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Effect of the state of carbon on ductility in Fe-0.017mass%C ferritic steel

Nobuyuki Yoshimura[a,*], Kohsaku Ushioda[a,b], Mitsuharu Yonemura[c], Motomichi Koyama[d], Masaki Tanaka[d], Hiroshi Noguchi[d]

[a] Technical Research & Development Bureau, Nippon Steel & Sumitomo Metal Corp., 20-1 Shintomi, Futtsu, Chiba 293-8511, Japan
[b] Kanazawa University, Kakuma, Kanazawa, Kanazawa 920-1192, Japan
[c] Technical Research & Development Bureau, Nippon Steel & Sumitomo Metal Corp., 1-8 Fuso, Amagasaki, Hyogo 660-0891, Japan
[d] Faculty of Engineering, Kyushu University, 744 Moto-oka, Nishi, Fukuoka, Fukuoka 819-0395, Japan

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ABSTRACT

The influence of the state of carbon on ductility in Fe-0.017mass%C alloy was systematically investigated. Moreover, the changes in dislocation density, dislocation substructure, and dislocation character with tensile strain were evaluated using X-ray line profile analysis together with transmission electron microscopy. The solute carbon maintains uniform elongation while simultaneously increasing the ultimate tensile strength by increasing the work-hardening rate; however, post-uniform elongation is significantly impaired by the occurrence of dynamic strain aging (DSA). The coarse intergranular cementite leads to superior uniform elongation; however, post-uniform elongation deteriorates presumably owing to the void formation in the cementite/matrix interface or the fracture of cementite. Meanwhile, the fine transgranular cementite increases the yield strength, thus impairing the uniform elongation; however, it maintains post-uniform elongation. This is because small cementites less than about 1 µm in size do not deteriorate the post-uniform elongation. The solute carbon prominently increases the dislocation density, particularly the edge dislocation density, with tensile strain owing to DSA, leading to the prohibition of dislocation cell structure formation.

1. Introduction

The control of carbon is extremely important to improve the mechanical properties of high-strength steels. The microstructure of high-strength steels is generally so complex that conducting an independent investigation regarding the influence of carbon is a difficult task. Therefore, in the present study, only the state of carbon in ferrite single-phase steel was varied, keeping the grain size, dislocation density, and texture constant.

It has been reported that the presence of carbon in a solid solution impairs post-uniform elongation owing to the occurrence of dynamic strain aging (DSA) during tensile deformation at room temperature [1–4]. Furthermore, when carbon precipitates as the fine transgranular cementites, uniform elongation is impaired owing to the increase in yield strength as compared with that of the specimen with intergranular cementites [2,3]. Meanwhile, the coarse intergranular cementites have been reported to impair post-uniform elongation owing to the easy and rapid nucleation of voids around cementite followed by their coalescence as compared with steels having fine transgranular cementites smaller than 1 µm [2,3]. Recently, Koyama et al. [5] conducted an in-situ scanning electron microscopy (SEM) observation to elucidate the effect of cementite morphology on damage formation during simple tensile and cyclic loading tests. They observed the crack initiation or void formation in the intergranular cementite plates, whereas in the specimen with transgranular cementite, intergranular cracking was also observed presumably owing to the slip localization associated with the limited available free slip path within the grain [5]. In reality, a detailed mechanism of the effect of the state of carbon on ductility has not been elucidated yet because systematic research has not yet been conducted. Therefore, this study aims to accurately obtain systematic experimental data by widely varying the state of carbon in Fe-0.017mass%C (hereafter, %) ferrite single-phase steel and elucidate the mechanism behind this. In the present study, analyses of the stress-strain curves of the tensile test and the void formation of fractured specimens were carefully conducted together with X-ray line profile analysis and transmission electron microscopy (TEM) observation focusing on the evolution of dislocation density and substructure considering its character with tensile strain.

* Corresponding author.
E-mail addresses: yoshimura.26c.nobuyuki@jp.nssmc.com (N. Yoshimura), ushioda.cd8.kohsaku@jp.nssmc.com (K. Ushioda), yonemura.4k8.mitsuharu@jp.nssmc.com (M. Yonemura), koyama@mech.kyushu-u.ac.jp (M. Koyama), masaki@zaiko.kyushu-u.ac.jp (M. Tanaka), nogu@mech.kyushu-u.ac.jp (H. Noguchi).

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Table 1
Chemical compositions of the steel used (mass%).

C	Si	Mn	P	S	Ni	Ti	Al	B[a]	N[a]	O[a]
0.017	< 0.003	< 0.003	< 0.002	< 0.0003	< 0.003	< 0.002	0.052	< 3	9	15

[a] Massppm.

