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Chaojie Yan

Northeastern University

Xiaozhao Zhang

Northeastern University

kai Wang

wangkai@epm.neu.edu.cn

Northeastern University

Chenhua Yuan

Northeastern University

Tie Liu

Northeastern University

Lijia Zhao

Northeastern University

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Growth kinetics of proeutectoid ferrite isothermal transformation in a Fe–0.4 C (mass%) alloy under a high magnetic field

Chaojie Yan^{1,2}, Xiaozhao Zhang^{1,3}, Kai Wang^{1,*}, Chenhua Yuan^{1,3}, Tie Liu¹, Lijia Zhao¹

¹Key Laboratory of Electromagnetic Processing of Materials (Ministry of Education), Northeastern University, Shenyang 110819, Liaoning, China

²Hebei Academy of Sciences, Shijiazhuang 050052, Hebei, China

³School of Materials Science and Engineering, Northeastern University, Shenyang 110819, Liaoning, China

Abstract: In this study, the effects of a high magnetic field on the growth kinetics of proeutectoid ferrite are investigated. The carbon content at the austenite/ferrite (γ/α) interface with and without a high magnetic field is characterized by a field emission electron probe microanalyzer. The results demonstrate that a high magnetic field increases the carbon content in the austenite at the γ/α interface. In addition, a high magnetic field increases the parabolic length growth rate constant of proeutectoid ferrite by approximately 15%–28% along the magnetic field direction from 993 K to 1033 K. Conversely, it inhibits the parabolic thickness growth rate constant of proeutectoid ferrite by approximately 11%–26% perpendicular to the magnetic field direction from 993 K to 1033 K. At this foundation, relationship between ferrite growth rates with and without a high magnetic field are illuminated, quantitatively. The mechanism of the moving γ/α interfaces is discussed from the viewpoint of carbon diffusion in austenite and the carbon content at the γ/α interface with the absence of high magnetic or not.

Keywords: High magnetic field; Ferrite phase transformation; Growth kinetics; Fe–C alloy.

*Corresponding author: Kai Wang

1. Introduction

Thermodynamic and kinetics behaviors of phase transformation play a fundamental role in almost all fields of materials science and engineering. And high magnetic field could affect significantly on phase transformation as its high energy density [1]. Therefore, thermomagnetic treatment is a promising method to control the microstructure evolution. Consequently, multiple investigations [2][3][4][5] have demonstrated that thermomagnetic treatment can result in microstructures that are unreachable without a magnetic field and improve the properties of materials. Furthermore, high magnetic fields are widely applied during the solid-state phase transformation in steel, influencing the phase equilibrium [6][7][8][9], microstructure evolution [10][11][12], solid solubility of solute atoms [13][14][15], atom diffusion [16][17][18][19], and precipitation growth behaviors [20][21]. In particular, high magnetic fields have been found to elongate ferrite grains and form aligned microstructure along the magnetic field direction in the austenite/ferrite (γ/α) transformation and the α/γ reversed transformation of Fe–C alloys [22][23]. Zeng et al. [23] found that high magnetic field can affect on phase growth, which leads to the alignment microstructure. Enomoto et al [24][25] found that high magnetic fields can change the ferrite grain growth behavior in Fe–C-based alloys. The reasons for this were primarily discussed in terms of the diffusion behavior effect of the alloying elements resulting from the high magnetic field with respect to the ferrite phase transformation. Zhou et al.[26][27] investigated that high magnetic fields could induce pearlite growth at early stage of phase transformation and affect its crystallographic orientation in Fe-C-based alloys. Zhang et al.[28] reported that high magnetic fields influence the growth behavior of cementite and change the morphology of

cementite from chain-like to particle-like. Hou et al. [29][30] described how high magnetic fields accelerate the growth rate of χ -Fe₅C₂ carbides at low temperatures. Moreover, high magnetic fields could also influence the precipitation of nanocrystalline in Fe₉₀Zr₇B₃ [31]. Onodera et al. [32][33] found that high magnetic fields change the growth behavior of the FeSiB phase. Jia et al. [34], however, found that high magnetic fields have an insignificant effect on the growth behavior of Fe₂₃B₆ phase. These studies demonstrate that the effects of high magnetic fields on the growth kinetics behavior in the solid-state phase transformation are subject to debate. In addition, there is a lack of quantitative illustrations concerning the effects of high magnetic fields on the growth kinetics behavior in the solid-state phase transformation.

Since magnetic susceptibility differs between austenite and ferrite greatly, ferrite growth rate may clearly reflect the effect of a high magnetic field. In this study, a high purity Fe–0.4 C (mass%) binary alloy is selected to investigate the growth kinetics of ferrite under a high magnetic field. The growth kinetics is investigated using rapid quenching equipment with a precise temperature controller under a high magnetic field. Furthermore, the growth rate of the proeutectoid ferrite grains is quantitatively analyzed. And the composition of this alloy can circumvent ferrite collision at the early stage of the γ/α transformation, which is conducive to observing the growth behaviors of ferrite under a high magnetic field.

2. Experimental procedure

To avoid the influence of substitutional alloy elements, a high-purity Fe–0.4 C (mass%) binary alloy was used in this study. The alloy was prepared via vacuum induction melting using high-purity electrolytic iron and graphite. The chemical composition of the alloy is given in Table 1.

Table 1. Chemical composition of the experimental alloy (mass%).

Alloy	C	Mn	Si	P	S	Fe
Fe-0.4 C (mass%)	0.4	0.005	0.006	0.006	0.003	Bal.

