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Structural Control of Fe-Based Alloys through Phase Transformations in High Magnetic Field

Hideyuki Ohtsuka, Xinjiang Hao and Hitoshi Wada
National Institute for Materials Science, High Magnetic Field Research Center,
3-13 Sakura, Tsukuba, Ibaraki 305-0003, JAPAN
Fax: 81-29-863-5441, e-mail: ohtsuka.hideyuki@nims.go.jp

Effects of high magnetic field on austenite to ferrite transformation and lath martensite to austenite reverse transformation have been investigated in an Fe-based alloy. Elongation of transformed grains in high magnetic field is observed in both of these transformations. In the case of austenite to ferrite transformation, an Fe-0.4C alloy was slowly cooled under a magnetic field of 10T. Ferrite grains are elongated and aligned along the direction of applied magnetic field in this heat treatment. In the case of reverse transformation, an Fe-0.4C alloy with lath martensite single phase was heated under a magnetic field of 10T. Austenite grains and ferrite grains are also elongated and aligned along the direction of magnetic field. The conditions for the elongation of transformed phases are clarified.
Key words: alignment, elongation, ferrite, austenite, reverse-transformation

1. INTRODUCTION

Magnetic field is expected to affect the alignment of product phase and transformed structure during solid/solid phase transformations and then affect the mechanical properties of materials. Therefore it is expected that new properties may be developed in the material or even a new material can be produced by applying magnetic field during transformations. Therefore magnetic field processing is considered to be promising for structural or functional control of materials. Fe-based alloys are very hopeful for such structural or functional control of materials by magnetic field because Fe-based alloys have various kinds of solid/solid phase transformations and therefore various structures. It is expected that the nucleation and growth rates, transformation kinetics, transformed structure and variants are affected by magnetic field since the magnetic moment of parent and product phases are different in these transformations, and also due to the magnetocrystalline anisotropy, shape magnetic anisotropy, induced magnetic anisotropy and magnetostriction.

The importance of study of magnetic field effects on phase transformations is as follows. First, phase transformation can be investigated from a new viewpoint of "magnetic field", and it is expected that a new aspect of transformation can be explored and the mechanism of nucleation and growth can be clarified. For example, Kakeshita et al..[1] studied the effects of magnetic field on martensitic transformation systematically and proposed a model that can explain both the isothermal and non-isothermal martensitic transformation kinetics, and made important consideration of nucleation. Shibata et al.[2] studied the effects of magnetic field, pre-deformation and heat treatment on martensitic transformation, and considered the potential for nucleation. Second, functional control of materials are explored. One of the examples is the shape memory alloy that works by magnetic field[3,4,5]. It is necessary to study the effects of magnetic field on martensitic transformation for developing this type of shape memory alloys. Third, it is expected that a new type of structural control can be developed. For example, a new thermomechanical heat treatment can be established by applying both the magnetic field and thermomechanical heat treatment.

In this study, structural change of transformed phases in high magnetic field is discussed. The structural alignment in solid/solid transformations in high magnetic field has been reported for spinodal decomposition[6], martensitic transformation[7] and reverse transformation from lath martensite to austenite[8]. Moreover, thermodynamic calculation of the equilibrium phase diagram of Fe-C binary system proposed that a high magnetic field increases the austenite(γ)/ferrite(α) equilibrium temperature, eutectoid carbon content and carbon solubility in α phase[9]. Recently, the effects of high magnetic field on phase transformation behaviors and microstructures have been extensively studied by our group[10,11], and we showed that the proeutectoid ferrite transformation in Fe-C based alloys is accelerated by a high magnetic field, which is mainly due to the increase in the nucleation rate of ferrite[12,13]. Also, one of the authors, Ohtsuka et al.[14] reported for the first time that α grains are aligned during $\gamma \rightarrow \alpha$ transformation in high magnetic field. In order to clarify the effects of several factors on the structural elongation, it is important to quantitatively evaluate the degree of elongation of the resulting microstructures. In this paper, degree of structural elongation was quantitatively evaluated for the transformed structure of Fe-0.4C alloy.

2.EXPERIMENTAL

The alloy used in the present study was Fe-0.4C alloy prepared by vacuum induction melting and its chemical composition was Fe-0.41C-0.08Si-0.003Al (in mass%). The Ae3 temperature of this alloy was calculated by Thermo-Calc to be about 785 ℃. After hot rolling and homogenization specimens were machined to 5mm× 5mm ×1mm.

Specimens were heat treated in a vacuum furnace installed in a helium-free type superconducting magnet, of which bore size was ϕ 100mm. Magnetic field was applied perpendicular to the 5mm× 5mm surface. During the heat treatments, the specimens were fixed in the center of magnetic field, where the magnetic force on the specimens was negligible. In the following heat treatments, magnetic field was increased at a speed of 0.37 T/min and kept constant during the heat treatments. After the heat treatments, magnetic field was decreased to 0 at the same speed.

