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Orientation Dependence of Transformation Induced Plasticity in High Carbon Bainitic Steel

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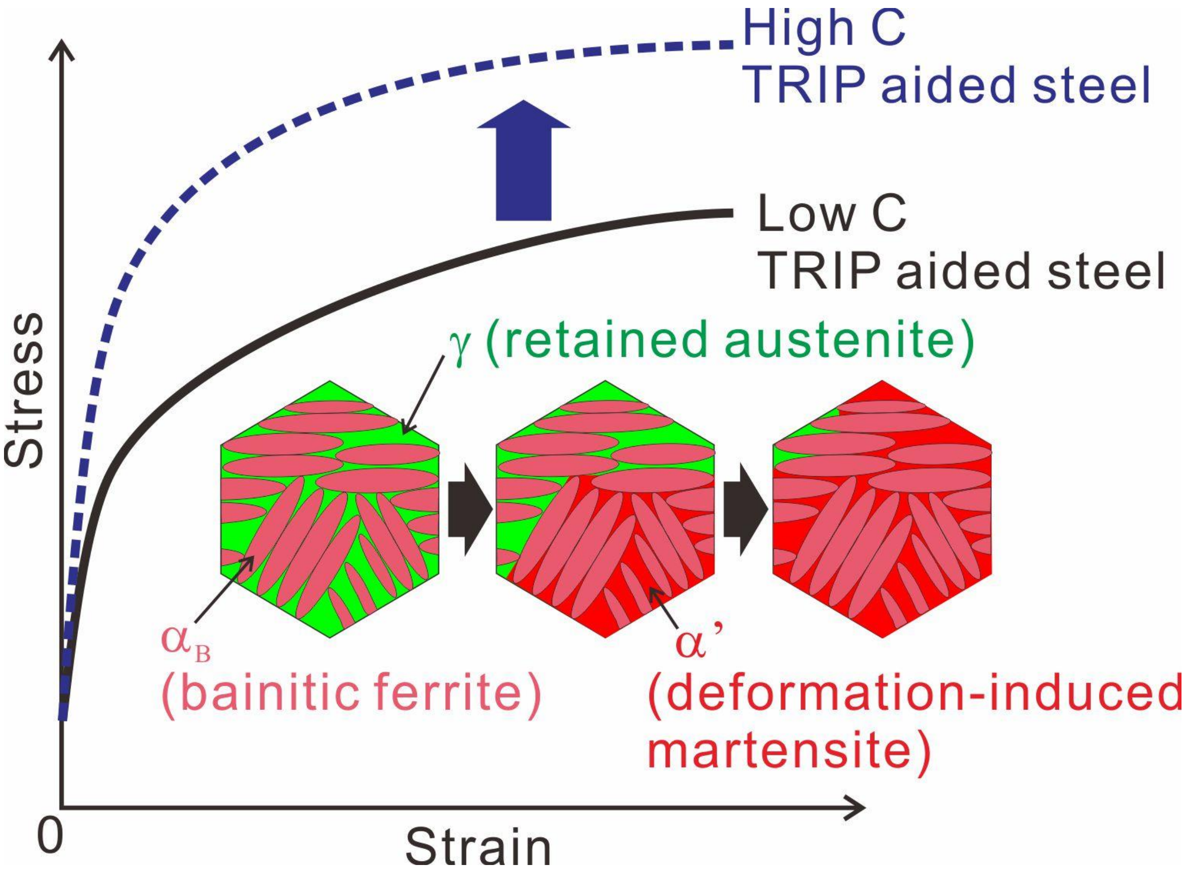
Transformation Induced Plasticity (TRIP) steel = advanced high strength steel



further strengthening

=

higher carbon content

+

deformation-induced martensitic transformation

optimization

- * microstructural morphology
- * crystallographic orientation of austenite (γ)