The hot forged ingots were homogenized at 1223 K for 2 h in a vacuum quartz tube furnace. Then, they were cut into cylindrical specimens with 10 mm in diameter and 15 mm in length. An accurate controlling system for high magnetic field rapid rate heating was designed to conduct the experiments; this system included a superconducting magnetic field, induction heating coil, and a dual-inverter high-frequency induction heating power supply based on a proportion integral derivative temperature controller. To improve the accuracy of the temperature measurement, a circular hole with a diameter of 6 mm and a depth of 5 mm, was made at the bottom of the specimens to directly measure the temperature. The accuracy of the temperature control was ± 5 K. The maximum heating rate of the specimen was approximately 120 K/min, enabling the stability of undercooled austenite between the γ/α phase region. The quenching device in the magnet cavity was a pneumatic device, and the quenching medium was a water bath. All specimens were rapidly heated to 1123 K and held for 15 min, producing a nominal austenite grain size of 106 ± 5 μm ; the samples were then rapidly cooled to 1033 K, 1013 K, and 993 K, holding for various times with and without a high magnetic field. Specimens were transferred into a water bath immediately after isothermal holding. The specimens were cut along the longitudinal direction, prepared using a standard polishing procedure, and immersed in 4% nital etchant to reveal their microstructure. The microstructure of each specimen was observed with optical microscope and field emission scanning electron microscopy (FE-SEM). Field emission electron probe microanalysis (FE-EPMA) was used to measure the carbon content at the γ/α interface. The

thicknesses and lengths of the ferrite grains were analyzed using sufficient FE-SEM maps to obtain a statistical result satisfying the stereological procedure and using the quantitative metallographic method[35]. The thickness and length growth rates of the ferrite grains with and without a high magnetic field were calculated from the fitted experimental results. The crystal orientations of the ferrite grains with and without a high magnetic field were measured via SEM equipped with electron backscatter diffraction (SEM-EBSD) under an accelerating voltage of 25 kV and a step size of 0.4 μm . The damaged layer on the specimen surface was removed via Ar ion milling after polishing with colloidal silica.

3. Results and discussion

Figure 1 shows the microstructure of the specimens quenched at 993 K for different times with and without a magnetic field of 8 T. Under both the field-treated and non-field-treated conditions, the microstructures are composed of martensite and ferrite. The ferrite grains preferentially nucleate (Fig. 1a and 1d) and grow at the austenite grain boundaries with and without a high magnetic field (Fig. 1b and 1e). Figure 1b shows that the ferrite grains are randomly distributed in the absence of a magnetic field. Under a high magnetic field, the ferrite grains elongate and align along the magnetic field direction with increasing isothermal time (Fig. 1e). Figure 1c and 1f indicate that a high magnetic field promotes the lengthening of the ferrite grains along the magnetic field direction. Because the majority of the ferrite grains align along the magnetic field direction, only the lengths and thicknesses of the ferrite grains along the magnetic field direction need to be analyzed with a high magnetic field.

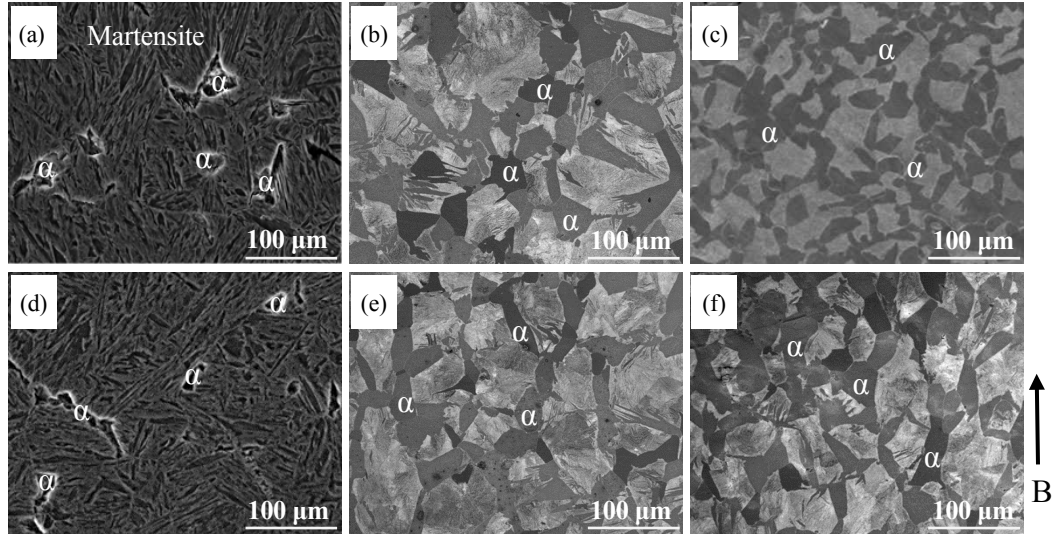


Fig. 1. Scanning electron microscopy (SEM) secondary electron micrographs of specimens transformed at 993 K with and without a magnetic field at different times: (a) 0 T, 6 s; (b) 0 T, 180 s; (c) 0 T, 1200 s; (d) 8 T, 6 s; (e) 8 T, 180 s; and (f) 8 T, 1200 s.

