Available online at www.sciencedirect.com
ScienceDirect
Acta Materialia 57 (2009) 5283–5291
Acta MATERIALIA
www.elsevier.com/locate/actamat

Relationship between local deformation behavior and crystallographic features of as-quenched lath martensite during uniaxial tensile deformation

M. Michiuchi *, S. Nambu, Y. Ishimoto, J. Inoue, T. Koseki

Department of Materials Engineering, Graduate School of Engineering, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan

Received 16 March 2009; received in revised form 5 June 2009; accepted 8 June 2009
Available online 2 September 2009

Abstract

Electron backscattering diffraction patterns were used to investigate the relationship between local deformation behavior and the crystallographic features of as-quenched lath martensite of low-carbon steel during uniform elongation in tensile tests. The slip system operating during the deformation up to a strain of 20% was estimated by comparing the crystal rotation of each martensite block after deformation of 20% strain with predictions by the Taylor and Sachs models. The results indicate that the in-lath-plane slip system was preferentially activated compared to the out-of-lath-plane system up to this strain level. Further detailed analysis of crystal rotation at intervals of approximately 5% strain confirmed that the constraint on the operative slip system by the lath structure begins at a strain of 8% and that the local strain hardening of the primary slip systems occurred at approximately 15% strain.

Keywords: Martensitic steel; Plastic deformation; Electron backscattering diffraction; Crystal rotation

1. Introduction

Conventional carbon and alloy steels generally form martensite when they are rapidly cooled or quenched from the austenite state, which is stable at elevated temperatures. Since the as-quenched martensite exhibits high-strength and hardness due to its distinct fine microstructure with supersaturated solid-solution carbon and a high density of dislocations, it is often used as the matrix in high-strength, hard steels. The phase, however, exhibits extremely low ductility, which has limited the use of martensitic steels as structural materials. Therefore, its deformation behavior needs to be clarified for the better use of the phase.

After the pioneering work by Vylezhnev et al., in which the decrease in the width of the X-ray interference line of as-quenched martensite during the early stage of deformation was first discovered [1], the combination of the cold-rolling process and X-ray diffraction (XRD) has been the favored method for investigating the microstructural evolution of as-quenched martensitic steels subjected to large deformations [2–5]. Khlebnikova et al. applied the procedure to the lath martensite of as-quenched pseudosingle crystals of medium-carbon steel, and identified a texture [0 0 1] (1 1 0) typical of body-centered cubic (bcc) metals after large reduction [4]. Schastlivtsev et al. inferred that the slip planes of as-quenched lath martensite were (1 1 0), (1 1 2) and (1 2 3), which are typical for bcc materials, and from further detailed analysis of the crystal orientation distribution, suggested that the primary slip plane in the as-quenched martensite of low-carbon steel is close to the (1 1 0) and (1 1 2) planes [5]. Even though the XRD studies revealed the overall deformation behavior of martensite, the detailed local deformation mechanism is not yet fully understood.

Recently, electron backscattering diffraction patterns (EBSPs) have been increasingly utilized as a powerful tool

* Corresponding author. Tel./fax: +81 3 5841 7111.
E-mail address: michiuchi@metall.t.u-tokyo.ac.jp (M. Michiuchi).

1359-6454/$36.00
doi:10.1016/j.actamat.2009.06.021

for clarifying the microstructural features of steels, such as the evolution of the microstructure during phase transformation [6,7]. The EBSP technique combined with a uniaxial tensile test can be used to evaluate the relationship between the local deformation behavior and the crystallographic features of the martensite phase [8]. However, since as-quenched martensitic steel generally fractures at small plastic strains, the EBSP analysis of as-quenched martensite during tensile loading has been limited to the very early stages of plastic deformation, less than 4% strain, even when ultra-low-carbon steel is employed [9].

This constraint can be eliminated by considering multilayered steel composites, in which as-quenched martensite steel can be elongated uniformly to over 50% strain by choosing a proper combination of the layer thickness and the mechanical properties of the components [10,11]. We recently studied the local deformation of as-quenched lath martensite by performing tensile tests on a multilayered steel composite, and showed that the slip bands develop primarily along martensite lath during an elongation of less than 20%, and that the work-hardening increases after strain of 15–20%. At this strain level the rate of increase of dislocation density increases significantly [11]. Even though slip band formation is a good indicator of the slip activity, it is difficult to identify the active slip systems exclusively from the shape of the slip bands. Accordingly, the present study aims to clarify the relationship between the local activity of the slip system and the crystallographic features of as-quenched lath martensite during uniform elongation of 20% by applying EBSP to a multilayered steel composite. In the present study, a crystallographic investigation of the same area of observation as that in the previous study [11] is presented first, which is followed by a detailed investigation conducted on the same material.

