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Original Research

Twin structure of the lath martensite in low carbon steel

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ABSTRACT

It has been well accepted that the martensites in quenched carbon steels exhibit two typical morphologies which are closely dependent on the carbon content, i.e. lath martensite in low carbon steels and lenticular martensite in high carbon steels. Based on conventional belief, the lath martensites in low carbon steels are with high density dislocations as the substructure, in contrast to twin substructure in lenticular high carbon martensite. In the present work, an intensive transmission electron microscopy investigation was made to characterize the microstructures of the lath martensite in a low carbon steel of 0.2 wt%C. It was found that lots of lath martensites consist of twin as their substructure, rather than high density dislocations. In addition, nanoscale precipitates cohering with ferrite matrix were found at the twin interfaces. The orientation relationships between the precipitates and the ferrite matrix are in good agreement with that of primitive hexagonal ω phase in titanium alloys and other bcc metals or alloys.

1. Introduction

It has long been recognized that rapid quenching of face-centered cubic (fcc) structured austenite in steels might result in the formation of body-centered cubic (bcc) or body-centered tetragonal structured martensite [1]. As one of the most important solid phase transformations in steels, the martensitic transformations have been consistently receiving much attention because of their technological importance and academic significance for the research and development of advanced steels [1–3]. In order to regulate the martensitic transformations and improve the mechanical properties of martensitic steels, numerous alloying elements such as C, N, Ni, Cr, Mn, etc. are usually incorporated in steels. Tremendous experimental investigations on martensitic transformation in steels have indicated that the microstructures and the mechanical behaviors of martensitic steels are closely related to the type and the content of alloying elements. Carbon, as the most important and effective alloying element in steels, could significantly influence the martensitic transformation behavior of carbon steels, including the volume fractions, the morphologies and the mechanical properties of martensites [1,4].

Although martensites can exhibit different morphologies in a large variety of alloying steels, i.e. lath, lenticular, butterfly, thin-plate, etc., martensites in Fe–C steels feature two typical shapes, lath and lenticular, depending on carbon content [5]. It was generally accepted that the lath martensites form in low carbon steels with 0~0.6 wt%C, whereas lenticular martensite becomes dominant morphology in high carbon steels with above 1.0 wt%C [6]. Nevertheless, there are some anomalous results reported on the morphologies of martensites in carbon steels. For example, some researchers observed lath martensites in quenched ultra-high carbon steel with 1.4 wt%C [7,8]. In addition, a trace of twin structure was observed in lath martensites in low carbon steel with 0.1 wt%C [9]. As a matter of fact, the mechanism for the dependence of martensite morphologies on carbon content is not clear, although this is very interesting and important for understanding the martensitic transformation in carbon steels.

Actually, the morphology, the crystallography and the microstructure of martensite in steels have been investigated for decades by numerous techniques such as optical microscopy, transmission electron microscopy (TEM) and scanning electron microscopy including electron backscattered diffraction [2, 10–13]. It was well acknowledged that the lath and lenticular (or plate) martensites in carbon steels possess different substructures inside the corresponding martensite variants, i.e. the lath martensites are with high density dislocations and lenticular martensites consist of numerous twins. In the early TEM observation on lath martensites of low carbon steels (< 0.5 wt%C), Kelly and Nutting claimed that the dislocations in lath martensites are with high density of the order of 10^{11}–10^{12} cm^{-2}, comparable to the dislocation density in very heavily cold-worked alloys [14,15]. Such

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high density of dislocations makes it impossible to analyze clearly the planes on which the dislocations occur or determine the Burgers vectors of these dislocations [14,15]. However, except for the steels with ultralow carbon content [4], 0.0026% for example, no researchers observed distinguishable high density dislocations in the martensites of low carbon steels with the carbon content greater than 0.1 wt%C. Note that low carbon martensitic steels perform good toughness even at as-quenched state with full lath martensite structure(or containing very few residual austenite phase). Apparently, this result is not supportable to the proposition that the lath martensite is with high density of dislocations comparable to severely deformed microstructures. Although some dark contrast areas were frequently observed inside the lath martensites on TEM observations, no convincing evidence was achieved to demonstrate that these contrast areas arise from high density of dislocations. In the present study, we carried out an intensive TEM investigation on low carbon steel of 0.2 wt%C, in attempt to clarify the microstructures of the lath martensite. It was suggested that the lath martensites of the present study are composed of twins as their substructure, rather than high density dislocations. In addition, the twin structures of the lath martensites were probed, and nanoscale precipitates cohering with ferrite matrix at the twin boundaries were observed.

2. Material and methods

Commercial low carbon steel with composition of C∼0.20 wt%, Mn∼0.85 wt%, Cr∼1.08 wt%, Fe∼ balance was selected in the present study. According to a model for predicting the martensitic transformation starting temperature (M_s), $M_s(\mathrm{K})=731-227(\mathrm{C+N})-17.6\mathrm{Ni}-22.5\mathrm{Mn}-17.3\mathrm{Cr}-16.2\mathrm{Mo}$, the M_s of the steel in the present study was calculated to be around 647 K [16]. The samples of $10\times10\times0.5$ (mm^3) were sealed in quartz tube under Ar atmosphere and austenitized at 1373 K for 30 min, followed by quenching into brine at 298 K. The specimens for TEM observation were prepared by grinding the discs to thickness of about 50 μm, and electro-polishing in a twin-jet electro-polisher with a chemical solution of 10% $HClO_4$ and 90% ethanol at 253 K. Phase constitutions were determined by X-ray diffraction with Cu Kα radiation at an accelerating voltage of 40 kV and a current of 200 mA. The microstructural observations were carried out on an optical microscope and a transmission electron microscope (JEM 2100F) operated at 200 kV.

