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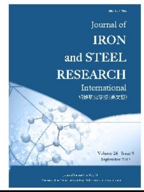

Effect of dissolved niobium on eutectoid transformation behavior

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ABSTRACT

The effect of dissolved niobium on the eutectoid transformation behavior in near-eutectoid high-carbon steels has been studied. Dissolved niobium is important in the eutectoid transformation behavior. It increases the eutectoid carbon content significantly (by ~0.0477% per 0.00001% dissolved niobium), increases the hardenability of steel markedly, yields finer, more uniform, polygonal proeutectoid ferrite, induces a transition in morphology of eutectoid cementite from lamellar to somewhat spheroidal, and increases the misorientation angle of pearlite colonies from being focused near 0° to near 60°.

1. Introduction

The effect of niobium (Nb) as a microalloying element in low-carbon steels, such as the ability to inhibit austenitic grain growth and retard recrystallization of deformed austenite, and the precipitation strengthening, has been researched and used successfully in the last half-century[1-5]. In medium- and high-carbon steels, the effect of Nb has not attracted extensive attention. According to the solubility product of NbC, the amount of dissolved Nb is too small to be of concern. Recent research work has shown that small amounts of dissolved Nb are important in terms of eutectoid transformation characteristics, because they influence the steel microstructure and mechanical properties significantly. The pearlite structure appears seldom in Nb-bearing low-carbon constructional steels but it is the main microstructure in medium- and high-carbon manufacturing steels, so the effect of Nb on eutectoid transformations is important. Medium- and high-carbon manufacturing steels have been used to produce machinery components, such as gears, shafts, springs, bearings, rails, and tools, which are applied extensively in machinery, automobiles, metallurgical engineering, chemical engineering, shipping, and the aviation industry[6-8]. Developments in the national economy of China from fundamental construction to manufacturing, especially at a high level, require the rapid development of manufacturing steels in the ensuing decades[9], and the effect of Nb in these steels must be determined.

Near-eutectoid steels were used to study the effect of dissolved Nb on the eutectoid transformation behavior and the morphology of the eutectoid transformation by means of time-temperature-transformation (TTT) curves, and an observation of the critical points of steels and the microstructure. The amount of dissolved Nb in steels was calculated theoretically to explain the role of Nb in high-carbon steel quantitatively.

2. Experimental Procedure

The chemical composition of the experimental steels is listed in Table 1. To avoid the influences of other alloying elements, experimental steels with a near-eutectoid C content were used and these did not contain other alloying elements except for C and Nb. Steel C contains no Nb, whereas Steels A and B contain 0.040 mass% and 0.064 mass% Nb, respectively. The steels were melted in a 25 kg vacuum induction furnace; the ingots were forged to 40 mm bars (heating temperature of 1200 ℃, initial forging temperature of 1150 ℃, and final temperature higher than 900 ℃; air cooled to room temperature) and rolled to 11 mm bars (heating temperature of 1100－1150 ℃, initial rolling temperature of 1000－1050 ℃, and final temperature of ~710 ℃; air cooled to room

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Table 1
Chemical composition of experimental steels at cast state (mass%)

Steel	C	Nb	S	N	Si	P	Mn	Fe
A (0.040Nb)	0.75	0.040	0.0052	0.0019	0.057	0.0076	<0.1	Balance
B (0.064Nb)	0.78	0.064	0.0051	0.0011	0.030	0.0080	<0.1	Balance
C (Nb-free)	0.70	0	0.0061	0.0028	0.074	0.0074	<0.1	Balance

temperature). Some experimental bars have been annealed fully to observe the equilibrium microstructure, and the full annealing process is shown in Fig. 1.

The metallographic samples were etched with 2 vol. % nital solution. A metallographic microscope was used to study the microstructure, and SISC IAS V8.0 software was used to determine the volume fraction of the non-eutectoid structure. The microhardness of the non-eutectoid structure was tested with load of 49 N.

