Quantitative Characterization of the Structural Alignment in Fe–0.4C Alloy Transformed in High Magnetic Field

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Structural alignment in Fe–0.4C alloy transformed in high magnetic field has been evaluated by quantitative microscopy analysis. An aligned two-phase structure is formed in high magnetic field by austenite to ferrite transformation during slow cooling. Ferrite grains are elongated and connected with each other along the direction of magnetic field. The degree of alignment can be evaluated by measuring the number of intersections between test lines and ferrite/austenite phase boundaries. Results of measurement show that the degree of alignment increases continuously with increasing magnetic field strength up to 10 Tesla.

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1. Introduction

It has been expected that external high magnetic field affects solid/solid phase transformation behaviors and transformed structures, and possibly improves the mechanical and magnetic properties of materials. In fact, the structural alignment in solid/solid transformations in high magnetic field has been reported for spinodal decomposition, martensitic transformation and reverse transformation from lath martensite to austenite. Moreover, thermodynamic calculation on equilibrium phase diagram of Fe–C binary system proposed that a high magnetic field increases the austenite/γ equilibrium temperature, eutectoid carbon content and carbon solubility in α phase. Recently, the effects of high magnetic field on phase transformation behaviors and microstructures have been extensively studied by our group, and we showed that the reaction of proeutectoid ferrite transformation in Fe–C based alloys was accelerated by a high magnetic field, which was mainly due to the increase in the nucleation rate of ferrite. Also, one of the authors, Ohtsuka et al. reported for the first time that α grains are aligned during γ → α transformation in high magnetic field without hot-rolling although Maruta and Shimotomai reported that a prior hot-rolling in γ region is essential to yield the aligned microstructure for γ → α transformation. In order to make clear the effects of factors on the structural alignment, it is important to quantitatively evaluate the degree of alignment of the obtained microstructures. In this paper, a method of quantitative characterization of the degree of structural alignment was introduced for the transformed structure of Fe–0.4C alloy. Moreover, the effect of magnetic field strength on the degree of structural alignment was investigated in γ → α transformation.

2. Experimental Procedure

The alloy used in the present study was Fe–0.4C alloy prepared by vacuum induction melting and its chemical compositions were Fe–0.41C–0.08Si–0.003Al (mass%). The Ae₃ temperature of this alloy was calculated by ThermoCalc to be about 785 °C. After hot rolling and homogenization specimens were machined to 5 mm × 5 mm × 1 mm, and heat treated in a vacuum furnace installed in a helium-free type superconducting magnet, of which bore size is φ100 mm. Magnetic field was applied perpendicular to the 5 mm × 5 mm surface. During heat treatment, specimens were fixed at the center of magnetic field and magnetic force heat treated in a vacuum furnace installed in a helium-free type superconducting magnet. Without magnetic field, the transformed microstructure was etched by 3% Nital and observed by optical microscope.

3. Results and Discussion

3.1 Evaluation of the degree of alignment

Figure 1 shows the micrographs of specimens transformed without magnetic field (Fig. 1(a)) and with a magnetic field of 10 Tesla (Fig. 1(b)). The specimens were austenitized at 950°C for 15 min and continuously cooled from 850°C to 700°C at a cooling rate of 0.1°C/min without (a) or with magnetic field of 10 T (b). Test lines forming an angle with the direction of magnetic field are applied to the micrograph to measure the degree of alignment by counting the number of intersections between test lines and ferrite/austenite boundary (black line) and ferrite/austenite boundary (black line).

Fig. 1 Microstructure of Fe–0.4C alloy. Specimens were austenitized at 950°C for 15 min and continuously cooled from 850°C to 700°C at a cooling rate of 0.1°C/min without (a) or with magnetic field of 10 T (b).
950°C for 15 min and rapidly cooled to 850°C and then slowly cooled to 700°C at a cooling rate of 0.1°C/min, followed by quenching by He gas. The white grains are α precipitated from γ above eutectoid transformation temperature, and the black regions are pearlite transformed from γ below eutectoid temperature. Without magnetic field, most of α grains are equiaxed and distributed randomly with γ grains. With magnetic field, it was noted that the microstructure is changed notably. First, α grains are elongated along the direction of applied magnetic field. Second, α grains are distributed head to tail and connected with each other along the direction of applied magnetic field, forming a chain-like structure within γ matrix.