3. Results and discussion

Because of the limited hardenability of low carbon steels, X-ray diffraction was conducted to inspect the constituents of the quenched samples. In order to analyze the diffraction of the quenched sample with 0.2%C with that of pure iron without carbon, Fig. 1 gives the diffraction profiles of these samples with the same treatments, i.e. austenization at 1373 K for 30 min, followed by quenching into brine at 298 K. One can see from the Fig. 1 that no trace of austenite or carbide was detected in the diffraction patterns, indicating that full martensitic microstructure forms in the 0.2%C sample during the quenching.

Fig. 2 shows the optical microscopy image and bright-field TEM micrograph of the quenched low carbon steel sample, in which typical morphology of lath martensite are observable, with the crystallographic features of packet and blocks. Fig. 2(b) indicates that under certain direction of incident electron beam, parallel martensite variants exhibit different contrast, i.e. bright blocks and dark blocks. Especially, in the dark martensite blocks, one can see large amounts of dotted black structures. Note that these dotted

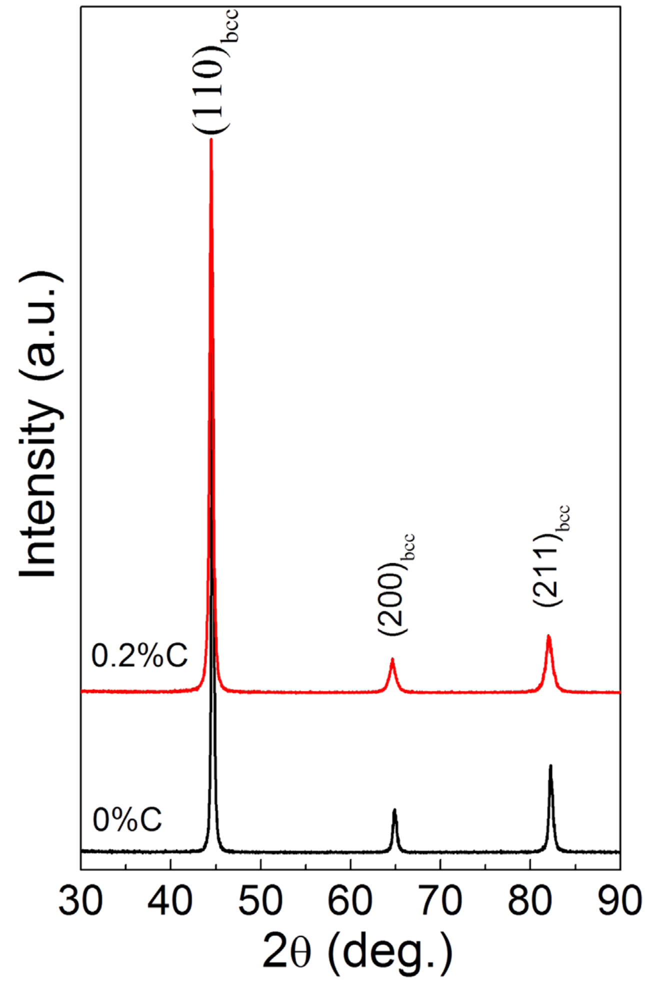

Fig. 1. X-Ray diffraction profiles of quenched pure iron and low carbon steel with 0.2%C.

black structures have long been considered as high density of dislocations [1,15]. In the present TEM observations, no distinct evidence of high density dislocations was observed. Actually, upon tilting the TEM specimen the contrasts of the bright blocks and dark blocks can be varied considerably, suggesting that these dotted black structures could not be ascribed to high density dislocations. Further, under proper tilting of the TEM specimen, twinned structures (as shown in Fig. 2(a)) emerge in some martensite variants. Thus, it is reasonable to conclude that twins, rather than high density dislocations, might be the substructure of the lath martensite in low carbon steels of the present study. As a matter of fact, high density dislocations were only observed in the martensite with ultralow carbon content such as 0.0026%C [2]. There is no convincing evidence to ascribe the dark contrasts of martensite blocks observed in early TEM studies to be high density dislocations.

In order to probe the detailed substructures inside the lath martensites, a further TEM characterization was carried out on the lath martensite variants. Fig. 3 shows the dark-field TEM micrograph and the corresponding selected area electron diffraction (SAED) patterns of a typical lath martensite. According to the bright field micrograph of twins as shown in Fig. 3(a) and the corresponding SAED pattern shown in Fig. 3(b), these twins are recognized to be {112} < 111> type, which is the most popular twin structure in bcc metals and alloys. This observation suggests that twins might be involved in lath martensite in low carbon steels. As for the contrast arising from dotted microstructures in