The microstructure of the specimens indicates that high magnetic would cause ferrite grains to elongate and align along the magnetic field direction. The effects of a high magnetic field on ferrite grains preferred crystallographic orientation is examined using EBSD. Figure 2 shows the microstructure of the specimens quenched at 993 K for 12 s with and without a magnetic field of 8 T. As shown in Fig. 2a and Fig. 2b, the microstructures are composed of martensite and ferrite with the high magnetic field or not. Compared to the absence of a magnetic field (Fig. 2c and 2e), ferrite grains do not exhibit a significant preferred crystallographic orientation with a high magnetic field (Fig. 2d and 2f). The results could be related to the fact that ferrite grains are magnetized to saturation at the low magnetic field[36], causing ferrite grains to lose its magneto-crystalline anisotropy with a high magnetic field.

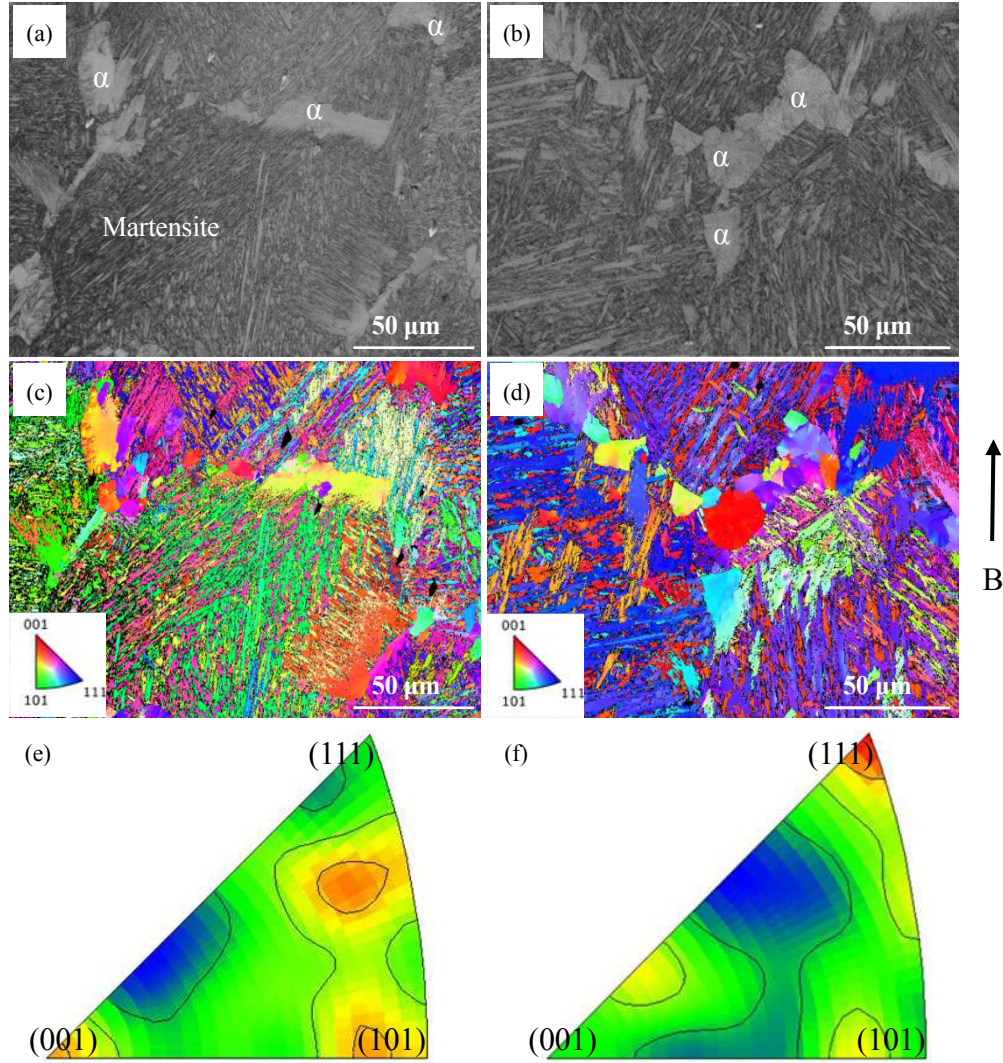


Fig. 2 Band contrast map of specimens (a, b), ferrite orientation maps of specimens (c, d) and inverse pole figures (e, f) transformed at 993 K with and without a magnetic field. (a) 0 T, 12 s; (b) 8 T, 12 s; (c) 0 T, 12 s; (d) 8 T, 12 s; (e) inverse pole figures, 0 T, 12 s; (f) inverse pole figures, 8 T, 12 s

To examine the effects of a high magnetic field on ferrite grain growth at the austenite grain boundary, the half-thickness and half-length of the ferrite grains were statistically analyzed based on the experimental results with and without a high magnetic field at different times. The results are shown in Fig. 3.

