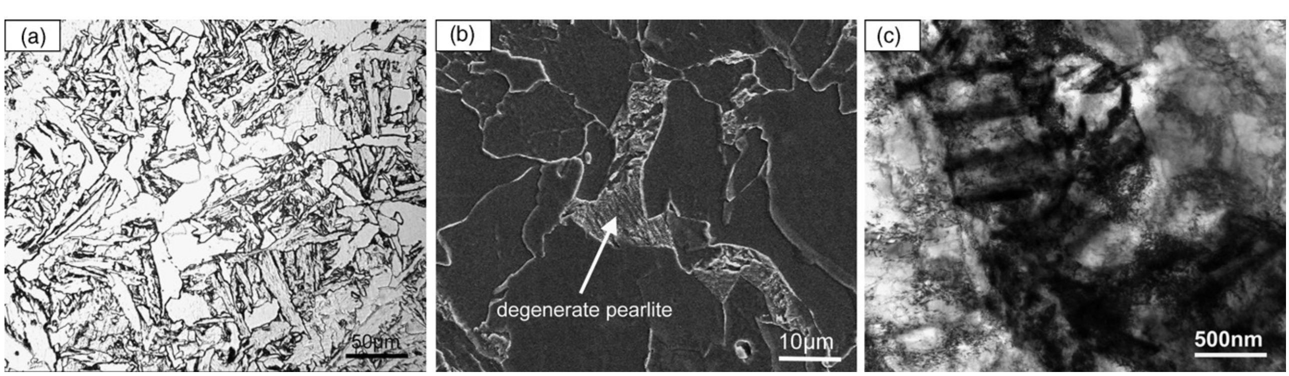

Fig. 2. Morphologies of grain boundary ferrite and degenerate pearlite of the steel A without Nb at a cooling rate of 1 K/s (a) optical micrograph, (b) SEM image indicating grain-boundary ferrite and degenerate pearlite, (c) magnified degenerate pearlite imaged by TEM.