For $\gamma \rightarrow \alpha$ transformation, specimens were austenitized at 950℃ or 1000℃ for 15 min and cooled to 850℃ at a cooling rate of 50℃/min, then slowly cooled at cooling rates of 0.1~0.5℃/min in $\alpha+\gamma$ dual-phase region to produce ferrite grains, followed by rapid cooling down to room temperature by helium gas. Without magnetic field, the heat-treatment itself was the same as that in magnetic field.

For lath martensite to austenite reverse transformation, specimens were austenitized at 900 or 1150℃ for 15 min and water quenched. This heat treatment was conducted without magnetic field. The structure is lath martensite single phase by this heat treatment. In a magnetic field of 10T, the specimen of lath martensite structure was heated to 745 ℃, isothermally held for 20 min and then cooled to room temperature by helium gas. For the specimen heat treated without magnetic field, the same pattern of heat treatment was applied.

The transformed microstructure was etched by 3% Nital and observed by optical microscopy. The surface parallel to the direction of applied magnetic field was observed by optical microscopy, so the direction of applied magnetic field is vertical in the figures in this paper.

3. RESULTS AND DISCUSSION

3.1. Austenite to Ferrite Transformation

Figure 1 shows the effect of magnetic field strength on the structural alignment. The specimens were austenitized at 1000℃ for 15 min and quickly cooled to 850℃ then slowly cooled to 750℃ at a cooling rate 0.5℃/min, followed by quenching by helium gas. Applied magnetic fields were (a) 0.5T and (b)10T. The transformed structure for 0T is quite similar to that of (a). The white grains are α precipitated from γ above eutectoid transformation temperature, and the black regions are pearlite transformed from γ below eutectoid temperature. In Fig. 1(a), most of α grains are equiaxed and distributed homogeneously in the specimen. With a magnetic field of 10 T(Fig.1(b)), 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, and as a result, well aligned structure

(a)

(b)

100 μm

Fig.1 Optical micrographs showing the effects of magnetic field strength on the transformed structure in Fe-0.4C alloy. Specimens were austenitized at 1000℃ for 15 min and continuously cooled from 850℃ to 750℃ at a cooling rate of 0.5 ℃/min in magnetic fields of (a) 0.5T and (b) 10T.

is formed. Recently Shimotomai et al.[15] showed that a prior hot-rolling in γ region is essential to yield the aligned microstructure for $\gamma \rightarrow \alpha$ transformation, but as is shown here, aligned structure is obtained without any pre-deformation. In order to show the effect of magnetic field strength on the degree of elongation of α grains quantitatively, the degree of alignment ω can be calculated from the following equation[16].

$$\omega=(N1-N2)/(N1+0.571\,N2)$$

Here N1 and N2 are the intersection number of ferrite/austenite boundary and test lines which are vertical or parallel to the direction of magnetic field, respectively. For the specimen transformed with magnetic field of 0.5T (Fig. 1(a)), the degree of alignment is about 10% and for the specimen transformed with magnetic field of 10T(Fig. 1(b)), the degree of alignment is about 40%. Figure 2 shows the degree of alignment ω as a function of magnetic field strength. It is found that the degree of alignment monotonously increases with increasing magnetic field, however, the rate of increase becomes smaller at higher magnetic field.

Effects of austenite grain size and cooling rate on the degree of alignment were investigated. Here, the degree of alignment was evaluated by measuring the ratio of the number of intersections between ferrite/austenite boundary and the lines perpendicular to

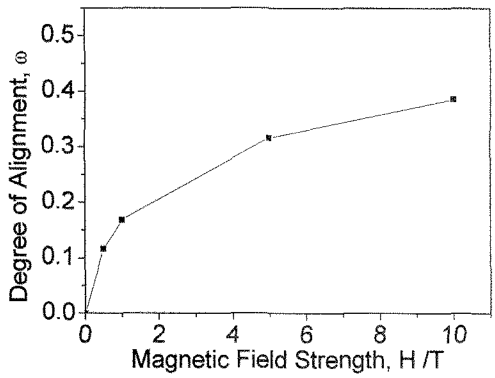
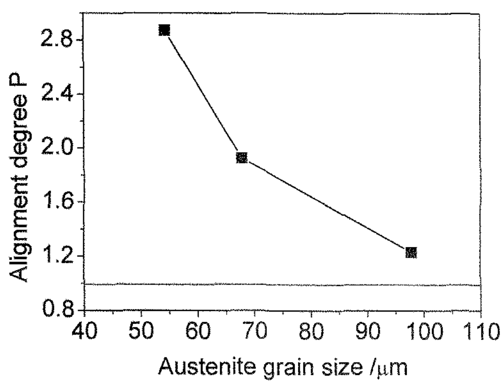
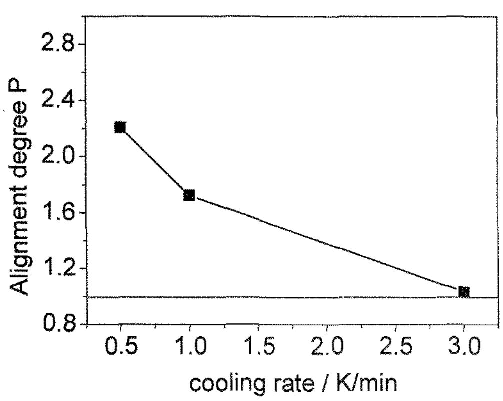


Fig.2 Effects of magnetic field strength on the degree of alignment of ferrite grains.