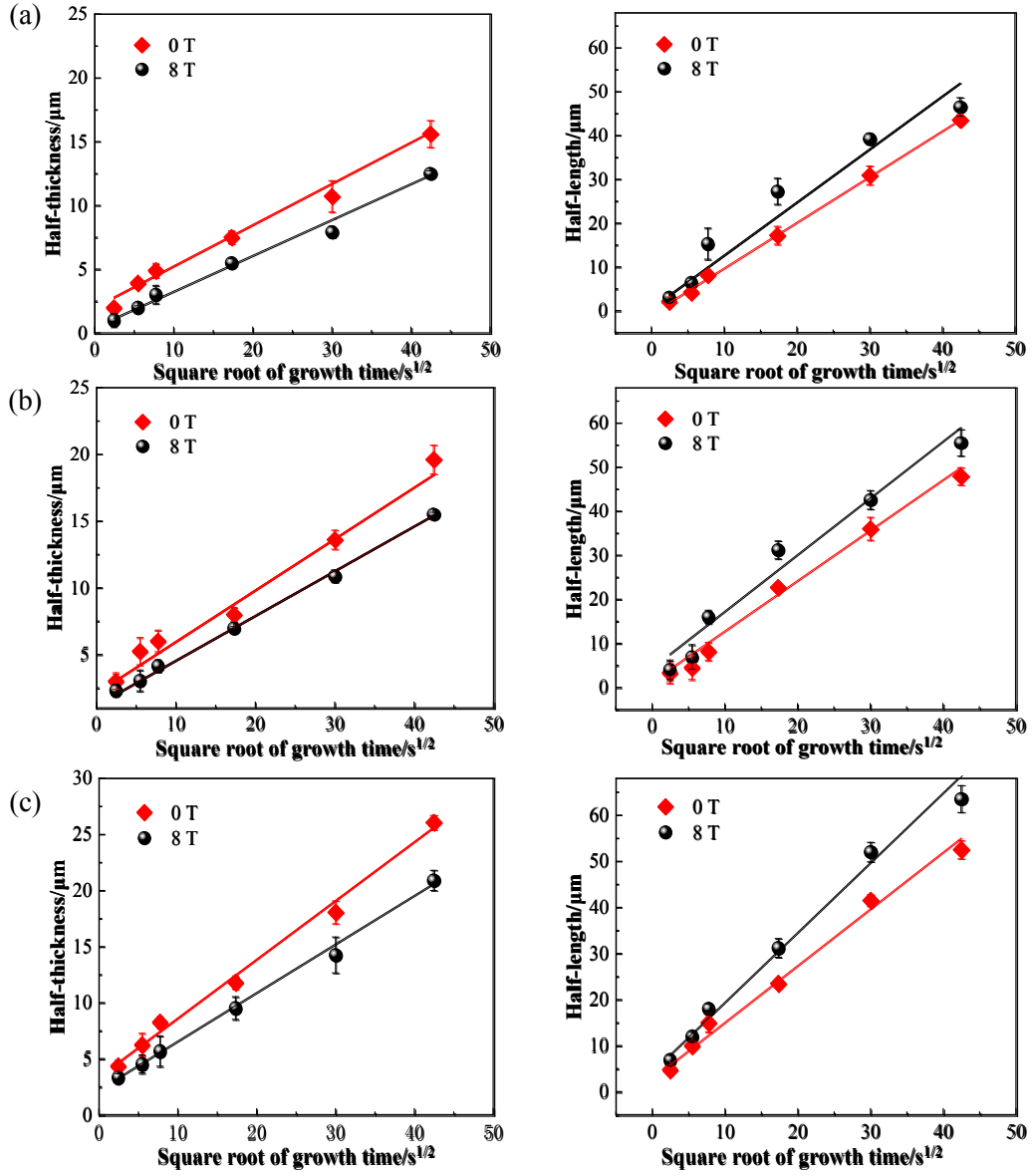


Fig. 3. Half-thickness and half-length of ferrite grains with (black circles) and without (red diamonds) a magnetic field of 8 T at different isothermal times at (a) 1033 K; (b) 1013 K; and (c) 993 K.

At 993 K, the half-length of the ferrite grains at 1800 s increased from 52.5 μm without a magnetic field to 63.5 μm with a high magnetic field. The length of the ferrite grains increased by approximately 21% under a high magnetic field. Conversely, the half-thickness at 1800 s decreased from 26.75 μm to 20.1 μm with a high magnetic field. In addition, the thickness of the ferrite grains decreased by approximately 25% with a high magnetic field.

The ferrite growth rate can be estimated by measuring the thickness and length of the ferrite grains versus the reaction time, which approximately follows a parabolic growth law[37], as shown in Fig. 4.