It is speculated that the degree of alignment was affected by γ grain size, undercooling and magnetic field strength. Therefore, it is necessary to quantitatively evaluate the degree of alignment for investigating the effects of these factors on the degree of alignment. First, a series of parallel lines in a round area forming a definite angle (θ) with the direction of magnetic field is drawn to the micrograph as shown in Fig. 1(a). The number of intersections between test lines and the α/α grain boundaries (Nα/α) is determined for this particular angle (shown ■ in Fig. 1(a)). At the same time, the number of intersections between test lines and α/γ boundaries (Nα/γ) is also determined (shown ○ in Fig. 1(a)). Then the parallel lines are drawn at another angle, and this process is repeated on Fig. 1. Figure 2 shows the results of this measurement. The angle was increased from 0° to 180° with a step of 30° for Fig. 2(a) (without magnetic field) and 10° for Fig. 2(b) (with magnetic field). For the specimen heat-treated without magnetic field, the intersection number N is almost constant with angle both for α/α grain boundary and α/γ phase boundary. For the specimen heat-treated in magnetic field, the intersection number Nα/α shows no significant change with θ. However, the intersection number Nα/γ changes dramatically depending on θ, it increases with increasing θ and reaches to the maximum value at around 90° and then decreases. In this figure, the total intersection number (Ntotal = Nα/α + Nα/γ) is also shown. Obviously, the degree of structural alignment should be evaluated by the intersection number Nα/γ. Figure 3 shows that the intersection number Nα/γ varies with angle θ in polar coordinates. It should be noted that the direction of applied magnetic field in Fig. 3 is vertical to that in Fig. 1. The length of the radius vector from the origin of coordinates is the value of Nα/γ for the corresponding direction of the test lines. Without magnetic field, the intersection numbers formed a round circle, and with magnetic field, the intersection numbers formed a curve, which is called rose-of-the-number-of-intersections. The degree of alignment ω can be calculated from the following equation:

$$\omega = \frac{N_\perp - N_\parallel}{N_\perp + 0.571N_\parallel}$$

in which N_\perp and N_\parallel are the intersection number (Nα/γ) when test lines are vertical or parallel to the direction of magnetic field, respectively. For the specimen transformed without magnetic field (Fig. 1(a)), the degree of alignment is 0%. For the specimen transformed with magnetic field (Fig. 1(b)), the degree of alignment is 52.9%.

3.2 Effects of magnetic field strength on the degree of alignment

Figure 4 shows the effect of magnetic field strength on the structural alignment. The specimens were austenitized at 1000°C for 15 min and quickly cooled to 850°C then slowly cooled to 750°C at a cooling rate 0.5°C/min, followed by
quenching by He gas. $\alpha$ grains precipitated from $\gamma$ during slow cooling and the untransformed $\gamma$ transformed to martensite during quenching. With a low magnetic field (0.5 T), most of $\alpha$ grains are equiaxed and the alignment is low (Fig. 4(a)). Increasing magnetic field to 1 T and 5 T (Fig. 4(b,c)), ferrite grains become elongated along the direction of magnetic field and the alignment becomes high. With a magnetic field of 10 T, well aligned structure is formed (Fig. 4(d)). However, which structure of Figs. 4(c) and (d) has the higher order of alignment is not so obvious. So, the method described in the previous section was used to measure the degree of alignment. The area for measurement is 0.11 mm$^2$ for each specimen. Figure 5 shows the degree of alignment $\omega$ as a function of magnetic field strength. It was found that the degree of alignment continuously increases with increasing magnetic field, however, the increasing rate becomes smaller at higher magnetic field. Increasing the magnetic field strength to 10 T (Fig. 4(d)), the degree of alignment reaches to 38.6%, which shows the higher degree of alignment than that of Fig. 4(c). The reason for $\alpha$ alignment is not clear by now. It is speculated that $\alpha$ grain elongated along the direction of magnetic field reduces the demagnetization field in $\alpha$ grains and therefore decreases the free energy of the system.

4. Conclusions

(1) Structural alignment in Fe–C alloys transformed in high magnetic field has been quantitatively evaluated.
(2) With increasing magnetic field strength up to 10 Tesla, the degree of structural alignment increased continuously.

REFERENCES