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Effect of magnetic field on the carbide precipitation during tempering of a molybdenum-containing steel

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ABSTRACT

The influence of a high magnetic field on the carbide precipitation during the tempering of an Fe–2.8C–3.0Mo(wt%) steel was investigated. As-quenched steels were tempered at 200 °C for various times with and without the presence of 12-T magnetic field. The applied field effectively promoted the precipitation of the relatively high-temperature monoclinic χ-Fe_5C_2 carbide, compared to the usual ε-Fe_2C and η-Fe_2C carbides precipitated without magnetic field. It is believed that the effect of applying a magnetic field is due to the reduction in the Gibbs free energy of the relatively higher magnetization phase. The denser distributions of the metastable carbides are attributed to the increased nucleation rate due to additional transformation force. The dispersed precipitation strengthening compensated for the decrease of hardness due to the loss of supersaturation of carbon atoms in the matrix.

1. Introduction

Quenching followed by tempering is often used in the heat treatment of high-strength steels in order to modify the microstructure and properties. With the increase of tempering temperature, the strength of the steel is usually decreased. On the contrary, low temperature tempering of most steels can improve the elongation without compromising the strength. However, the implementation of low temperature tempering is usually very difficult to realize in industry because the heating is often carried out in gas combustion furnaces. With the development of electric and magnetic heating, such heat treatments can be carried out at low temperature both in industrial and laboratory scales. The aim of the present work is to investigate the effect of low temperature tempering on the hardness of an Fe–C–Mo alloy within a high-intensity magnetic field.

In the recent years, the effects of strong magnetic fields on various phase transformations in steels, such as martensite [1], bainite [2], ferrite [3] and pearlite [4] transformations, have attracted much interest. It has also been reported that the grain boundary character distribution and grain microstructure evolution are altered by applying a magnetic field [5]. The magnetic field can affect the morphology of carbide by increasing the carbide/ferrite interfacial energy and the magnetostrictive strain energy [6,7]. Previous work showed that the precipitation of some specific carbides in a medium carbon steel was considerably affected by applying strong magnetic fields [8,9]. Another aim of the present work is to investigate the effect of high magnetic field on the precipitation of transition carbides and alloy carbides in an Fe–2.8%C–3.0Mo(wt%) steel during low temperature tempering.

2. Experimental

In order to avoid any possible complication due to interactive effects of multiple solutes, the alloy studied was prepared by vacuum induction melting utilizing high purity electrolytic iron, graphite and molybdenum. The chemical composition is shown in Table 1. The alloy was homogenized at 1250 °C for 48 h after hot forging. Specimens of $7 \times 7 \times 25$ mm^3 were cut from the homogenized sample and austenitized at 915 °C for 30 min in an argon atmosphere followed by quenching in ice cooled brine to obtain a martensitic microstructure before subsequent tempering. The specimens were heat treated with and without a magnetic field of 12 T at 200 °C for 10 min and 60 min, respectively. After heat treatment, some specimens were polished and etched in a solution of 3 vol% nital for microscopy analysis. Two types of specimens were examined using transmission electron microscopy (TEM): thin foils and carbon extraction replicas. Some slices were cut from bulk specimens, and then mechanically ground to about 50 μm thickness. These specimens were further thinned using a twin-jet electro-polisher at 40 V. The electrolyte consisted of 10 vol% perchloric acid and 90 vol% glacial acetic acid. The thin foil samples were examined in a JEM-2010HT microscope operating at 200 kV for selected area electron diffraction (SAED) analysis in order to determine the overall microstructures and orientation relationship

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Table 1
Chemical composition of the investigated steel (wt%).

C	Mo	Si	Mn	P	S	Fe
0.28	3.0	< 0.004	< 0.001	< 0.003	< 0.004	Bal.

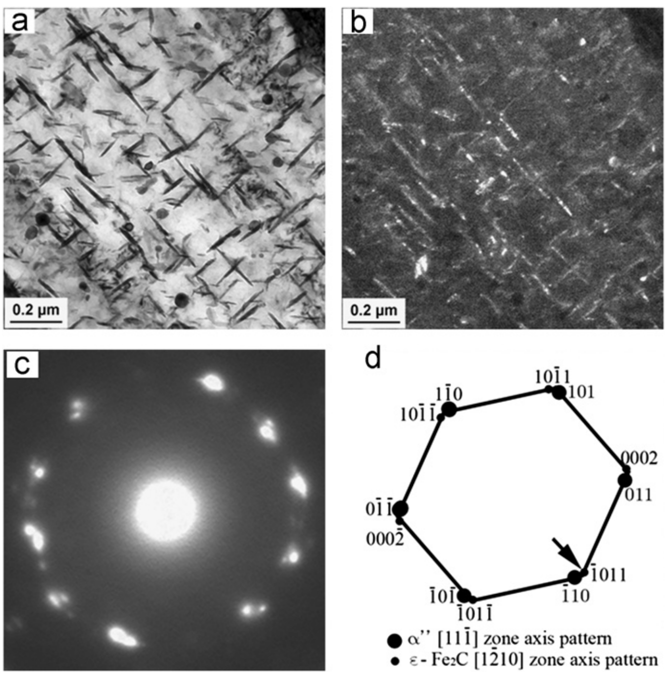

Fig. 1. Morphology and SAED patterns of ε-Fe_2C in the specimen tempered at 200 °C for 60 min at the presence of 12 T magnetic field. (a) Bright field, (b) dark field, (c) SAED pattern and (d) interpretation for the SAED pattern. Arrow in (d) marks the diffraction spot of a dark field pattern.