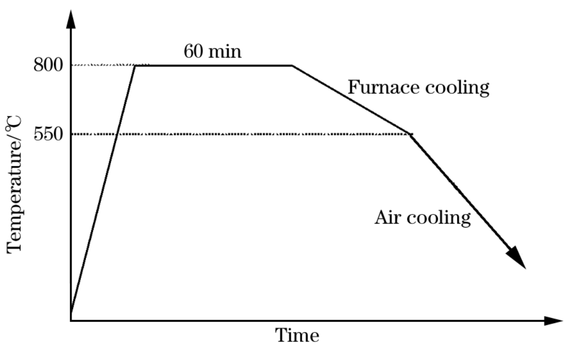

Fig. 1. Schematic of full annealing process.

The annealed bars were cut into column samples with sizes of 3 mm in diameter and 10 mm in height. Ultrasonic washing was used for degreasing. A Formastor-F II dilatometer was used to test the critical points of steels with a heating rate for the reheating transformation and a cooling rate for the cooling transformation at 200 ℃/h. For Steel C (no Nb) and Steel A (Nb content of 0.040 mass%), the equilibrium transformation curves have been tested with an austenization temperature of 800 ℃ and by holding for 5 min.

3. Results and Discussion

3.1. Theoretical calculation for Nb solubility

The equilibrium dissolved amounts of Nb (w_{Nb}^{e}) and C (w_{C}^{e}) for Nb-bearing steels can be calculated from the solubility-product equation by considering the influences of alloying elements, and the stoichiometric equations are as follows[5,7,10]:

$$\log(w_{Nb}^{e} \cdot w_{C}^{e})_{\gamma} = 3.555 - 8800/T + (1320/T - 0.044)w_{C} \quad (1)$$

$$\frac{w_{Nb} - w_{Nb}^{e}}{w_{C} - w_{C}^{e}} = \frac{92.9064}{12.011} = 7.7351 \quad (2)$$

where, w_{Nb} and w_{C} are the Nb and C contents in steel, respectively, mass%; $(w_{Nb}^{e} \cdot w_{C}^{e})$ is the Nb and C solubility in austenite, mass%; and T is the temperature, K.

For Steels A and B, Eq. (1) becomes $\log(w_{Nb}^{e} \cdot w_{C}^{e})_{\gamma} = 3.522 - 7810/T$ (C content of 0.75 mass%) and $\log(w_{Nb}^{e} \cdot w_{C}^{e})_{\gamma} = 3.521 - 7770/T$ (C content of 0.78 mass%), respectively.

At an annealing temperature of 800 ℃ (1073 K), the equilibrium-dissolved Nb quantity can be calculated from the above equations as 0.000235% or 0.000246%, and the mass fraction of undissolved NbC is 0.04502% or 0.07200% (fixed C quantity as 0.00514% or 0.00824%) for Steel A or B, respectively.

3.2. Proeutectoid ferrite quantity and influence of Nb on eutectoid C content

The metallographic photographs of the experimental steels are shown in Fig. 2, and the non-pearlite structure can be observed as white parts. The non-eutectoid structure was ferrite as determined by microhardness and X-ray analysis. The volume fractions of proeutectoid ferrite in an annealed state are 10.10 vol. %, 15.3 vol. %, and 12.6 vol. % for the three steels, respectively.

If the steel contains no alloying elements, the eutectoid C content would be 0.77%. Thus, the mass fraction of proeutectoid ferrite would be (0.77−0.70)/(0.70−0.0218)=9.36% for Steel C and (0.77−0.75)/(0.75−0.0218)=2.67% for Steel A, whereas some proeutectoid cementite rather than proeutectoid ferrite exists for Steel B. Because the experimental steels contain no other alloying elements except Nb, it can be supposed that the trace of dissolved Nb would affect the eutectoid C content. The calculated eutectoid C content was 0.8815% for Steel A and 0.8893% for Steel C. The calculated mass fraction of C that was fixed by undissolved NbC was 0.005% and 0.008% for Steels A and B, respectively, at 800 ℃. By deducting the fixed C, the calculated eutectoid C content was found to be 0.8810% for Steel A and 0.8885% for Steel C. The eutectoid C content increased 0.1110% or 0.1185% by dissolving 0.000235% or 0.000246% Nb in Steel B or C respectively, which is ~0.0477% per 0.00001% dissolved Nb. Thus, the trace of dissolved Nb increases the eutectoid C content significantly.