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Citation

Issue Date
2015-01-01

URL
http://hdl.handle.net/2433/217363

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Type
Journal Article

Textversion
publisher

Kyoto University
Relationship between local stress field in austenite and variant selection in deformation-induced martensitic transformation in Fe-24Ni-0.3C alloy

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Abstract

The present study investigated the relationship between local stress fields in austenite grains and variant selections in deformation-induced martensitic transformation in an Fe-24Ni-0.3C (mass \%) polycrystalline alloy. The local stress fields in austenite grains were measured by synchrotron radiation X-ray diffraction in SPring-8. We examined the variant selection rule based on the interaction energy between applied stress and shape deformation accompanying transformation (according to Patel and Cohen model). The results indicated that the formed martensite variants had positive interaction energy calculated using either the local stress field measured or the macroscopic tensile stress as the applied stress. The interaction energy criterion using the measured local stress field could show the better correlation with the observed variant selection in deformation-induced martensitic transformation than that using uniaxial tensile stress, although the variant selection was still not completely explained.

Keywords: Fe polycrystalline alloy; deformation-induced martensitic transformation; variant selection; local stress field; synchrotron radiation

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1. Introduction

Deformation-induced martensitic transformation plays an important role on transformation-induced plasticity (TRIP) and super-elasticity in metallic materials. It is well known that ferrous $\alpha'$ martensite with bcc or bct structure satisfies Kurdjumov–Sachs orientation relationship with respect to parent austenite: $\{111\}_A // \{011\}_M$, $<101>_A // <111>_M$, where the subscripts A and M represent austenite and martensite, respectively. Accordingly, there are 24 equivalent crystallographic variants of martensite that can be transformed from a single grain of austenite. Generally, some specific variants of martensite preferentially form in deformation-induced martensitic transformation, which is so-called variant selection. Although several models for explaining the variant selection in deformation-induced martensitic transformation have been proposed (Patel-Cohen model [1], Bogers-Burgers model [2], etc.), variant selection rules, especially in polycrystalline materials, have not yet been clearly understood. Ueda et al. [3] reported that Patel-Cohen model could not explain the variant selection of stress-induced martensite (happening in elastic deformation region of austenite) in the vicinity of tilt boundaries in Fe-Ni bicrystals. Recently, Chen et al. [4] reported that neither Patel-Cohen model nor Bogers-Burgers model could account for the martensite variants formed by deformation-induced martensitic transformation in a polycrystalline SUS304 stainless steel. A problem in the previous studies up to now is the assumption that the stress condition inside a grain is uniform and it is the same as the externally applied stress. Nowadays, Kajiwara et al. [5] developed a novel technique to evaluate local stress field inside polycrystalline materials through synchrotron radiation X-ray diffraction. In this study, local stress fields in austenite grains during uniaxial deformation were in-situ measured by synchrotron radiation X-ray diffraction in SPring-8, and relationship between the measured local stress field in austenite and the variant selection in deformation-induced martensitic transformation was investigated.

2. Experimental procedure

An Fe-24Ni-0.3C (mass %) alloy was used in the present study. The specimen was austenitized at 1300 °C for 10 min in vacuum and then water-quenched. The mean austenite grain size of the specimen measured by line interception method was 350 μm, and the martensitic transformation start temperature (Ms) measured by differential scanning calorimetry was -20 °C. After the heat treatment, the specimen was electro-polished in a solution of 10 % HClO4 + 90 % CH3COOH to remove the surface deformed layer. Then, a tensile test specimen with gage length of 1.5 mm, width of 2.1 mm, and thickness of 0.21 mm was prepared. The specimen was deformed in uniaxial tension manually at room temperature on a tensile testing machine settled at beam-line BL28B2 in SPring-8. During the tensile test, white X-ray micro beam with dimensions of 30 μm × 30 μm was scanned on the specimen. The crystal lattice plane spacing was measured from wave length and diffraction angles of each diffraction spot in the Laue pattern obtained. Two-dimensional stress tensor of the measured point was derived from the change in lattice plane spacing using elastic constants $C_{11} = 179.1$ GPa, $C_{12} = 109.5$ GPa, and $C_{44} = 115.7$ GPa [6]. These elastic constants were measured by using single crystal of Fe-25Ni-0.3C (mass %). The detailed procedures for measuring the local stress field by synchrotron radiation X-ray diffraction are described in a reference [5]. The microstructure of the specimen during tensile test was observed by optical microscopy. Crystallographic orientation analysis of the deformation-induced martensite in an identical area was carried out by electron backscattering diffraction (EBSD) analyzer in scanning electron microscopy (SEM, FEI: XL30S-FEG) operated at 15 kV.

