Identical Area Observations of Deformation-Induced Martensitic Transformation in SUS304 Austenitic Stainless Steel

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In this study, an identical area of a SUS304 austenitic stainless steel specimen was observed by electron backscattering diffraction measurements at different strains in tensile test at ambient temperature, in order to investigate the details of deformation-induced martensitic transformation. Firstly, a number of thin deformation twins were formed in austenite grains. Most of the martensite crystals were observed either near grain boundary triple junctions or inside the deformation twins. Secondly, it was found that martensite crystals preferentially appeared in the austenite grains whose ⟨001⟩ crystal directions were close to the tensile direction. Furthermore, when austenite grains had several martensite crystals inside, only one or two variants were observed among 24 variants possible under Kurdjumov-Sachs orientation relationship, which indicated the existence of variant selection rules. Patel and Cohen model and Bogers-Burgers model were examined to understand the variant selection, but both models could not explain the variant selections. The result suggests that complicated stress states govern the deformation-induced martensitic transformation in polycrystalline austenite.

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1. Introduction

Martensitic transformation in steels usually occurs when austenite is rapidly cooled down below a certain temperature, which is called Ms temperature. When deformation is applied to austenite below T0 temperature, at which austenite and martensite of a certain chemical composition have the same free energy, martensitic transformation can also happen even above Ms temperature, which is known as deformation-induced martensitic transformation. The deformation-induced martensite increases strain-hardening so that both good ductility and strength could be achieved sometimes. This is known as transformation-induced plasticity (TRIP) phenomenon. A number of research works have been reported about deformation-induced martensitic transformation occurred in single crystals but its details in polycrystalline materials has not been fully understood yet. The present study aims to clarify the details of deformation-induced martensitic transformation occurred in a polycrystalline specimen of SUS304 austenitic stainless steel at ambient temperature through identical area observations during tensile test using electron backscattering diffraction (EBSD) measurements.

2. Experimental Procedure

A metastable austenitic stainless steel SUS304 was used in the present study. The chemical composition of the steel is shown in Table 1. A fully-recrystallized homogenous microstructure of austenite single phase was obtained by annealing the as-received sheets at 1000°C for 3 h in vacuum. The mean grain size of the specimen after annealing was 26 µm, which was measured by mean interception method. EBSD measurements in SEM were employed for observing the microstructure and crystallographic orientation, and for distinguishing the austenite and martensite from each other.

Table 1 Chemical composition of the SUS304 steel studied (mass%).

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Ni</th>
<th>Cr</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.06</td>
<td>0.63</td>
<td>1.02</td>
<td>0.027</td>
<td>0.003</td>
<td>8.07</td>
<td>18.19</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

Several groups reported that the deformation-induced α martensite formed at the intersections of ε martensite. However, ε martensite was scarcely observed in the EBSD phase maps of the specimens deformed at 40% or 80%. Accordingly, only α martensite (BCC) is considered in this study.

First, an area was chosen in the gage part of a tensile specimen 1 mm in thickness, 10 mm in gage length and 5 mm in gage width, as the area for identical area observation, and the initial microstructure of the area was measured by EBSD. Then tensile test was carried out at room temperature at an initial strain rate of $8.3 \times 10^{-4}$ s$^{-1}$. The tensile test was once stopped at a tensile strain of 56.5%, and then EBSD measurements were employed on the same area. The same procedures were repeated at tensile strains of 73.1% and 89.2%. The EBSD measurements were carried out in a scanning electron microscope (SEM, FEI: XL30Siron) operated at 15 kV and EBSD analysis was performed with TSL-OIM (Data Collection ver.5.31) system.

3. Results and Discussion

3.1 Tensile properties

Figure 1(a) shows a nominal stress–strain curve of the SUS304 specimen. The 0.2% proof stress, tensile strength, uniform elongation and total elongation of the material are 253 MPa, 723 MPa, 128% and 137%, respectively. Figure 1(b) shows the nominal stress–strain curve of the specimen used for the identical area observation, which agrees well with Fig. 1(a). When restarting the tensile test after microstructure observation, the yield stress shows higher values than the final flow stresses of the former steps,
and yield drop phenomenon is observed. The reasons for these phenomena are unclear at this moment.

3.2 Microstructures at different strains

Orientation color maps of the identical area at different strains are shown in Fig. 2. Colors in the maps indicate the crystallographic orientation parallel to the tensile direction, according to the key stereographic triangle shown in the figure. Three grains are indicated by the symbols, A, B and C in the figures, for recognizing the identical grains easily. In the initial microstructure (Fig. 2(a)), many annealing twins are observed, and the orientation distribution is nearly random as there is no tendency in colors of the map. Area fraction of the black points at which orientation analysis failed increases with increasing strain. One main reason for this is the surface relief of the specimen after relatively large tensile strains. After 56.5% tensile strain, most of the austenite grains appear in red or blue color (Figs. 2(b), 2(c), 2(d)), indicating that they have rotated to (001) or (111) orientation by tensile deformation. The (001) and (111) parallel to the tensile direction are known as typical deformation texture in FCC metals and alloys after tensile deformation. Within the grain-B of the starting microstructure, several bands with red color are observed (Fig. 2(a)). They are annealing twins. However, other bands showing similar colors also appear within the grain-B with increasing strain (Figs. 2(b), 2(c), 2(d)). They are the deformation twins, which are also observed in other grains.