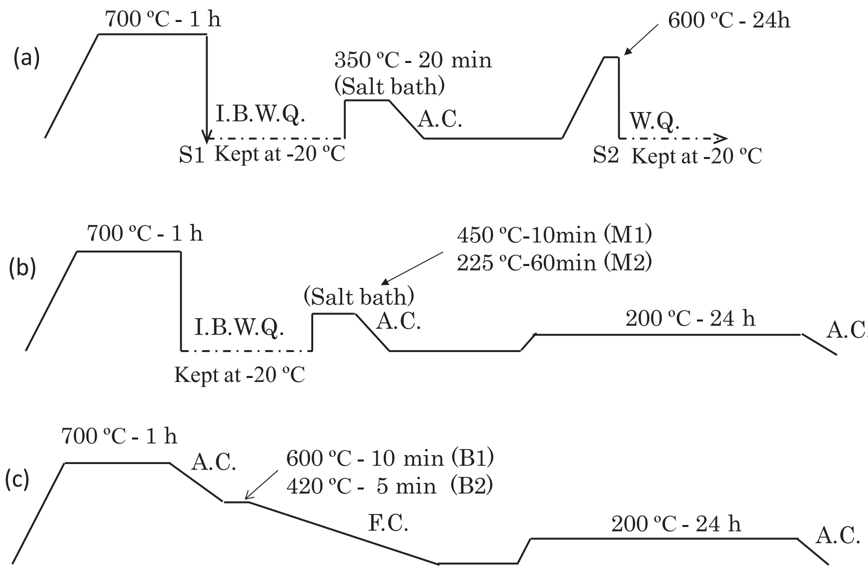

Fig. 1. Heat treatments to change the states of carbon. (a) Solute carbon (S1, S2), (b) transgranular cementite (M1, M2), and (c) intergranular cementite (B1, B2). I.B.W.Q.: iced-brine-water quenching, W.Q.: water quenching, A.C.: air cooling.

2. Experimental procedures

The steel used herein has a ferrite single phase with 0.017%C, whose chemical compositions are given in Table 1. A vacuum-melted ingot with the addition of 0.05%Al was prepared to control the grain structure by fixing N as AlN. The ingot after annealing at 1050 °C for 60 min was hot rolled in the austenite region from 125 to 13 mm in thickness and subsequently air cooled to room temperature. The average grain diameter was approximately 50 µm. The plates with 120-mm width, 200-mm length and 13-mm thickness were annealed at 700 °C for 60 min followed by iced-brine-water quenching to keep the carbon in solid solution. The quenched plates were subsequently subjected to the heat treatment described in Fig. 1(a)–(c). Fig. 1(a) shows the heat treatment to keep carbon in solid solution. Specimen S1 quenched from 700 °C is expected to have more carbon in solid solution than the specimen S2 quenched from 600 °C. The quenched specimens were kept below −20 °C to prevent carbon diffusion except for the periods for specimen preparation such as cutting and grinding. Fig. 1(b) shows the heat treatment for precipitating carbon as fine transgranular cementites without solute carbon. The specimen aged at 450 °C (M1) is expected to have fine transgranular cementites, whereas the specimen aged at 225 °C (M2) has comparatively finer and denser transgranular cementites. Fig. 1(c) shows the heat treatment for precipitating carbon as coarse intergranular cementites without solute carbon. The specimen after air cooling from 700 to 600 °C followed by furnace cooling (B1) is expected to have coarse intergranular cementites, whereas the specimen air cooled from 700 to 420 °C followed by furnace cooling (B2) is expected to have slightly smaller intergranular cementite.

Tensile tests were conducted in the rolling direction of the specimen with different states of carbon, whose dimensions in the parallel part were 25 mm (length) × 14 mm (width) × 12 mm (thickness). An extension meter with a 24-mm gage length was used. The nominal strain rate was $6.9 \times 10^{-3}\,s^{-1}$. To investigate the necking and void formation of the fractured specimen, the plane parallel to the longitudinal section was cut and polished for observation.

Rigorous X-ray line profile analysis was conducted to evaluate the change in not only the dislocation density but also the arrangement and character of dislocation with tensile strain by exploiting the recently developed procedure by Ungár et al. [6]. One of the present author, Yonemura et al. [7], has previously applied X-ray line profile analysis to evaluate the development of dislocation density and substructure during cold rolling of the Ni-20%Cr alloy. They verified the results of X-ray line profile analysis by simultaneously performing the positron annihilation lifetime analysis and TEM observation. Therefore, in the present study, the simultaneous evaluation of dislocation by means of X-ray line profile analysis and TEM observation was performed to investigate the influence of the state of carbon on dislocation behaviors during tensile deformation. X-ray diffraction was performed by means of the general focused optical system using RIGAKU ULTIMATE-III exploiting a Cu target operated at 40 kV and 40 mA. The six diffraction profiles of {110}, {200}, {211}, {220}, {310}, and {222} for different Bragg reflections within the 2θ angle range of 140° were measured. The $K\alpha$ peak was separated into $K\alpha_1$ and $K\alpha_2$ components by a *pseudo* Voigt function. As the measured intensity is the convolution of the facility and true profile functions, the correction was performed to obtain the true physical profile function using LaB_6 (NIST SRM 660b) with the fine uniform grain having good crystallinity. Rigorous X-ray line profile analysis was conducted simultaneously using the *modified* Williamson–Hall and the *modified* Warren–Averbach methods [6,7]. The elastic anisotropy was assumed to quantitatively evaluate the dislocation density, size of the strain field of dislocations, and fraction of the screw/edge components during tensile deformation as a function of the carbon states. Furthermore, TEM observation was undertaken to observe the evolution of the dislocation substructure as a function of tensile strain considering the effect of the carbon states. Burgers vector of dislocations of the specimen strained by 5% was determined by TEM based on the well-known procedure $\mathbf{g}\cdot\mathbf{b} = 0$, where $\mathbf{g}$ is the reciprocal lattice vector and $\mathbf{b}$ is Burgers vector. Thus, the result of X-ray line profile analysis was verified by TEM.