(a)



(b)

Fig.3 Effects of austenite grain size and cooling rate on the degree of alignment.

the direction of magnetic field to that between ferrite/austenite boundary and the lines parallel to the direction of magnetic field. Figure 3 shows the results which were measured in a picture of about 500X500 μ m for each specimen. Figure 3(a) shows the effect of austenite grain size on the degree of alignment P, which

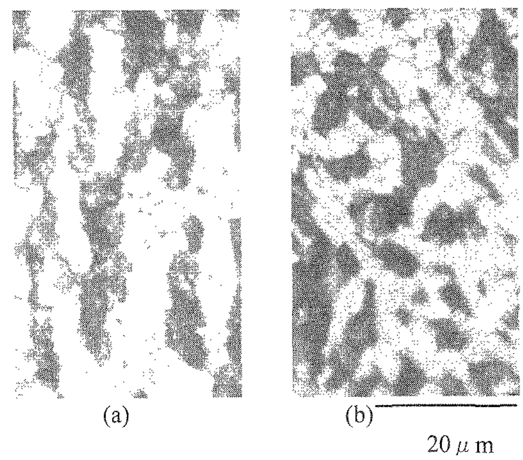


Fig. 4 Effects of magnetic field on reverse-transformed stucture. Specimens were austenitized at 900℃ for 15 min and quenched to room temperature to form lath martensite without magnetic field, and then isothermally held at 745℃ for 20 min in magnetic fields of (a) 10T and (b) 0.5T.

is defined by N2/N1. The values of ω and P are different, but the dependence of these values on the grain size and cooling rate is similar. The alignment degree P decreases with increasing austenite grain size, that is, well elongated and aligned structure is obtained for a small austenite grain. Figure 3(b) shows the effect of cooling rate on the degree of alignment in a magnetic field of 10T, which decreases with increasing cooling rate, that is, well elongated and aligned structure is obtained for slow cooling rate. The degree of alignment is affected by not only magnetic field strength but γ grain size and cooling rate. As is shown, the conditions for the alignment of ferrite grains are (1)austenite grain size is relatively small, (2)cooling rate is relatively small and (3)magnetic field is high enough. When austenite grain size or cooling rate is relatively large, plate type ferrite is formed irrespective of the direction of applied magnetic field, and the degree of alignment is decreased. The reason for ferrite alignment is not clear yet, but it is speculated that ferrite grain elongated along the direction of magnetic field reduces the demagnetization field in austenite grains and therefore decreases the free energy of the system. The orientation of elongated ferrite grains was investigated by Electron Backscatter Diffraction, but the orientation was rather random and no preferential texture was observed. The volume fraction of ferrite is increased in magnetic field as is shown in Fig. 1, which is already pointed out in ref.[9] by the thermodynamic consideration.

3.2. Lath Martensite to Austenite Reverse Transformation

The effects of magnetic field on microstructure formed by reverse transformation from lath martensite to austenite are investigated. Figure 4 is the optical micrograph showing the effects of magnetic field on reverse transformed structure. Specimens were austenitized at 900℃ for 15 min and quenched to room temperature to form lath martensite without magnetic field, and then isothermally held at 745℃ for 20 min in magnetic field of (a) 10T and (b) 0.5T. The dark region is the reverse transformed austenite which transformed to pearlite during final cooling, and the bright region is ferrite. Both reverse transformed austenite and ferrite are elongated along the direction of applied magnetic field in Fig.4(a), but they are almost equiaxed and not elongated in Fig. 4(b). The structure formed without magnetic field is quite similar to this structure. The degree of elongation was not measured quantitatively in this case, but it is clearly seen from Fig. 4 that the degree of alignment increases with increasing applied magnetic field.

4. Summary

Effects of high magnetic field on austenite to ferrite transformation and lath martensite to austenite reverse transformation have been investigated in Fe-0.4C alloy. For austenite to ferrite transformation, elongation and alignment of ferrite grains in high magnetic field are observed. The degree of elongation increases with decreasing austenite grain size and cooling rate, and with increasing magnetic field strength. For lath martensite to austenite reverse transformation, elongation and alignment of ferrite and austenite grains in high magnetic field are observed. The degree of elongation increases with increasing magnetic field strength.

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