Aim of this study

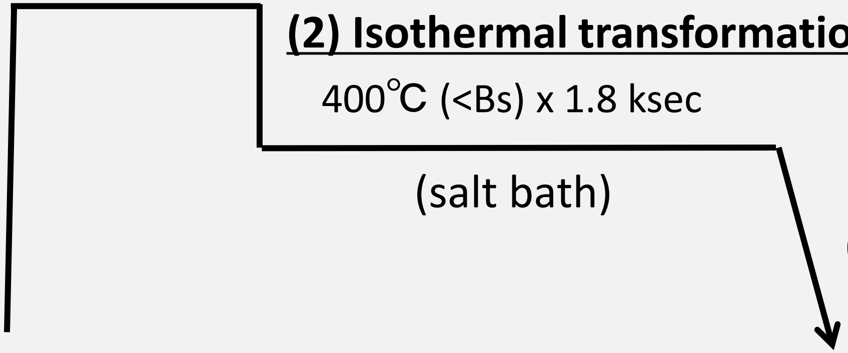
To clarify the behaviors of deformation-induced martensitic transformation in high carbon TRIP steels with different prior-austenite grain sizes.

Experiments

【Chemical composition】

C	**Si**	Mn	Cr	Fe
0.62	**2.02**	0.23	1.01	Bal.

【Heat treatment】 Austempering



(1) Austenitization

850℃ or **1050℃** (>A3)
X 600sec

(2) Isothermal transformation

400℃ (<Bs) x 1.8 ksec

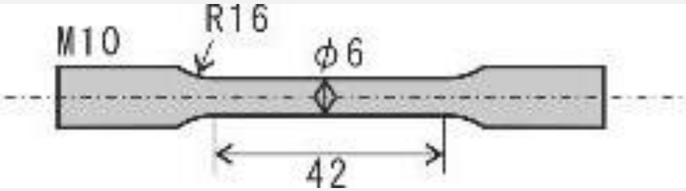
(salt bath)

(AC)

