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An atomic mechanism for the formation of nanotwins in high carbon martensite

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ABSTRACT

High carbon martensite possesses outstanding hardness and strength but poor ductility, even though it consists of numerous twins which have been regarded as the favorable structure for deformation in metals and alloys. So far, the role of high density of twins in the conflict, fully twined structure and poor ductility, in high carbon martensite is not clear. In this letter, we proposed an atomic mechanism for the formation of nanotwins to reveal the nature of poor ductility of high carbon martensite. This mechanism suggests that interstitial carbon atoms stabilize ω phase which facilitates the nucleation and termination of {112} <111> type nanotwins in high carbon martensite. The nanoscale ω particles embedded in boundaries of nanotwins pins naonotwins, impeding the motion of twins in the martensite. This mechanism constructs a correlation between the nanotwins and poor ductility of martensite in high carbon steels.

1. Introduction

Owing to the good balance of mechanical properties and cost, high carbon steels have been popular in railroad and construction industries for more than a century. In order to improve their mechanical properties such as hardness and strength, a convenient heat treatment is always employed to manipulate the microstructure by martensitic transformation [1–5]. By the transformation, the generated martensites are characterized by morphology of plates with distinguished {112} <111> type twins and the thickness of twins depends upon the contained carbon content (higher carbon content, thinner plate martensite and narrower twins) [6–9]. Limited to near-sonic speed of martensitic transformation with elevated transformation start temperature, the details of twin forming in ferrous martensite cannot be in-situ observed. So far, the formation mechanism of the transformation twining has not been fully understood, although several models based on the shuffle mechanism were proposed to explain the formation of transformation twins [10,11]. According to this shuffle mechanism, transformation twins could be obtained by a repeated translation ($\pm a/6\langle 1\bar{1}1\rangle$) of successive groups of three $\{\bar{1}12\}$ planes, where the relative alterations of certain subsets of atoms are less than an interatomic distance [10]. Actually, the shuffle mechanism is successful only in explanation of the motion of twins themselve, but cannot be employed to explicate the contradictory, i.e. numerous ultra-fine twins and poor ductility of high carbon martensite [6]. Crystallographically, ultrafine twins, with a small twinning shear and low magnitude of shape strain, are normally considered as the favorable substructure for plastic deformation in metals and alloys [12,13].

Very recent intensive characterizations by transmission electron microscopy (TEM) demonstrated that the martensites in carbon steels are not uniform solid solutions of ferrite, but a mixture of twined ferrite and nanoscale ω phase in twin boundaries [14–17]. The ω phase is a common phase often observed in bcc metals and alloys, such as β-Ti (Zr or Hf) alloys, β-brass, heavily deformed Mo and Ta as well as some Fe-based high alloys [18–23]. It has long been recognized that the presence of ω phase greatly degrades the ductility of the metals and alloys. As such, in the context of the negative influence of ω phase on ductility and the affinity between the twins and ω phase, revisiting the formation mechanism of ultrafine twins in high carbon martensite could provide new insight into the outstanding hardness and poor ductility of martensite in

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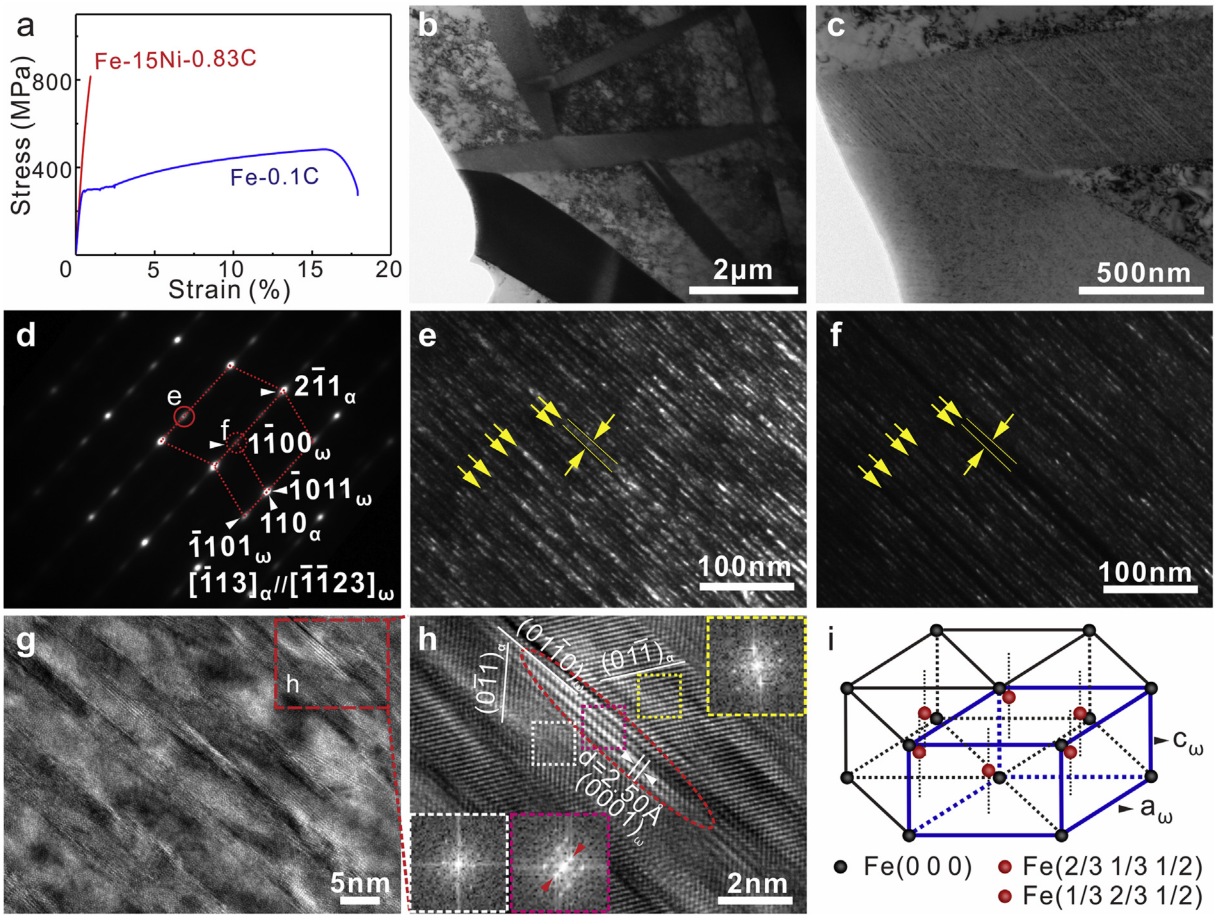

