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Effects of High Magnetic Field on Ferrite Transformation Behavior and Structure

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Effect of a high magnetic field of 10 T on microstructure and kinetics of ferrite transformation in Fe-1.5Mn-0.1C-0.05Nb steel was investigated systematically using a vacuum electric furnace installed in a superconducting magnet. It was found that a magnetic field of 10 T stimulated ferrite transformation significantly. The rates of ferrite nucleation and growth with and without magnetic field were measured. It was found that a high magnetic field increased the nucleation rate of ferrite, and increased the thickening parabolic rate constant above a certain temperature between 973 K and 993 K, but decreased below this temperature. The possible mechanism was discussed.

Key words: high magnetic field, Fe-1.5Mn-0.1C-0.05Nb, ferrite transformation, nucleation rate, grain growth rate

1. INTRODUCTION

There are many studies showing that an external magnetic field can affect martensitic transformation in ferrous alloys and steels[1-4]. However, there are few studies on the effect of a magnetic field on diffusional transformations, such as, ferrite and pearlite transformations. Peters et al. studied the effect of magnetic field on ferrite transformation in Fe-Co alloys and reported that a magnetic field stimulated the ferrite transformation[5]. Enomoto studied the effect of a magnetic field of 7.5T on ferrite transformation in Fe-C and Fe-C-X alloys, and reported that the magnetic field increases Ae_3 temperature and stimulates ferrite transformation[6]. But the effect of a high magnetic field on ferrite transformation, especially on the kinetics of ferrite transformation is not reported in details. The purpose of this paper is to show the effect of a high magnetic field on ferrite transformation, especially on the kinetics of ferrite transformation in detail.

2. EXPERIMENT PROCEDURE

A low carbon alloy having a chemical composition of Fe-1.5%Mn-0.1%C-0.05%Nb (mass%) was investigated. The alloy was vacuum-melted, hot rolled and finally cold rolled to a thickness of 0.4 mm. Then $4.5\times4.5\times0.4$ mm^3 specimens were cut, and the heat treatment was carried out in a vacuum electric furnace installed in a superconducting magnet. The specimen was fixed on a ceramics holder and a thermocouple was set to get in touch with the surface of specimen in order to measuring the specimen's temperature more accurately. The specimens were austenitized at 1373 K or 1423 K for 0.9 ks in vacuum then rapidly cooled by a flow of helium gas to several temperatures from 923 K to 993 K for isothermal reaction, finally cooled to room temperature by a flow of helium gas again. The microstructure was observed on both longitudinal and transverse section of specimens. The area of transformed ferrite grains and total number of ferrite grains were measured. The determination of the thickening kinetics of grain boundary allotriomorphs was carried out by a method developed by Bradley and Aronson et al.[7,8]. That is, the largest half-thickness of grain boundary-nucleated ferrite in each specimen was determined and plotted vs the square root of the reaction to obtain the parabolic rate constants for thickening.

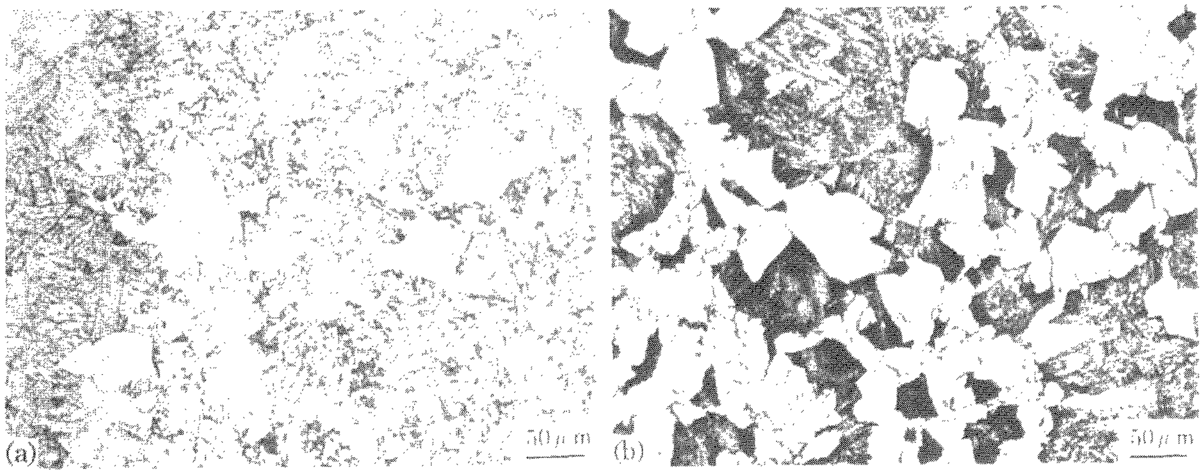

Fig. 1 Optical micrographs showing the isothermally transformed microstructure at 953 K for 0.6 ks: (a) without a magnetic field, and (b) with a magnetic field of 10 T.