sample size
14mm x 14mm
x 150mm

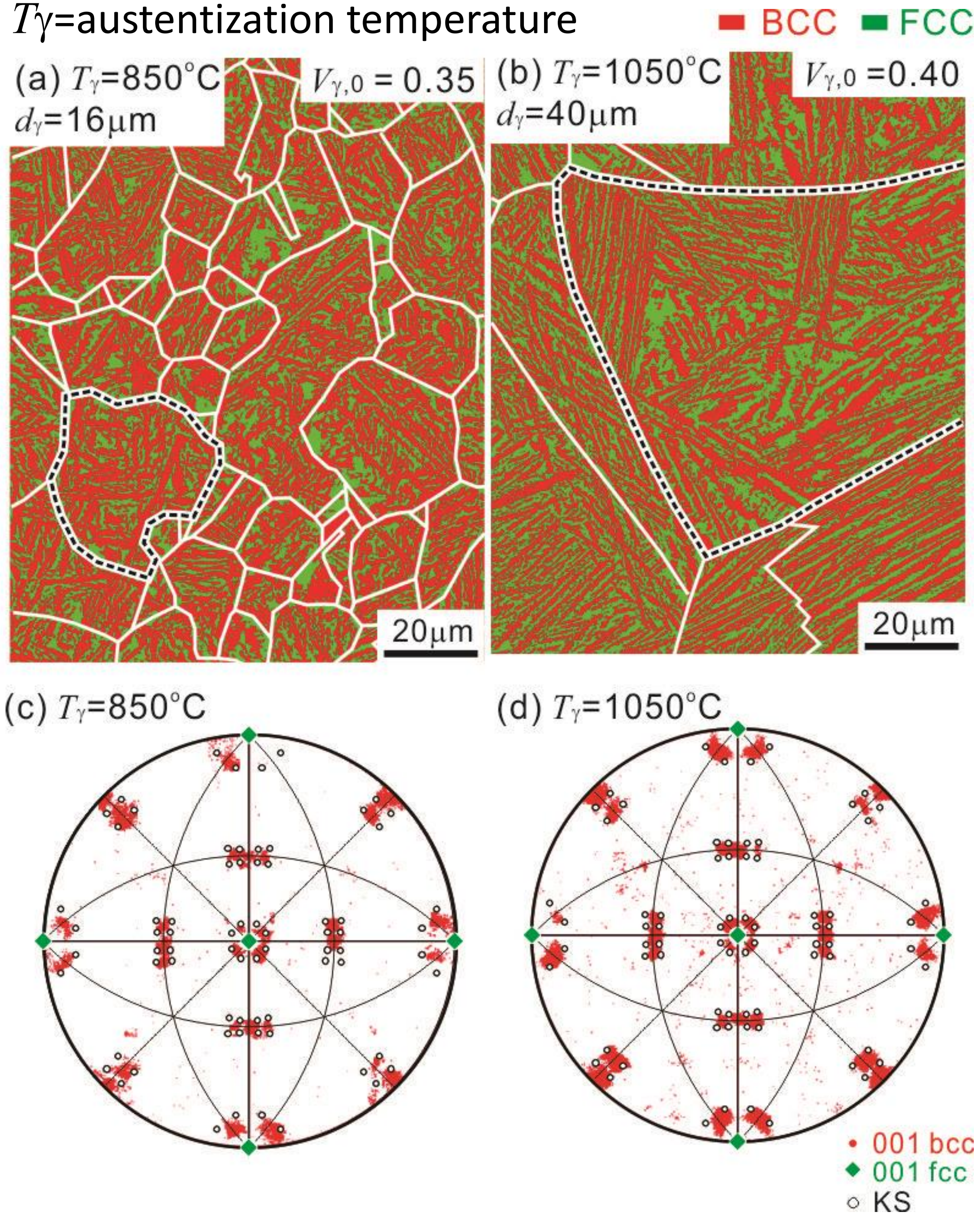
【Evaluation】

Tensile test at room temperature (0.85 mm/min)
SEM/EBSD
(prior austenite grain size, volume fraction of retained austenite
tensile orientation)