Figure 3 shows EBSD phase maps of the same areas as those shown in Fig. 2, where FCC (austenite) and BCC (deformation induced martensite) phases are indicated in dark red and green colors, respectively. Area fraction of deformation-induced martensite measured from the phase

Fig. 1 (a) Nominal stress–strain curve of the SUS304 at ambient temperature. (b) Nominal stress–strain curve of the specimen used for the identical area observation.

Fig. 2 EBSD Orientation color maps of the identical area at different tensile strains of (a) 0%, (b) 56.5%, (c) 73.1% and (d) 89.2%. Colors indicate the crystallographic orientation parallel to the tensile direction. A, B and C indicate the same grains.

Fig. 3 EBSD phase maps of the same area as Fig. 2 at different tensile strains of (a) 0%, (b) 56.5%, (c) 73.1% and (d) 89.2%. Dark red and green colors indicate FCC and BCC phases, which correspond to austenite and deformation-induced martensite, respectively.
maps is plotted as a function of tensile strain in Fig. 4. Even when the strain is approximately 90%, the fraction of martensite phase is only 3.7%.

Figure 5(a) is an enlarged phase map of the region of white rectangle in Fig. 3(b), measured by EBSD in a finer pitch again. Figures 5(b), 5(c) are further enlarged maps of the regions of white broken rectangles in Fig. 5(a). The black solid lines represent high angle grain boundaries with misorientations larger than 15°, while yellow solid lines represent Σ3 twin boundaries. In the region shown in Fig. 5(b), deformation-induced martensite crystals are observed near grain boundary triple junctions of austenite. Meanwhile, in the region shown in Fig. 5(c), deformation-induced martensite appears along yellow solid lines, i.e., Σ3 twin boundaries. As mentioned before, both annealing twins and deformation twins are observed in this grain (grain-B in Figs. 2 and 3). In order to confirm from which twins the deformation-induced martensite appears, the phase map shown in Fig. 5(c) is compared with the orientation color maps of the same area before and after the tensile deformation in Fig. 6. White arrows in Fig. 6 point out two annealing twins existed from the initial state. Many deformation twins newly appear in the 56.5% deformed specimen (Figs. 6(b), 6(c)). It is obvious that the annealing twin boundaries turn to black boundaries after 56.5% tensile deformation (Fig. 6(b)), which means that the annealing twins no longer satisfy Σ3 orientation relationship with the matrix due to significant crystal rotation in deformation. It should be noted that no martensite crystals are observed within the annealing twins, but all they appear along the deformation twin boundaries (yellow boundaries). Furthermore, it can be found from Figs. 6(b), 6(c) that the martensite crystals appear inside the deformation twins.

In order to clarify the influence of orientation of austenite matrix on the formation of deformation-induced martensite, the crystallographic orientations of the austenite grains and deformation twins within which martensite crystals are observed are shown in Figs. 7(a), 7(b), respectively. The orientations plotted are those after 56.5% tensile deformation. It can be clearly seen from Fig. 7(a) that all the austenite grains that showed deformation-induced martensite have nearly (001) orientation, although the deviations up to about 28° from the exact (001) are recognized. The tendency is the same for the deformation twins. Orientations of all the deformation twins within which martensite crystals are observed distribute near (001) (Fig. 7(b)). The results indicate that the orientation of austenite significantly affects the deformation-induced martensitic transformation.

3.3 Variant selection of martensite

The morphology of deformation-induced martensite observed in this study is the lath martensite. We confirmed that the formed lath martensite satisfied Kurdjumov-Sachs (K-S) orientation relationship with respect to the surrounding austenite matrix through the analysis of crystallographic orientations. Therefore, twenty four variants of martensite can form from a single grain of austenite. It has been reported that some specific variants preferentially form in case of deformation induced martensite. In order to investigate if any variant selections happened in the present study, several austenite grains within which some martensite crystals formed were selected. Two austenite grains with three or four different martensite crystals formed inside are shown in Figs. 8(a), 8(b), respectively. The [001] pole figures of martensite corresponding to Figs. 8(a), 8(b), which are represented in the same colors as the corresponding martensite crystals in the maps, are shown in Figs. 8(c), 8(d). It can be easily found that less than two variants are formed within each austenite grain, which indicates that variant selection happens in the present deformation-induced martensitic transformation.