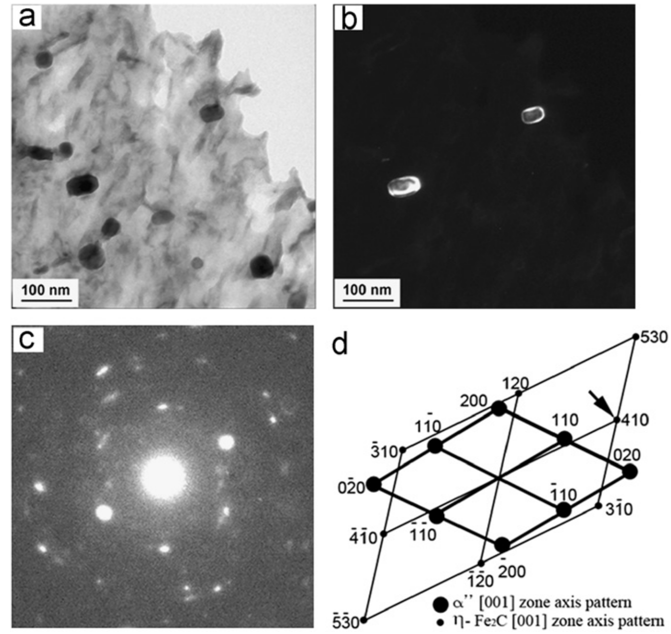

Fig. 2. Morphology and SAED patterns of η-Fe_2C in the specimen tempered at 200 °C for 10 min without the presence of magnetic field. (a) Bright field, (b) dark field, (c) SAED pattern and (d) the interpretation for the SAED pattern. Arrow in (d) marks the diffraction spot of a dark field pattern.

between the precipitation and the matrix. The carbon replica specimens with 3 mm diameter were hot-mounted in bakelite molding powder, and ground with silicon carbide paper down to 2000 grit and then polished using an Al_2O_3 suspension solution to a particle size of 0.5 μm. They were then chemically etched with a solution of 4 vol% nital for a few seconds. A carbon coating of 20–30 nm (brown gold color) was deposited onto the etched surface in a vacuum of 10^{-5} Torr. This film was then scored with a sharp blade to divide it into several smaller squares ($\sim$1 mm^2), followed by etching in a solution of 8 vol% nital to remove the carbon film, which was then washed in methanol and rinsed with distilled water. Finally, these replica films were mounted on copper grids before inserting them in the TEM.

3. Results

3.1. Identification of carbides

Figs. 1 and 2 show the morphology, the SAED patterns and the interpretation of the carbides precipitated in the specimens tempered at 200 °C. The diffraction analysis in Fig.1 shows that the carbide is ε-Fe_2C, precipitated from tempered martensite α″ since the orientation relationship satisfies $\left[11\bar{1}\right]_{\alpha''}//[1\bar{2}10]_{\varepsilon}$[10]. The dark field image was taken for ε-($\bar{1}011$) spot. Similarly, η-Fe_2C carbide in Fig. 2 was identified by the diffraction analysis, confirming that the orientation relationship between η-Fe_2C and martensite α″ is $[100]_{\alpha''}\|[001]_{\eta}$, which is in good agreement with the relationship reported in the literature [11]. The dark field image was taken for the η-(410) spot. Monoclinic χ-Fe_5C_2 was identified in the carbon extraction replicas using the SAED pattern from the [01$\bar{1}$] zone, as shown in Fig. 3.

3.2. Nucleation and morphology of carbides

Depending on the tempering conditions, carbides with various morphologies were precipitated in the matrix of martensitic laths/plates or their interfaces, as shown in Fig. 4. For instance, ε-Fe_2C formed as 100–200 nm long and 10–20 nm thick laths, whereas η-Fe_2C and χ-Fe_5C_2 have plate and flake shapes with 30–50 nm and 50–80 nm in width, respectively.

3.3. Precipitation sequence of carbides

Fig. 4 and Table 2 show TEM micrographs of iron carbides and carbide types in the specimens tempered at 200 °C for 10 min and 60 min, respectively. Only ε-Fe_2C and η-Fe_2C particles in (Fig. 4a) were formed in the specimens tempered for shorter holding time when a 12 T magnetic field was not applied. However, the specimens tempered for longer holding time, ε-Fe_2C, η-Fe_2C and χ-Fe_5C_2 particles were precipitated when a 12 T magnetic field was applied (Fig. 4b); in contrast, only ε-Fe_2C and η-Fe_2C particles were precipitated when tempered for longer holding time without the presence of the magnetic field. This indicates that the precipitation of χ-Fe_5C_2 was promoted by the high magnetic field.

4. Discussion

4.1. Influence of high magnetic field on carbide area fraction of carbides

Fig. 5 shows that the area fraction of the lath-like carbides (ε-Fe_2C) increases from about 0.30% in the specimen tempered for 10 min at 200 °C without the presence of high magnetic field to 2.4% in the specimen tempered for 60 min with the presence of high magnetic