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Effects of Magnetic Field Intensity on Carbon Diffusion Behavior in Pure Iron in $\alpha$-Fe temperature region

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Abstract
Effects of magnetic field intensity on carbon diffusion behavior in pure iron in the $\alpha$-Fe temperature region were investigated by means of microstructure observation and EPMA analysis. A high purity iron was carburized in $\alpha$-Fe temperature region applying with different magnetic field intensity. The carbon diffusion coefficient was calculated according to the Fick’s second law. It is found that the magnetic field intensity can significantly affect the carbon diffusion behavior in pure iron in the direction parallel to the magnetic field direction in the $\alpha$-Fe temperature region, and the average carbon diffusion distance and the average carbon diffusion coefficient of specimens decrease gradually with the enhancement of the magnetic field intensity. The application of a magnetic field is likely to change the diffusivity of carbon owing to the change in the fraction of carbon atoms at octahedral and tetrahedral sites. The greater the magnetic field intensity, the stronger of the inhibiting of magnetic field on carbon diffusion.

Key words: Magnetic field intensity, Carbon diffusion, Pure iron

Introduction
With the rapid development of superconducting technique, the high magnetic field heat treatment technology has risen gradually in the materials science research. Studies on the effects of magnetic fields on solid/solid phase transformation behaviors and microstructures have become popular in the last several years [1-6]. During the phase transformation, the atomic diffusion processes are considered as the main driving force for the distribution of solutes and significantly influence the transformation rate. Youdelis et al [7] reported that a 3T magnetic field retarded the diffusion of copper in aluminium. Nakajima et al [8] observed no magnetic effects on the diffusion of nickel in titanium. Pokoev et al [9-10] measured the diffusivity of nickel in $\alpha$-Fe and Fe-1.94%Si alloy and the magnetic effect on diffusivity were not monotonic as a function of applied magnetic field.

The carbon diffusion is a very important process in diffusional transformations in steels, and most changes in microstructure of steels occur by diffusion. Accordingly, it is of particular importance to study the effect of magnetic field annealing on carbon diffusion behavior in iron. So far, a few reports have been made on the effects of a magnetic field on carbon diffusion in steels. In 2005, Nakamichi et al [11] studied the effects of magnetic field and magnetic field gradient on the diffusion of carbon in $\gamma$-Fe and found that the carbon diffusion in $\gamma$-Fe was retarded by the application of a 6 T magnetic field. The diffusion of carbon in $\gamma$-Fe could be enhanced in a magnetic field gradient when carbon atoms moved towards the direction with a higher magnetic field strength, but be retarded when the opposite magnetic field gradient was applied. In 2006, Ohtsuka [12] studied the influence of 10T magnetic field on carbon diffusion in steel. The results showed that the high magnetic field retarded the carbon diffusion along the magnetic field direction at 1073K, but had unnoticeable effect at 1203K. In 2011, Fujii and Tsurekawa [13] studied the carbon diffusion in iron under magnetic fields using a diffusion couple made by pure Fe and Fe-0.87C alloy. The results showed that the
diffusivity of carbon in α-Fe decreased under a magnetic field, while it increased by twice under a magnetic field gradient of 45 T/m.

The above studies have great importance on elucidating the mechanism and the influence rule of high magnetic field on carbon diffusion in Fe-C alloy. However, till now, the study about the magnetic field intensity on carbon diffusion is rarely mentioned. So in this work, we further studied the effect of magnetic field intensity on carbon diffusion behavior in pure iron in the α-Fe temperature region using cementation process. Then the carbon diffusion coefficient was calculated according to the Fick’s second law.

Experimental
The material used in this study was high purity iron (99.99%) ingot. The specimens with a dimension of 10mm×8mm×7mm were cut from the ingot. Specimens were buried in an air-proof melting pot filled up with cementation agent (C: Na₂C₂O₄: Na₂CO₃=55:30:15), and respectively subjected to isothermal annealing at 1023K for 4h with a heating rate of 5°C /min, and then cooled in the furnace. The experimental apparatus is based on a superconducting magnet (JMIDT-12 T100, JASTEC, Japan). A magnetic field with different intensity (0 T, 0.1 T, 0.4 T, 0.7 T, 1 T, 6 T, and 12 T) was applied during the whole heating, isothermal holding and cooling processes. During the magnetic field annealing, the specimens were fixed at the center of the applied field, with their long sides (10 mm) parallel to the magnetic field direction (H).

After the heat treatment, the specimens were mechanically polished and then etched with 4% nital. The microstructural observation was performed with an OLYMPUS/ GX71 optical microscope equipped with the analysis software. The metallographic observation surface was the 10mm×8mm section of the specimen which was parallel to the magnetic field direction (H). To study the field effect on the carbon diffusion distance, the area percentage of pearlite was examined: The measurement starts from the specimen surface along the carbon diffusion direction (Jc) with a step size of 2μm (The measuring width perpendicular to Jc is 200μm). When the measured area percentage of the pearlite is less than 1%, the distance between this point and the specimen surface is defined as “the carbon diffusion distance”. The average carbon diffusion distance of each specimen was calculated from more than 20 measurement data.

