Orientation dependence of transformation induced plasticity in high carbon bainitic steel

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Abstract. The crystallographic orientation dependence of the transformation induced plasticity (TRIP) in the high carbon bainitic steel was studied. 0.6%C-2.0%Si-1%Cr steels were austenitized at two conditions to obtain different size of prior-austenite grains. Subsequently, they were austempered to evolve the bainitic structure composed mainly of bainitic ferrite and retained austenite. The characteristic of this sample is that it has much larger amount of carbon content compared with that of the conventional low alloyed TRIP steels. The bainitic steels with different sizes of mean prior-austenite grain show high strength with large ductility. The measurement of electron back scattering diffraction (EBSD) of the samples both before and after the tensile test clarified that much of the retained austenite transformed to ferrite while the austenite grains having the tensile orientation nearly parallel to \(<111>\) kept remaining after the fracture. This change indicates that the retained austenite with its tensile axis parallel near to \(<001>\) is preferential for the deformation-induced martensitic transformation. This behavior was found in the samples with different prior-austenite grain sizes.

1. Introduction
Transformation induced plasticity (TRIP) steel [1] is one of the advanced high strength steels. It is well known that the strengthening of TRIP steel is achieved by the increasing of carbon content [2], although the research works on the TRIP steel with relatively higher carbon content is limited to a few papers [3]. In addition, for the optimization of mechanical properties, the relationship between the microstructural morphology, such as prior-austenite grain size, and the deformation-induced martensitic transformation should be studied adequately. Consequently, this paper is aimed to clarify the behaviors of deformation-induced martensitic transformation in high carbon TRIP steels with different prior-austenite grain sizes.

2. Experimental procedures
A high-carbon Si-bearing steel (0.62%C-2.02%Si-0.23%Mn-1.01%Cr-bal.Fe) was examined. The samples with a dimension of 14 mm x 14 mm x 150 mm were austenitized at 850 °C or 1050 °C for 600 sec. Subsequently, the samples were soaked in a salt bath at 400 °C and kept for 1800 sec. The heat treated samples were cut to the tensile test pieces with a gage length of 42 mm and a diameter of 6 mm. Tensile test was conducted at ambient temperature at a constant cross head speed of 0.85 mm/min. Microstructures were examined by a scanning electron microscope (SEM) with an EBSD measurement system.
3. Results and discussion

Figure 1(a,b) shows the phase color maps of the austempered samples austenitized at \( T_\gamma = 850 \, ^\circ\text{C} \) (a) or \( T_\gamma = 1050 \, ^\circ\text{C} \). The white lines indicate the prior-austenite grain boundaries. The higher temperature for the austenitization brought the larger mean diameter of prior austenite grains, \( d_\gamma \). Both of the samples were fulfilled with bainitic ferrite with retained austenite. The retained austenite in the smaller prior-austenite grains (a) shows relatively equiaxed morphology, while the coarse prior-austenite grains have the elongated grains of retained austenite. The 001 pole figures (c,d) show the BCC phase orientations in one prior-austenite grain indicated by the dotted line in (a) and (b). These distributions were reasonable for the Kuldumov-Sachs (KS) orientation relationship [4,5].

The true stress, \( \sigma \), - true strain, \( \varepsilon \), curves of these two austempered samples were shown in Fig.2. The ends of the stress - strain curves indicate the breaking of the test pieces. Both of the austempered samples show high strength with adequate ductility. The difference between the samples with different prior-austenite grain sizes was not significant. The work hardening, \( d\sigma/d\varepsilon \), curves corresponding to these stress - strain curves were also presented in Fig.2. The work hardening in both samples kept higher than true stress, indicating that the fracture occurs without necking.

The samples were tensile deformed not only to the fracture but also to some tensile strains, and the samples deformed to different strains were examined by EBSD. These results were shown in Fig.3 or Fig.4 for the samples austenitized at 950\(^\circ\text{C}\) or 1050\(^\circ\text{C}\), respectively. These figures indicate the BCC and FCC orientations parallel to the tensile orientations according to the color key at the top-right of these figures. Both samples with different prior-austenite grain sizes show similar changes: with increasing of the tensile strain, the retained austenite transformed to martensite and the volume fraction of austenite (\( V_\gamma \)) decreased. Although the deformation-induced transformation created new grains, the block (the aggregation of martensitic crystals with similar orientations [4,5]) kept its original size.
similar to that of the as-austempered samples, indicating that the orientation of deformation-induced martensite was similar to that of pre-existing adjacent bainitic ferrite.
Figure 5 shows the fraction of retained austenite in the samples deformed to $\varepsilon$. The reference data of several steels which perform the deformation-induced martensitic transformation are shown in addition [6-14]. The conventional low-alloyed low-carbon TRIP steels have relatively small amount of retained austenite before the deformation, while the metastable austenitic stainless steels such as 304 consist of only austenite when these keep solution-treated state. The high carbon TRIP steel in this work shows

**Figure 4.** Orientation color maps of the steel austenitized at 1050 °C (a) and then tensile strained to a true strain of 0.05 (b), 0.13 (c) or 0.23 (d). The normal direction on the observation plane is parallel to the tensile axis
the behavior between the conventional low-alloyed TRIP steels and metastable austenitic stainless steels. The volume fraction of austenite is larger at the initial state and reduces more rapidly by the tensile deformation than those in the conventional low-alloyed TRIP steels.

Figure 6 shows the inverse pole figures of the tensile orientations of austenite. With increasing tensile strain, the distribution of the tensile orientation favored <111>. This means that the deformation-
induced martensitic transformation occurs more preferentially in the grains in which the tensile orientation is around \(<001>\) than in those around \(<111>\). This tendency is found in both samples with different prior-austenite grains sizes. The authors lately found that the orientation dependence on the deformation-induced martensitic transformation can be explained by the first primitive shear for the transformation when the elastic isotropy is taken into account [15]. This implies that the tensile orientation dependence on the transformation is controlled by the stress condition which is influenced by the tensile orientation rather than the grain/phase boundaries. Consequently, the finding of this study seems consistent to the controlling mechanism of the deformation-induced martensitic transformation.

4. Summary

The crystallographic orientation dependence of the transformation induced plasticity in the high carbon bainitic steel (0.6%C-2.0%Si-1%Cr-Fe) with two different mean sizes of prior-austenite grains (16\(\mu\)m, 40\(\mu\)m) was studied. The bainitic steels with different sizes of mean prior-austenite grain diameters show high strength with large ductility. In both samples, the austenite grains having the tensile orientation nearly parallel to \(<111>\) kept remaining as FCC even after the fracture. This tendency implies that the process determining the tensile orientation dependence on the martensitic transformation is mainly affected by the tensile orientation rather than the grain/phase boundaries.

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