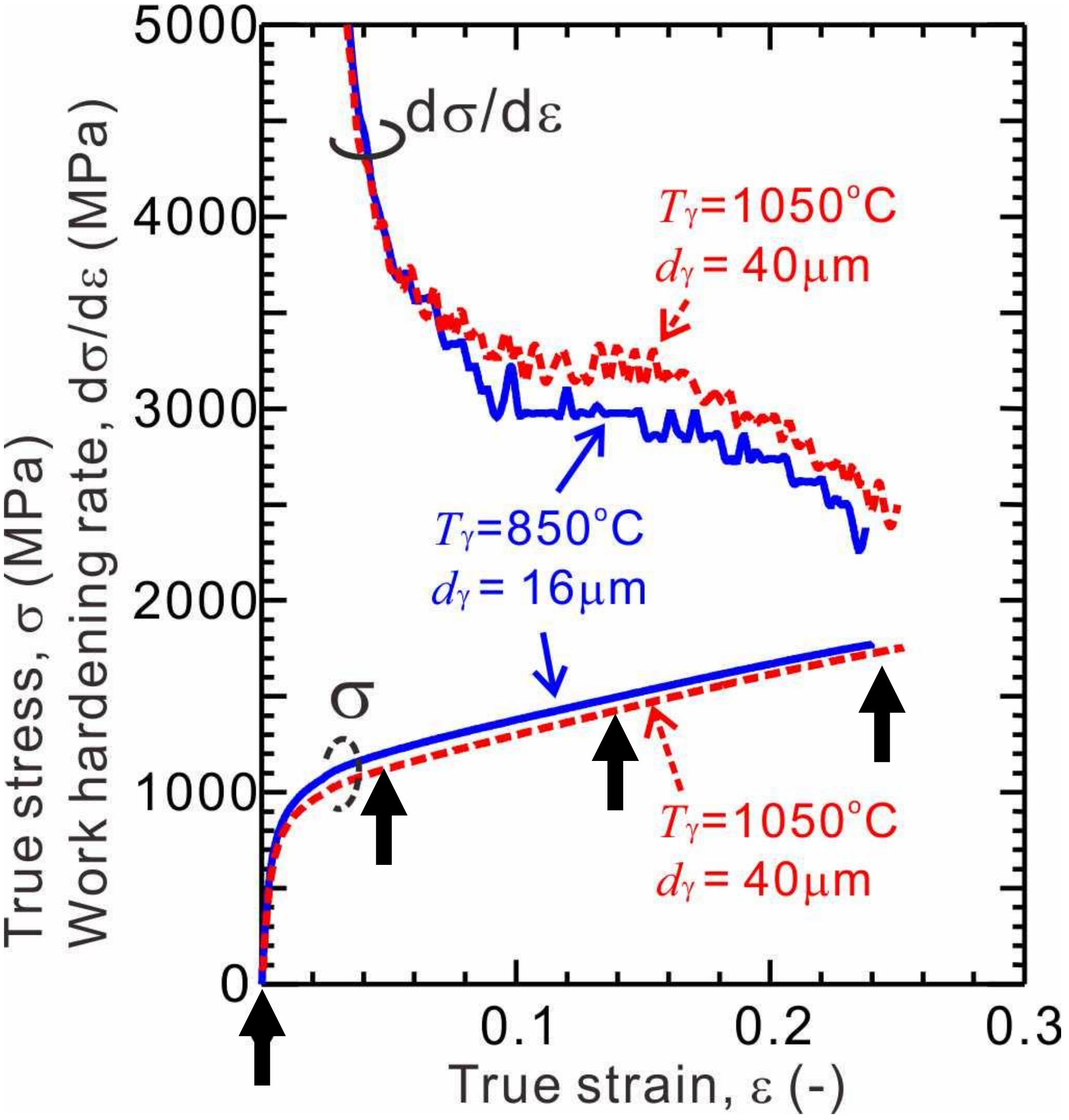
Results & discussion

Tγ=austentization temperature



	T_γ=850ºC	T_γ=1050ºC
prior ϒ size	16 μm	40 μm
average diameter of retained ϒ	0.6 μm	0.7 μm
maximum diameter of retained ϒ	6.4 μm	11.8 μm
volume fraction of retained ϒ	35%	40%

Figure 1. Phase map (a,b) and 001 pole figure (c,d) of high carbon steels austenitized at 850 °C (a,c) or 1050 °C (b,d) followed by isothermal holding at 400 °C. The pole figure shows the distribution of $\langle 001\rangle_{bcc}$ with both the horizontal and vertical axes parallel to $\langle 001\rangle_{fcc}$. Open circles indicate $\langle 001\rangle_{bcc}$ orientations having the Kurdjumov-Sachs (KS) orientation relationship.



↑ = EBSD measurements

High strength
(TS ~ 1.3GPa)
+
Adequate ductility
(Elongation ~25%)

↑ *effective*

higher carbon
content

Figure 2. True stress (σ) - true strain (ε) curves and work hardening rate (dσ/dε) of high carbon steels austenitized at 850 °C or 1050 °C followed by isothermal holding at 400 °C.