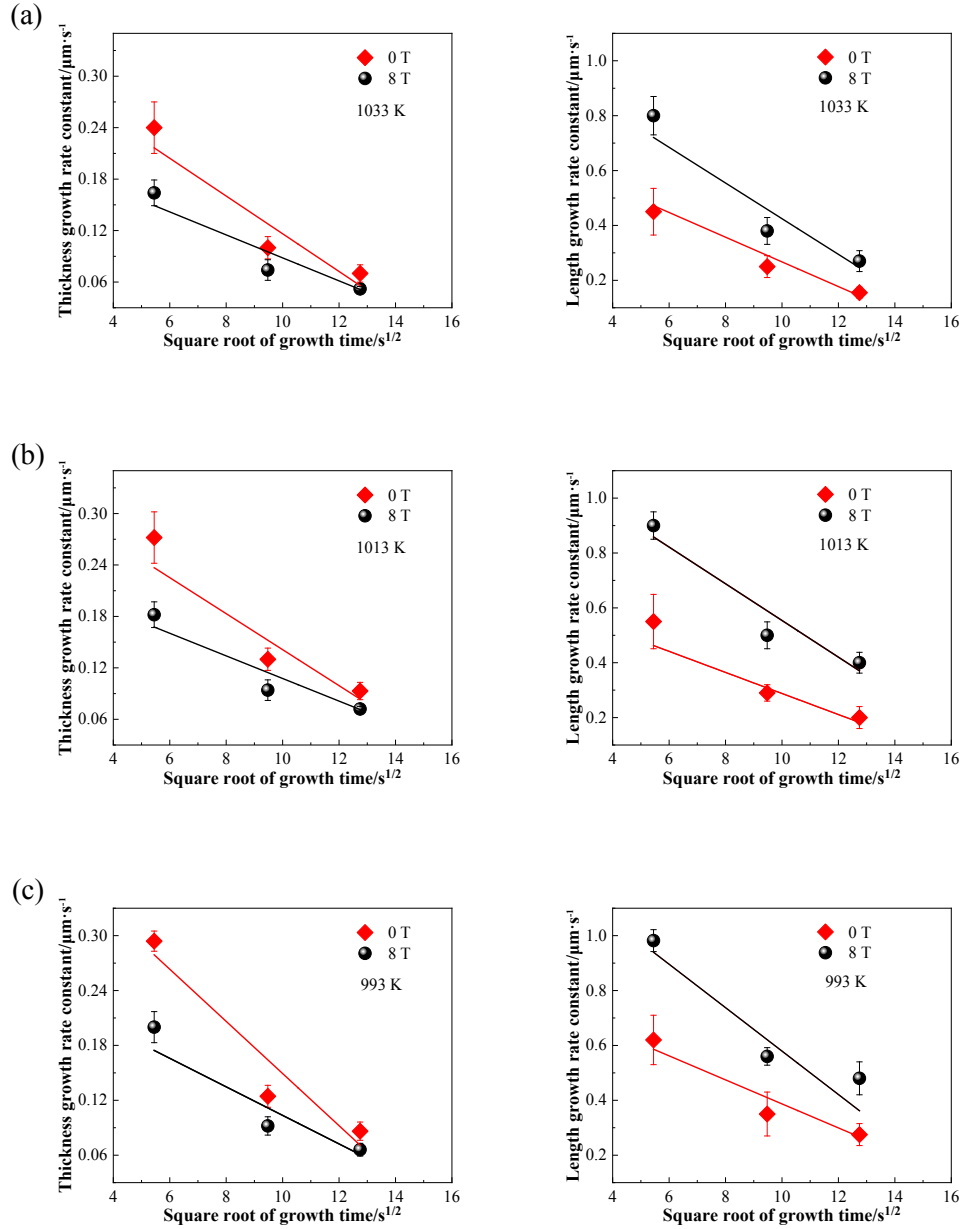


Fig. 4. Thickness and length growth rate constants of ferrite grains with (black circles) and without (red diamonds) a magnetic field of 8 T at different times at (a) 1033 K; (b) 1013 K; and (c) 993 K.

Figure 4 shows that the thickness growth rate constant of the ferrite grains decreases with a high magnetic field. However, the length growth rate constant of the ferrite grains

increases with a high magnetic field. The slopes represent the average thickness and length growth rate constants of the ferrite grains. The average thickness growth rate constants of the ferrite grains decrease by approximately 26% and 11% at 993 K and 1033 K, respectively, with the application of a high magnetic field; however, the average length growth rate constants increase by approximately 28% and 15% at 993 K and 1033 K, respectively. This study shows that a high magnetic field promotes the lengthening of ferrite grains along the magnetic field direction. However, a high magnetic field inhibits the thickening of the ferrite grains perpendicular to the magnetic field direction.