The carbon penetration profiles from the surface to iron were measured by Field Emission Electron Probe Micro analyzer of JXA-8530F. The carbon diffusivities in iron under the magnetic field were measured from the carbon penetration profiles. The carbon diffusion coefficients in iron were determined according to Fick’s second law, given by

$$ \frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial x^2} $$

(1)

Where C is the concentration of atoms, t is the diffusion time, D is the diffusion coefficient, x is the diffusion length.

Results and discussion
Fig. 1 shows the microstructures of the specimens annealed at 1023K for 4h with different magnetic field intensity with the carbon diffusion direction parallel to the magnetic field direction. As the Fig. 1 shows, the black area in the left part of each picture is the carbon diffusion layer of the specimen, they are some phase transition product formed in the cooling process— pearlite (black regions) and Widmanstaten structure ferrite like needle and plate (gray regions), the gray area in the right part of each picture is the ferrite grains where carbon atoms haven’t spread to. When the magnetic field intensity is less than 1T, the carbon diffusion layers of annealed specimens all have relatively flat interface and homogeneous thickness, when the magnetic field intensity is higher than 1T, the carbon diffusion layers of annealed specimens begin to have undulating interface and obviously thinner thickness, when the magnetic field is 12T, the carbon diffusion layer disappeared basically.
of the specimens is that the magnetic field annealing obviously restrains carbon diffusion remarkably with further increase of the magnetic field intensity. And on the whole, the carbon diffusion distance and the carbon diffusion coefficient of the specimens decrease gradually with the increase of the magnetic field intensity, especially when the magnetic field intensity is higher than 1T, the carbon diffusion distance decreases remarkably with further increase of the magnetic field intensity. It is seen that both the carbon diffusion distance and the carbon diffusion coefficient of field annealed specimens are all shorter than that of the non-field annealed specimen, which indicates that the magnetic field annealing obviously restrains the carbon diffusion in pure iron in the α-Fe.

For the case of a pair of semi-infinite solids such as the diffusion couples used in this study, a solution to the diffusion equation is generally given by the error-function solution which can be expressed as following equation:

\[
\text{erf}^{-1}\left(1 - \frac{C(x,t)}{C_s}\right) = \frac{1}{2\sqrt{\pi} D t}
\]

Where \( \text{erf} \) stands for the error function, \( D \) is the carbon diffusion coefficient, \( t \) is the annealing time for diffusion, and \( x \) is the penetration distance of carbon in iron. From Equation (2), the inverse error function of carbon concentration is proportional to diffusion distance, and the values of \( \text{erf}^{-1}[1 - C(x,t)/C_s] \) could be plotted against the penetration distance of carbon atoms as shown in Fig. 2, then \( D \) was estimated by the slope of the fitted lines.

Fig. 3 shows the average carbon diffusion distance and the average carbon diffusion coefficient of the specimens carburized with different magnetic field intensity at 1023K, respectively. It is seen that both the carbon diffusion distance and the carbon diffusion coefficient of the specimens decrease gradually with the increase of the magnetic field intensity, especially when the magnetic field intensity is higher than 1T, the carbon diffusion distance decreases remarkably with further increase of the magnetic field intensity. And on the whole, the carbon diffusion distance and the carbon diffusion coefficient of field annealed specimens are all shorter than that of the non-field annealed specimen, which indicates that the magnetic field annealing obviously restrains the carbon diffusion in pure iron in the α-Fe.
temperature region when the magnetic field direction parallel to the carbon diffusion direction, and this effect increased with further enhancement of the magnetic field intensity.

From the viewpoint of site occupancy of carbon in iron, the carbon atoms in α-Fe are predominantly located in the octahedral sites of the bcc lattice; thermodynamic calculations have revealed that the percentage of the tetrahedral-site occupancy is not more than 0.1% in α-Fe. When a magnetic field is applied, a <100> direction is extended because of a positive value of the volume magnetostriction constant for the <100> directions in α-Fe. Thus, the octahedral sites would be energetically more favorable for carbon atoms in α-Fe under a magnetic field than the tetrahedral sites. Although the fraction of carbon atoms at the tetrahedral sites is extremely small in the α-Fe temperature region, the overall diffusion coefficient is significantly affected by the carbon atoms in the tetrahedral sites because the diffusion coefficient of carbon at tetrahedral sites is ~1000× larger than at octahedral sites [13]. Thus the application of a magnetic field is likely to change the diffusivity of carbon owing to the change in the fraction of carbon atoms at two distinct interstitial sites. The greater the magnetic field intensity, the stronger of the inhibiting of magnetic field on carbon diffusion. Therefore, the carbon diffusion in pure iron in the α-Fe temperature region is retarded by the applied magnetic field, and this effect increases with the enhancement of magnetic field intensity.

Conclusions
Effects of magnetic field intensity on carbon diffusion behavior in pure iron in the α-Fe temperature region were investigated. The results showed that the magnetic field intensity can significantly affect the carbon diffusion behavior in pure iron in the α-Fe temperature region along the direction parallel to the magnetic field direction, the average carbon diffusion distance and the average carbon diffusion coefficient of specimens decrease gradually with the enhancement of the magnetic field intensity. The application of a high magnetic field is likely to change the diffusivity of carbon owing to the change in the fraction of carbon atoms at two distinct interstitial sites. The greater the magnetic field intensity, the stronger of the inhibiting of magnetic field on carbon diffusion.

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