For understanding the variant selection rule(s) happened in the present study, Patel and Cohen model and Bogers–Burgers model were applied on the two areas shown in Figs. 8(a), 8(b). According to Patel and Cohen model, the mechanical work (U) done by the applied stress for the martensitic transformation can be calculated by the equation shown below.

\[
U = \sigma_0 \varepsilon_0 + \tau \gamma_0
\]

Where \(\sigma_0\) is the resolved normal stress perpendicular to the habit plane, \(\varepsilon_0\) is the normal component of the transformation strain, \(\tau\) is the resolved shear stress along the shear direction on the habit plane, and \(\gamma_0\) is the transformation shear strain. In this model, martensite variants with larger positive \(U\) were expected to form preferentially. The habit plane orientation \((-0.4124228962 -0.8070449673 -0.4225941047)\), and shear direction \(0.5094316946 -0.5888861564 0.6274491557\) used in this study were obtained from the phenomenological theory of martensite. The calculated mechanical works for the 24 martensite variants are shown in Figs. 9(a), 9(b), which correspond to Figs. 8(a), 8(b), respectively.

Meanwhile, Bogers–Burgers model is based on a transformation process from FCC crystal to BCC crystal. Two sets of shear are involved in the model: the first shear is \(a_{fcc}/18\) on \{111\} plane to change the atomic configuration on the close-packed plane of FCC, and the second shear is \(a_{fcc}/16\) on \{111\} plane to change the stacking sequence from FCC to BCC. In the present study, only the first shear was considered because it was considered at the nucleation stage of the martensitic transformation. The Schmid factors for the first shears corresponding to the twenty four variants of martensite were calculated. The martensite variants with larger positive Schmid factors are expected to transform.
preferentially. The calculated Schmid factors of the first Bogers–Burgers shear for the 24 martensite variants are shown in Figs. 10(a), 10(b), which also correspond to Figs. 8(a), 8(b), respectively.

As explained above, the martensite variants with relatively large positive values of \( U \) or Schmid factors are expected to appear preferentially. However, such tendency is not observed from both Figs. 9 and 10, which indicates that neither Patel and Cohen model nor Bogers–Burgers model can explain the variant selection occurred in the present study.

One reason for this is that both Patel and Cohen model and Bogers–Burgers model consider a simple uniaxial external...
stress. For single crystals in which deformation condition is relatively simple, the uniaxial tensile stress might control the major process of deformation induced martensitic transformation in single crystals. However, in the present study using a polycrystalline specimen, the local stress conditions, especially near grain boundary triple junctions and within thin deformation twins where martensite crystals have been actually observed, are expected to be much more complicated. For understanding the variant selection rules occurred in polycrystalline materials, further discussion is required.

4. Conclusions

In this study, the details of deformation-induced martensitic transformation were investigated through observing an identical area of a SUS304 austenitic stainless steel specimen by EBSD measurements at different strains in tensile test at ambient temperature. The major results obtained are as follows.

1. The 0.2% proof stress, tensile strength, uniform elongation and total elongation of the SUS304 specimen were 253 MPa, 723 MPa, 128% and 137%, respectively. In the initial microstructure, many annealing twins were observed and the orientation distribution was nearly random. After 56.5% tensile strain, austenite grains have rotated to $\{001\}$ or $\{111\}$ orientation by tensile deformation. Many deformation twins were

![Fig. 7](image7.png)

**Fig. 7** Inverse pole figures showing the crystallographic orientations parallel to the tensile direction of (a) the austenite grains and (b) the deformation twins within which deformation-induced martensite appeared. The orientations are those after 56.5% tensile deformation.

![Fig. 8](image8.png)

**Fig. 8** (a), (b) EBSD maps of the same areas as Figs. 5(b), 5(c), showing deformation-induced martensite crystals, and (c), (d) corresponding ($001$) pole figures of martensite in (a), (b). The poles are represented in the same colors as the corresponding martensite crystals.

![Fig. 9](image9.png)

**Fig. 9** The calculated mechanical works for the 24 martensite variants based on Patel and Cohen model. (a) and (b) correspond to Figs. 8(a) and 8(b), respectively.

![Fig. 10](image10.png)

**Fig. 10** The calculated Schmid factor of the 24 martensite variants based on Bogers-Burgers model. (a) and (b) correspond to Figs. 8(a) and 8(b), respectively.
observed, while annealing twins no longer satisfied $\Sigma 3$ orientation relationship with the matrix.

(2) Deformation-induced martensite crystals were mainly observed either near grain boundary triple junctions of austenite or within deformation twins. It was found that martensite crystals preferentially appeared in the austenite grains whose (001) crystal directions were nearly parallel to the tensile direction.

(3) Variant selection in deformation-induced martensitic transformation was confirmed in the present study. Neither Patel and Cohen model nor Bogers–Burgers model could explain the variant selection rule. The result suggested that complicated stress states governed the deformation-induced martensitic transformation in polycrystalline austenite.

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