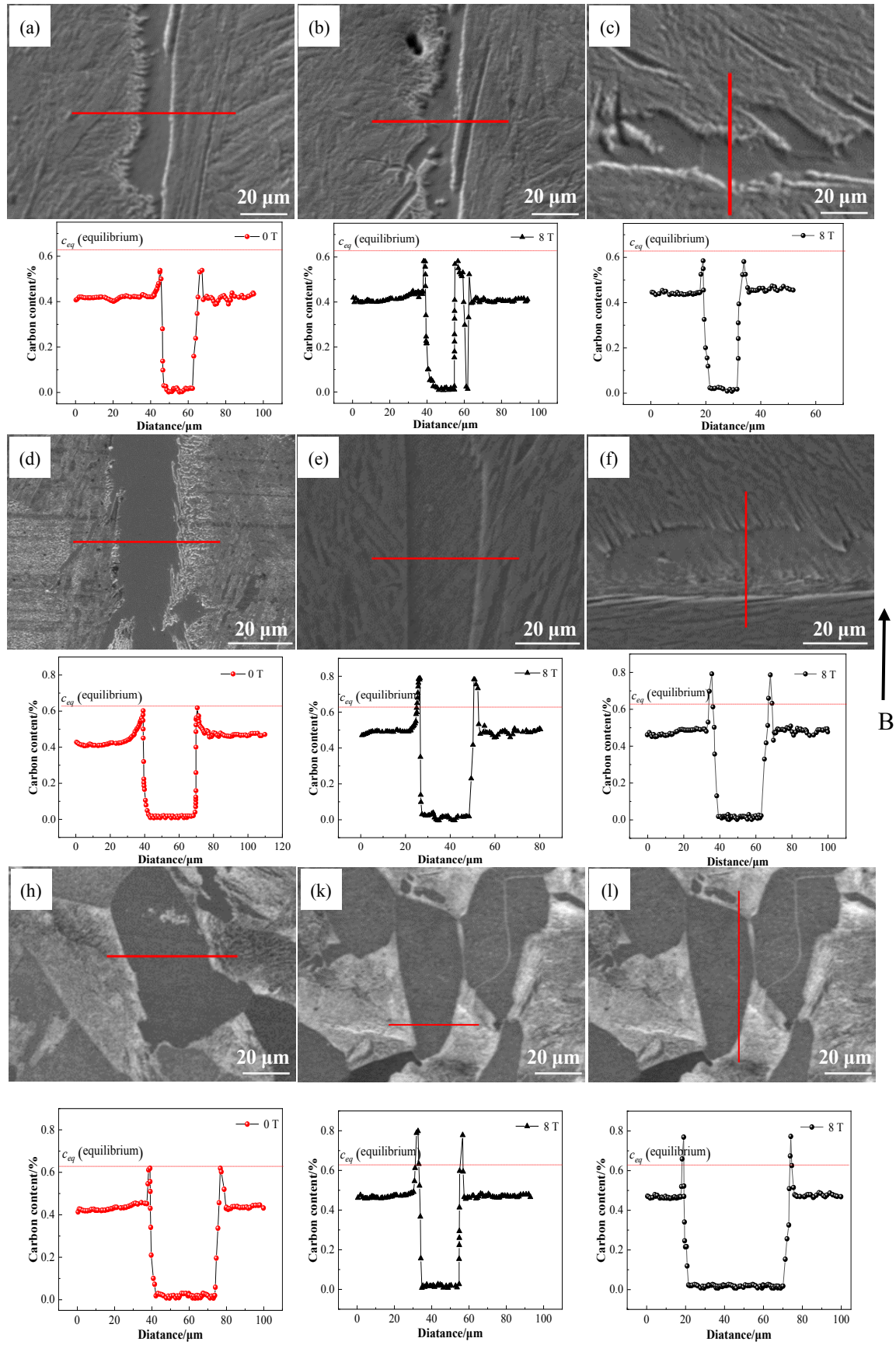


Fig. 5. Carbon content profiles across the austenite/ferrite (γ/α) interface measured using a field

emission electron probe microanalyzer (FE-EPMA) for the specimen transformation at 993 K with (black curve) and without (red curve) a magnetic field at different times: (a) 0 T, 60 s; (b) 8 T, 60 s; (c) 8 T, 60 s; (d) 0 T, 120 s; (e) 8 T, 120 s; (f) 8 T, 120 s; (h) 0 T, 1200 s; (k) 8 T, 1200 s; and (l) 8 T, 1200 s.

Figure 5 shows the microstructures and corresponding carbon content profiles across the γ/α interface in specimens transformed at 993 K at different times with and without a high magnetic field. The data for each condition were averaged from between 5–8 measurements. The γ/α interface is indicated at the maximum carbon content points in Fig. 5, and the equilibrium carbon content is denoted by the red dashed line (the equilibrium carbon content at the γ/α interface determined by the Thermo-Calc method calculation in the absence of a magnetic field [38]). For ferrite transformed at 993 K, the carbon content in the austenite at the γ/α interface notably deviates from the equilibrium carbon content during the early stage transformation (60 s) without a magnetic field (Fig. 5a). Conversely, with the application of a high magnetic field, the carbon content in the austenite at the γ/α interface is close to the equilibrium carbon content at the same holding time (shown in Fig. 5b and 5c). As the isothermal time increases (120 s), the carbon content in the austenite at the γ/α interfaces approaches the equilibrium carbon content (Fig. 5d and 5h) in the absence of a magnetic field. However, the carbon content in the austenite at the γ/α interface is higher than the equilibrium carbon content under a high magnetic field (Fig. 5e, 5f, 5k, and 5l). With the application of a high magnetic field, the carbon content in the austenite at the γ/α interface increases from 0.59 mass% (the equilibrium carbon content at the γ/α interface) to 0.786 mass%. However, a high magnetic field has an insignificant effect on the carbon content in the ferrite at the α/γ interface. The carbon content in the ferrite at the α/γ interface increases from 0.017 mass% to 0.018 mass% with a high magnetic field.

According to solid-state phase transformation theory, ferrite grain growth is mainly controlled by carbon diffusion in austenite [39][40][41]. Ferrite formation involves the transfer of carbon atoms from ferrite to austenite and carbon diffusion in austenite, which causes a carbon mass flux J_D , as described by Fick's first law [42] [43]:

$$J_D = -D \cdot \left(\frac{dc^\gamma}{dx} \right), \quad (1)$$

where D is the carbon diffusion coefficient in austenite and dc^γ/dx denotes the gradient of the austenite carbon content.

The growth rate of ferrite grains is determined by the carbon bulk diffusion in austenite and the variation in the carbon content at the γ/α interface. Here, it is assumed that the thickness growth rate of the ferrite grains perpendicular to the austenite grain boundaries is mainly controlled by the carbon diffusion in the austenite [41]. This can be expressed as

$$v = \frac{K_1(D)^{1/2}(c^{\gamma/\gamma+\alpha} - c^\gamma)}{2t^{1/2}(c^{\gamma/\gamma+\alpha} - c^{\alpha/\alpha+\gamma})} = \frac{K_1\alpha^*}{2} \sqrt{\frac{D}{t}}, \quad (2)$$

where K_1 is a constant, α^* is the parabolic thickness growth rate constant of ferrite, $c^{\gamma/\gamma+\alpha}$ is the carbon content in the austenite at the γ/α interface, c^γ is the carbon content in the parent austenite, $c^{\alpha/\alpha+\gamma}$ is the carbon content in the ferrite at the γ/α interface, and t is time.

Based on Eq. (2), it is necessary to determine whether a high magnetic field has a significant effect on the carbon diffusion in the austenite and the carbon concentration at the γ/α interface. Previous studies indicate that high magnetic fields inhibit carbon diffusion in austenite [17][44]. Therefore, a high magnetic field could inhibit the thickness growth of ferrite grains, which agrees with the experimental results of this study. In the absence of a magnetic field, the carbon diffusion coefficient in austenite can be expressed as $D = 5.6 \times 10^{-6} \exp(-128000 / RT)$, whereas with a high magnetic field, the carbon diffusion

coefficient in austenite can be described as $D_M = 5.7 \times 10^{-6} \exp(-133000 / RT)$ [17].