Fine prior-austenite grains

d_γ = 16 μm

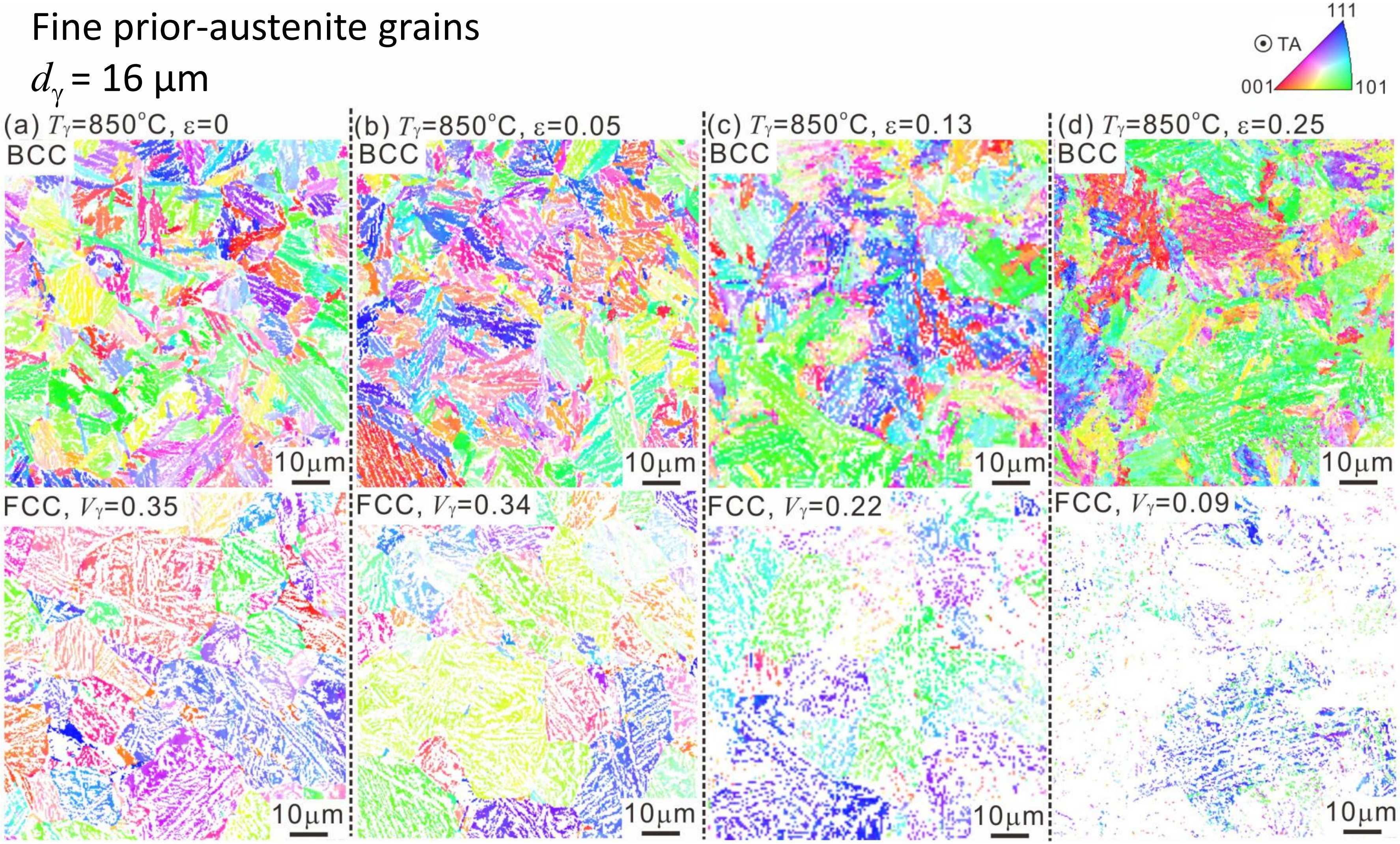


Figure 3. Orientation color maps of the steel austenitized at 850 ^{o}C (a) and then tensile strained to a true strain of 0.05 (b), 0.13 (c) or 0.25 (d). The observation direction is parallel to the tensile axis.

BCC : Deformation induced martensite has the orientation similar to that of adjacent bainitic ferrite.
FCC : Grains with TA//<111> keeps remaining preferentially.