Fig. 1. The tensile curves of quenched carbon steels and the TEM results of as-quenched Fe-15Ni-0.83C. a) Tensile stress-strain curves of as-quenched Fe-15Ni-0.83C and Fe-0.1C. b) Bright-field micrograph of plate martensite. c) Bright-field micrograph of a martensite with large amounts of nanotwins. d) The SAED pattern of the twin region in the martensite of Fig. 1c. e) and f) Dark field images captured by using the diffraction spots outlined by solid and dotted circle in Fig. 1c, respectively. g) HRTEM image of {112}< 111> twins together with the ω phase at the twinning boundaries. h) Localized magnification of {112}< 111> twins together with the ω phase at the twinning boundaries and corresponding FFT patterns. i) Schematic crystal structure of ω phase in carbon steels.

high carbon steels.

In this letter, we prepared high carbon steel of Fe-15Ni-0.83C (wt %) with martensitic transformation start temperature below room temperature, and meticulously investigated the microstructure of nanotwins in the martensites induced by cryogenic quenching and by deformation, respectively. According to the TEM results, a new mechanism for the nanotwin formation was proposed to reveal the correlation between the embrittlement of high carbon martensite and the microstructure of nanotwins. This mechanism could provide new insight into the origin of the poor ductility of high carbon martensitic steels.

2. Materials and methods

High carbon steel of Fe-15Ni-0.83C (wt %) ingot was melted in a vacuum induction furnace and then hot forged. The chemical compositions were analyzed by infrared absorption spectrum and inductively coupled plasma-atomic emission spectroscopy. All specimens for tensile tests were sealed into quartz tubes under Ar atmosphere and austenized for 30 mins at 1373 K. After austenization, part of specimens were quenched into liquid nitrogen, and part of specimens were quenched into brine at 298 K. The phase constitutions of the specimens were determined by X-ray diffraction with Cu Kα radiation at an accelerating voltage of 40 kV and a current of 200 mA. The tensile test of specimens was performed on a Sans 5504 mechanical tester at a tensile strain rate of 1×10^{-3} s^{-1}. To compare the mechanical properties of as-quenched high carbon steel with low carbon steel, Fe-0.1C (wt %) specimens for tensile test were fabricated by the same melting method and treatments with Fe-15Ni-0.83C (wt %) steel. The specimens for transmission electron microscopy (TEM) were prepared by electro-polishing in a twin-jet electro-polisher with a chemical solution of 10% $HClO_4$ and 90% ethanol. Microstructural observations were carried out on a JEM 2100F operated at 200 kV.

3. Results and discussion

3.1. The mechanical properties and microstructure of the quenched martensite

Owing to the structural stability of Fe-15Ni-0.83C (wt %) alloy, the specimens are fully metastable austenite with face-centered cubic (*fcc*) crystal structure after austenization and then quenching into 298 K brine. To introduce the martensitic transformation by quenching, the austenized specimens were quenched into liquid nitrogen (77 K). Similar to other high carbon steels, the as-quenched Fe-15Ni-0.83C exhibited very poor ductility without obvious plastic deformation before fracture, in contrast to the as-quenched low carbon steel with a remarkable elongation, as shown in Fig. 1a. To probe the structural aspects responsible for