3. Results and Discussion

Figure 1(a) is an optical microscopy image of the specimen after tensile deformation to a strain of 0.94 % (external stress of 47.5 MPa). The measured local stress fields are expressed as two vectors corresponding to the 2-dimensional principal stress. The color of arrows (vectors), i.e., red or blue, represent tensile or compressive stress, respectively. In addition, the length of arrows corresponds to the magnitude of the principal stress. It is found from Fig. 1(a) that the local stress fields in austenite grains are very much different from the uniaxial tensile stress externally applied. An optical microscopy image of the same area as (a) after tensile deformation to a strain of 7.0 % (external stress of 63.9 MPa) is shown in Fig. 1(b). The deformation-induced martensite can be observed as surface relieves. Figures 2(a) and (b) are EBSD phase map and orientation map (showing only martensite) of the specimen.
after tensile deformation to a strain of 14 %. The measured area corresponds to the white broken rectangle in Figs. 1(a) and (b). The red and green colors in Fig. 2(a) indicate austenite and martensite, respectively. By comparing the experimentally measured \{001\}_M poles with those showing ideal orientations of 24 martensite variants that can transform from the austenite grain (Fig. 2(c)), it was found that V7, V15, and V16 formed preferentially.

Fig. 1. Optical microscopy images of the specimen after tensile deformation to strains of (a) 0.94 % and (b) 7.0 %. Local stress fields are also shown as arrows corresponding to the local principal stresses in (a). The color of arrows represent tensile stress (red) or compressive stress (blue), and the length and direction of arrows correspond to the magnitude and direction of the local principal stress. The tensile direction is parallel to the horizontal direction in the figure.

Fig. 2. (a) A phase map and (b) an orientation map obtained by EBSD analysis of the specimen after tensile deformation to a strain of 14 %. The measured area corresponds to the white broken rectangle in Fig. 1. (c) A \{001\}_M pole figure showing \{001\} poles of martensite experimentally obtained (colored) together with \{001\} poles of the ideal 24 K-S variants of martensite that can appear from the austenite grain (black).

Fig. 3. \(U\) values calculated for 24 martensite variants using (a) the experimentally measured local stress field and (b) the uniaxial tensile stress externally applied.

According to Patel and Cohen [1], interaction energy \(U\) between the applied stress field and shape deformation accompanying martensitic transformation can be expressed as:

\[
U \text{ (Mpa)} = \frac{1}{100} \times \sum_{i=1}^{24} U_i
\]
where \( \tau \) is the shear stress resolved on the habit plane, \( \sigma \) is the stress component normal to the habit plane, \( \gamma \) and \( \varepsilon \) are the shear and dilatational strains associated with the shape deformation in martensitic transformation. According to the model, it is expected that the martensite variants with large positive \( U \) values preferentially form in deformation-induced martensitic transformation. The \( U \) values for 24 martensite variants were calculated and summarized in Fig. 3(a). The value of \( \gamma \) and \( \varepsilon \) calculated from the phenomenological theory of martensite crystallography (PTMC) are 0.2303 and 0.005215, respectively. For the PTMC calculation, the lattice parameters of 0.3590 nm (austenite) and 0.2854 nm (martensite) in Fe-33Ni were used [7]. In Fig. 3(a), the \( \tau \) and \( \sigma \) were obtained from the synchrotron-measured local stress field before martensitic transformation at the area indicated by the white broken rectangle shown in Fig. 1(a). For comparison, \( U \) values calculated using the uniaxial tensile stress externally applied (63.9 MPa) are also shown in Fig. 3(b). As shown in Figs. 3(a) and (b), the observed martensite variants of V7, V15 and V16 have positive \( U \) values in both cases. When the externally applied uniaxial tensile stress is used for calculation, several variants which did not form actually, i.e., V1, V2, V8, V23 and V24, also have large \( U \) values. In contrast, the formed variants of V15 and V7 have the maximum and second maximum \( U \) values based on the calculation using the measured local stress field. However, there are still several variants whose \( U \) values are higher than the formed V16 in Fig. 3(b). The results suggest that the Patel and Cohen interaction energy criterion using the measured local stress field can show the better matching with the actual variant selection. However, it is still insufficient to explain the variant selection completely even when the measured local stress field is taken into account. Although the results are not shown here, the same tendency for variant selection was observed in the other analyzed regions.

4. Conclusions

Local stress fields in austenite during tensile deformation were measured by synchrotron radiation X-ray diffraction and the relationship between the variant selection in deformation-induced martensitic transformation and the measured local stress field in austenite was investigated. It was found that the formed martensite variants have positive interaction energy according to Patel and Cohen model between the applied stress field and shape deformation accompanying transformation, after the calculation using either the synchrotron-measured local stress field or the macroscopic uniaxial tensile stress. The interaction energy criterion using the measured local stress field could show the better correspondence with the actual variant selection than that using the uniaxial tensile stress. However, it was not enough to explain the variant selection completely even if the measured local stresses were used.

Acknowledgements

This study was financially supported by the Grant-in-Aid for Scientific Research on Innovative Area, “Bulk Nanostructured Metals” (area No.2201), the Grant-in-Aid for Scientific Research (A) (No. 24246114), and the Elements Strategy Initiative for Structural Materials (ESISM), all through the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan (contract No. 22102002). The authors greatly appreciate all the supports. The synchrotron radiation experiments were performed at BL28B2 in SPring-8 with the approval of the Japan Synchrotron Radiation Research Institute (JASRI) (Proposal No. 2013B1547, 2014A1578).

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