Consequently, the thickness growth rate of ferrite grains with a high magnetic field can be approximately stated as

$$v_M = \frac{K_1(D_M)^{1/2}(c_M^{\gamma/\gamma+\alpha} - c^\gamma)}{2t^{1/2}(c_M^{\gamma/\gamma+\alpha} - c_M^{\alpha/\alpha+\gamma})} = \frac{K_1\alpha_M^*}{2} \sqrt{\frac{D_M}{t}}, \quad (3)$$

where α_M^* is the parabolic thickness growth rate constant of ferrite with a high magnetic field and $c_M^{\gamma/\gamma+\alpha}$ and $c_M^{\alpha/\alpha+\gamma}$ represent the carbon contents in the austenite and ferrite, respectively, at the γ/α interface with a high magnetic field.

Based on Eqs. (2) and (3), the relationship between the thickness growth rate of ferrite grains with and without a high magnetic field can be calculated such that

$$\frac{v_M}{v} = \sqrt{\frac{D_M}{D}} \times \frac{\alpha_M^*}{\alpha^*}. \quad (4)$$

According to the Zener–Hillert equation [45], the length growth rate of ferrite grains is

$$G = \frac{D}{4r_0} \frac{c^{\gamma/\gamma+\alpha} - c^\gamma}{c^\gamma - c^{\alpha/\alpha+\gamma}} = \frac{D}{4r_0} \times \alpha_l^*, \quad (5)$$

where r_0 is the radius of curvature of the ferrite tip and α_l^* is the parabolic length growth rate constant of ferrite. With a high magnetic field, the length growth rate of ferrite grains is approximately

$$G_M = \frac{D_M}{4r_0} \frac{c_M^{\gamma/\gamma+\alpha} - c^\gamma}{c^\gamma - c_M^{\alpha/\alpha+\gamma}} = \frac{D_M}{4r_0} \times \alpha_{l,M}^*, \quad (6)$$

where $\alpha_{l,M}^*$ is the parabolic length growth rate constant of ferrite with a high magnetic field. Similarly, according to Eqs. (5) and (6), the relationship between the length growth rate constant of ferrite grains with and without magnetic field is

$$\frac{G_M}{G} = \frac{D_M}{D} \times \frac{\alpha_{l,M}^*}{\alpha_l^*}. \quad (7)$$

Using Eqs. (4) and (7), the relationship between the thickness and length growth rates of ferrite grains with and without a magnetic field can be calculated. The terms $\frac{\alpha_M^*}{\alpha^*}$ and $\frac{\alpha_{l,M}^*}{\alpha_l^*}$ in Eqs. (4) and (7), respectively, can be calculated from a quantitative measurement of the carbon content at the γ/α interface characterized by FE-EPMA with and without a high magnetic field. The theoretical calculation results are shown in Fig. 6.

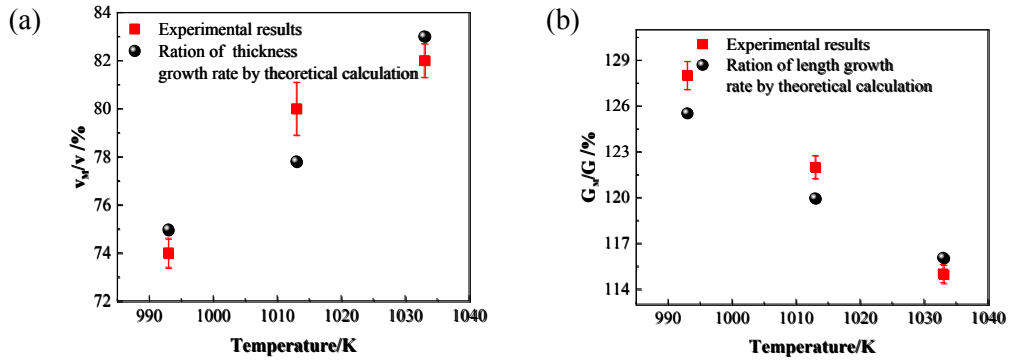


Fig. 6. Relationships between the (a) thickness and (b) length growth rates of ferrite grains at different temperatures with and without a high magnetic field.

Figure 6a indicates that the ratio of the ferrite thickness growth rate according to the theoretical calculation decreases by approximately 25.3%, 22.5%, and 17% at 993 K, 1013 K, and 1033 K, respectively, with a high magnetic field. As shown in Fig. 6b, the ferrite length growth rate increases by approximately 25.8%, 20%, and 16.1%, respectively, according to the theoretical calculation under a high magnetic field. The experimental results of ferrite thickness growth rate decreases about 25.9%, 20%, and 18% at 993 K, 1013 K, and 1033 K in Fig. 6a. Similarly, as shown in Fig. 6b, the experimental results of ferrite length growth rate increase about 27.9%, 22.1% and 14.9% at 993 K, 1013 K, and

1033 K. The theoretical calculation results are approximately consistent with the experimental results.

With the application of a high magnetic field, the Gibbs free energy can be decreased in the ferrite phase transformation. Because the magnetization of ferrite (the ferromagnetic phase) is much higher than that of austenite (the paramagnetic phase), within the experimental temperature, the magnetization energy of austenite can be neglected [46]. Therefore, the decrease in the amount of energy per unit volume because of magnetization can be represented as [46]

$$\Delta G^M = - \int_0^{M^\alpha} \vec{B}_0 d\vec{M}^\alpha, \quad (8)$$

where the superscript α denotes ferrite and M and B_0 refer to the magnetization and induction of the applied magnetic field, respectively. Consequently, the application of a high magnetic field results in an increase in the driving force for ferrite transformation significantly [7]. Based on Eq. (8), the variation in the carbon content at the γ/α interface and the Gibbs free energy in the ferrite transformation with and without a magnetic field can be visualized in Fig. 7.