3. RESULTS AND DISCUSSION

3.1 The effect of magnetic field on microstructure

The microstructure of the specimens austenited at 1423 K for 0.9 ks followed by a rapidly cooling to room temperature by a flow of helium gas with and without magnetic field was examined. A completely transformed lath martensite and bainite morphology was observed for both of the specimens heat treated with and without magnetic field. The average grain size of austenite was measured as 87.2 μ m in the specimens austenited without magnetic field, and 75.1 μ m in the specimens austenited with a magnetic field of 10T . This result indicates that a magnetic field retards the grain growth of austenite, which is consistent with our previous results in Fe-3%Si steels[9,10].

Figure 1 is the optical micrographs showing the structures after austenizing at 1423 K for 0.9 ks then transformed at 953 K for 0.3 ks without magnetic field (a) and with a magnetic field of 10T (b), respectively. The bright regions are equiaxed ferrite grains formed mainly at grain boundaries and the dark regions are lath martensite and bainite formed during cooling to room temperature. Figure 2 shows the measured results of the transformed fraction for the specimens austenited at 1373 K for 0.9 ks then isothermally transformed at 997 K. The ferrite transformation began within a very short holding time and progressed quickly for specimens heat treated with a magnetic field. These results indicate that a magnetic field of 10 T stimulates ferrite transformation significantly.

The effect of a magnetic field on the change of Gibbs free energy was considered by Chen et al.[11] as follows.

$$dG=-SdT+VdP-MdH$$

Where G is the Gibbs free energy, S is the entropy, T is the temperature, V is the volume, P is the pressure, M is the intensity of magnetization and H is the strength of

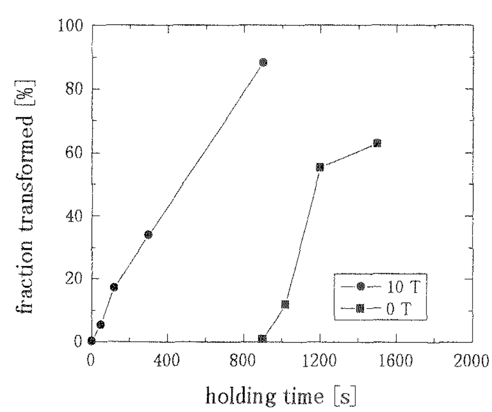

Fig. 2 Effect of a magnetic field of 10 T on the transformed fraction of ferrite at 993 K.

the external magnetic field. As M can be expressed by the spontaneous magnetization Mf and the permeability χ as

$$M= M_f + \chi H$$

the free energy caused by an external magnetic field G_H can be expressed as

$$G_H= -M_f H-(1/2)\chi H^2$$

Choi et al.[12] calculated phase diagram changes of Fe-C binary system as a function of magnetic field strength basically according to the above consideration, and concluded that the Ae_3 temperature increases with the applied magnetic field strength. Thus the stimulation effect of a magnetic field on ferrite transformation can be interpreted by a thermodynamic consideration.

3.2 The effect of magnetic field on ferrite nucleation rate

Figures 3 shows the effect of magnetic field on total number of ferrite grains for the specimens austenited at 1423 K for 0.9 ks then isothermally transformed at 993 K. The total area for measuring the number of ferrite grains was 2.08mm^2 in each specimen. It was found that a magnetic field stimulated the formation of ferrite grain significantly.

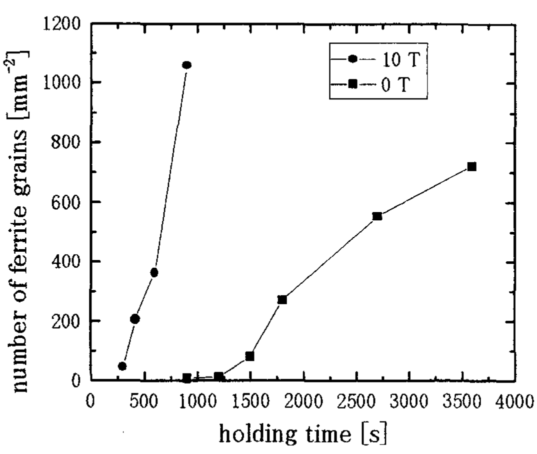

Fig. 3 Effect of a magnetic field of 10 T on the number of ferrite grains transformed at 993 K.