2. Experimental procedure

The multilayered steel composite consists of high-strength (HS) steel and highly ductile steel layers. Carbon steel (0.13wt.%) was employed as the HS steel layer, and type 304 stainless steel (SS304) was used as the ductile component. The chemical composition of each component is shown in Table 1. The initial thicknesses of HS steel and SS304 were 6 and 15 mm, respectively. The HS steel was sandwiched by SS304, and pure Ni sheets (0.5 mm in thickness) were inserted between the HS steel and SS304 as a decarburization barrier. The thickness of the as-sandwiched steel composite was reduced to 1.0 mm by hot-rolling at 1473 K and subsequent cold-rolling, so that the final thickness of the HS steel layer was approximately 150 μm.

Table 1
Chemical compositions of constituent steels (wt.%).

	C	Si	Mn	Ni	Cr	Cu	Mo	Fe
HS steel	0.13	0.25	0.92	0.02	0.83	0.18	0.32	Bal.
SS304	0.05	0.54	0.90	8.08	18.14	–	–	Bal.

The resulting laminate steel was machined to a specimen size of $1.0 \times 5.0 \times 25.0\ mm^3$. The specimen was water-quenched after heat treatment at a temperature of 1373 or 1473 K for 120 s, to obtain a full lath martensitic structure in the HS steel layer. Prior to the tensile test, the surface of the specimen was electrochemically polished with chromic–phosphoric acid solution. The crystallographic analysis of martensite during the tensile test was performed with a Tex SEM Laboratories EBSP automatic analysis system attached to a Carl Zeiss LEO 1550 scanning electron microscope (SEM) with a scan step of 0.2 or 0.5 μm. The rolling (RD), transverse (TD) and normal (ND) directions of the specimen were used for the standard coordinate system in the crystallographic orientation analysis. The tensile direction corresponds to RD in this study.

3. Crystallographic analysis of lath structure

In the case of low-alloy steels, the Kurdjumov–Sachs (K–S) relationship is generally accepted as the relationship between the crystal orientations of prior austenite (γ) and martensite (α′), which is expressed as $(1\,1\,1)\gamma \| (1\,1\,0)\alpha'$ $[1\,0\,1]\gamma \| [1\,1\,1]\alpha'$. The martensitic transformation breaks down the prior austenite grain into a three-level hierarchical microstructure: martensite lath, block and packet [12–14]. A martensite lath is a single-crystal with high dislocation density and lath-like unit cell that is parallel to both the $\{1\,1\,0\}\alpha'$ and $\{1\,1\,1\}\gamma$ planes. A block is a bundle of martensite laths with approximately the same crystal orientation. A packet is a bundle of blocks developed with a common invariant $\{1\,1\,1\}\gamma$ plane. Consequently, the microstructure of a packet can be assumed to be a stack of $(1\,1\,0)\alpha'$ planes (lath planes) with a common rotation axis $[1\,1\,0]\alpha'$ [15,16]. Knowing this fact, the crystallographic orientations of the lath boundary and lath plane in a single packet can be identified by finding a common pole from at least three independent blocks in the $(1\,1\,0)\alpha'$ pole figure. For example, the $(1\,1\,0)\alpha'$ pole figure obtained from three independent blocks (B1, B2 and B3) in the same packet is shown in Fig. 1. The three different symbols in the pole figure (Fig. 1b) correspond to the $(1\,1\,0)\alpha'$ poles of the three blocks; the same symbols are used in the crystal orientation map (Fig. 1a). The three independent blocks enable us to determine a unique common pole as indicated by the arrow in Fig. 1b.

4. Results and discussion

4.1. Difference in overall microstructure between as-quenched and plastically strained martensites

Optical micrographs of as-quenched specimen and of specimen that was quenched and then subjected to 20% tensile load are shown in Fig. 2. The multilayered steel composite was water-quenched after annealing at 1373 K for 120 s. The as-quenched HS steel exhibited a fully developed lath martensite structure, where the average grain