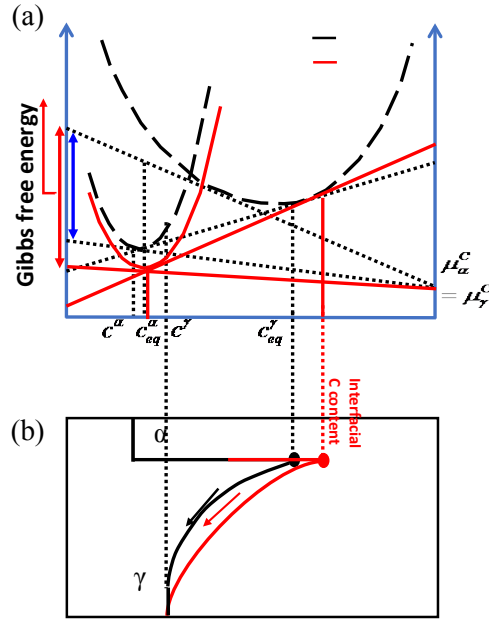


Fig. 7. (a) Schematic illustration of the variation in the Gibbs free energy (ΔG and ΔG^M) in the γ/α transformation with and without a magnetic field, respectively. μ_{α}^C and μ_{γ}^C indicate the carbon chemical potentials in ferrite and austenite, respectively. c^{α} represents the carbon content in the product ferrite. c_{eq}^{α} and c_{eq}^{γ} denote the equilibrium carbon contents in ferrite and austenite, respectively, in the absence of a high magnetic field. (b) Schematic representation of the effects of a high magnetic field on the carbon content profile across the γ/α interface. J indicates the carbon diffusion flux.

According to the local equilibrium model and solid-state phase transformation theory, Fig. 7a schematically shows that a high magnetic field decreases the Gibbs free energy of ferrite while the Gibbs free energy of austenite remains nearly unchanged. The common tangent construction method can be used to define the local equilibrium carbon concentration at the γ/α interface for austenite and ferrite [39]. The carbon content profile, which evolves during the ferrite growth, is shown schematically in Fig. 7b with and without a high magnetic field.

it is clear that $c_M^{\gamma/\gamma+\alpha}$ is higher than $c^{\gamma/\gamma+\alpha}$.

In terms of the ferrite transformation, the thickness growth of ferrite grains is mainly determined by the carbon bulk diffusion in austenite. According to the carbon content at the γ/α interface, as characterized by FE-EPMA, the $\frac{\alpha_M^*}{\alpha^*}$ term in Eq. (4) was determined to be approximately 1.01, 1.04, and 1.06 at 993 K, 1013 K, and 1033 K, respectively. The ratio of $\sqrt{\frac{D_M}{D}}$ in Eq. (4) was identified as being approximately 0.74, 0.77, and 0.83 at 993 K, 1013 K, and 1033 K, respectively. This indicates that a high magnetic field has an insignificant effect on the α_M^* term in Eq. (3). Because a high magnetic field inhibits carbon diffusion in austenite, the thicknesses of the ferrite grains decrease with a high magnetic field. It is known that the length growth of ferrite grains along the austenite grain boundary is mainly related to the carbon content at the γ/α interface [47]. Similarly, the $\frac{\alpha_{l,M}^*}{\alpha_l^*}$ term in Eq. (7) was calculated to be approximately 2.24, 1.99, and 1.65 at 993 K, 1013 K, and 1033 K, respectively, and the ratio of $\frac{D_M}{D}$ in Eq. (7) was identified as being approximately 0.55, 0.60, and 0.69 at 993 K, 1013 K, and 1033 K, respectively. This indicates that a high magnetic field has a significant effect on the $\alpha_{l,M}^*$ term in Eq. (6). This demonstrates that a high magnetic field has a major impact on the interface reaction during the lengthening of ferrite grains along the austenite grain boundaries.

4. Conclusions

The growth kinetics of the ferrite transformation were studied using a Fe–0.4 C (mass%) alloy. A high magnetic field was found to inhibit the thickness growth rate of ferrite grains

by approximately 25%, 21%, and 17% at 993 K, 1013 K, and 1033 K, respectively. The high magnetic field promoted the length growth rate of the ferrite grains by approximately 26%, 20%, and 16% at 993 K, 1013 K, and 1033 K, respectively. The experimental results and the theoretical calculation growth rates of ferrite were in reasonable agreement. The high magnetic field increased the carbon content in the austenite at the γ/α interface. The proposed equations for the thickness and length growth rates of ferrite grains in the presence of a high magnetic field are $v_M = v \times \sqrt{\frac{D_M}{D}} \times \frac{\alpha_M^*}{\alpha^*}$ and $G_M = G \times \frac{D_M}{D} \times \frac{\alpha_{l,M}^*}{\alpha_l^*}$, respectively.

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Declaration

conflict of interests: We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work and there is no professional or other personal interest of any nature or kind in any product, service and company

Data and code availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Ethical approval

Written informed consent for publication of this manuscript was obtained from the Northeastern University and all authors

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