The rate of nucleation of grain boundary ferrite is properly expressed in terms of N_s, the number of ferrite nuclei formed per second per unit area of unreacted grain boundary, which can be evaluated from the following relationship[13].

$$N_s= 1/u(t) \cdot dn_v/dt \cdot 1/S_r$$

Where u(t) is the fraction of the austenite untransformed at a given time and S_r the austenite grain boundary area per unit volume. N_v is the nunber of nuclei per volume. According to microstructure observation, the ferrite was always grain boundary-nucleated at initial transformed stage. So the ferrite nucleation rate N_s can be assessed using the measured results at initial transformed stage. The calculation results of N_s for different holding time at 993 K with and without a magnetic field show that N_s increases rapidly with time in the specimens heat treated with a magnetic field of 10 T.

3.3 Effect of magnetic field on growth kinetics of ferrite grain

The largest half-thickness as a function of the square root of the reaction time for specimens isothermally transformed with and without magnetic field was determined. The thickening parabolic rate constant α was determined from the slope of least squares lines through these plots. Figure 4 shows the measured parabolic rate constants for thickening as a function of reaction temperature for the specimens transformed with

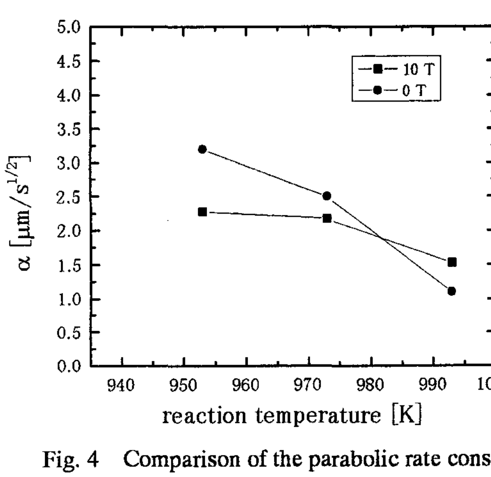

Fig. 4 Comparison of the parabolic rate constant α, with and without a magnetic field, as a function of reaction time.

and without magnetic field. The α of both specimens transformed with a magnetic field and without magnetic field is seen to increase with decreasing transformation temperature. The α of specimens transformed at 993 K without magnetic field was lower than the α of the specimens transformed with a magnetic field, but increased faster with decreasing temperature and became higher than the α of the specimens transformed with 10 T at a temperature between 973 K and 993 K.

In order to interpret the effect of magnetic field on thickening parabolic rate constant, we now consider the Zener model as shown below[14].

$$\alpha = D^{1/2}(C_\gamma - C_0)/[(C_\gamma - C_\alpha)^{1/2}(C_0 - C_\alpha)^{1/2}]$$
$$= D^{1/2} \cdot \mathbf{A}$$

Where D is the diffusivity of carbon in austenite. C_γ and C_α are the carbon concentrations in austenite at the austensite:ferrite boundary and in ferrite, respectively. C_0 is the bulk carbon content of the austenite prior to transformation. If we write

$$\mathbf{A} = (C_\gamma - C_0)/[(C_\gamma - C_\alpha)^{1/2}(C_0 - C_\alpha)^{1/2}],$$

then the thickening parabolic rate constant is given by two factors, D and A. We evaluated the ratio of **A** at 10 T and 0 T ($\mathbf{A}_{10T}/\mathbf{A}_{0T}$) as a function of transformation temperature in Fe-0.1%C steel. It is found that this ratio is larger than 1.25 within a wide temperature range from 1040 K to about 1200K, which indicates that a magnetic field increases the factor **A** in Fe-0.1C steel. Thus, it is considered that the factor **A** is also increased by a magnetic field in Fe-1.5Mn-0.1C-0.05Nb. On the other hand, Iijima et al.[15] studied the self-diffusion and isotope effect in α-iron and reported that the self-diffusion coefficient in α-iron decreases with the increase of the magnetization parameter s. Thus, it seems that the diffusivity of carbon may be also suppressed by a magnetic field, and this suppression effect should be obvious with decreasing temperature since the value of s increases rapidly with decreasing temperature[16]. Thus, if the factor **A** is increased and the diffusivity D is decreased by an applied magnetic field, it is considered that the thickening parabolic rate constant is increased above a certain temperature and is decreased below this temperature by a magnetic field.

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