Coarse prior-austenite grains
d_γ = 40 µm

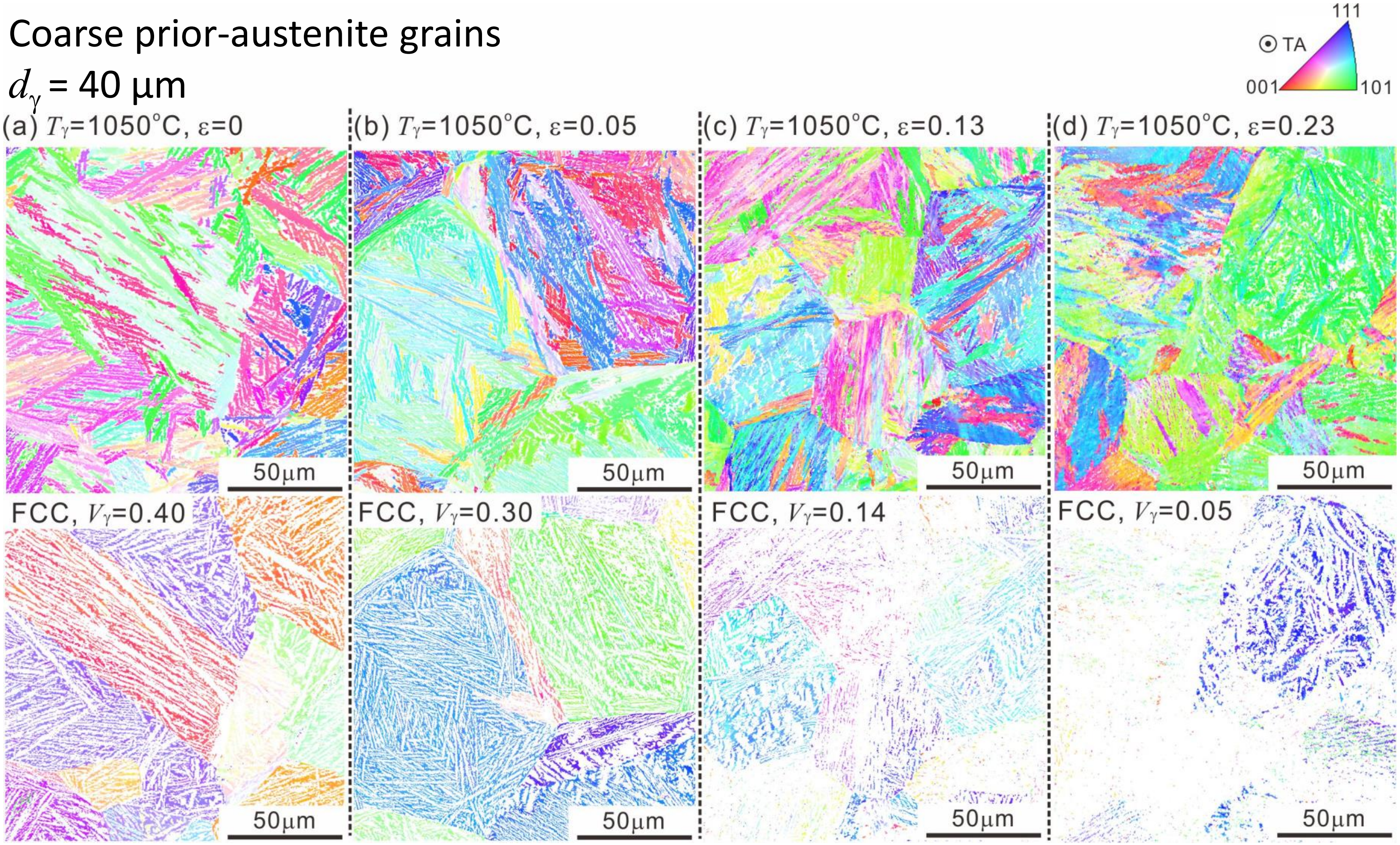


Figure 4. Orientation color maps of the steel austenitized at 1050 °C (a) and then tensile strained to a true strain of 0.05 (b), 0.13 (c) or 0.23 (d). The observation direction is parallel to the tensile axis.

BCC : Deformation induced martensite has the orientation similar to that of adjacent bainitic ferrite.
FCC : Grains with TA//<111> keeps remaining preferentially. **Same as the d_γ=16µm sample**

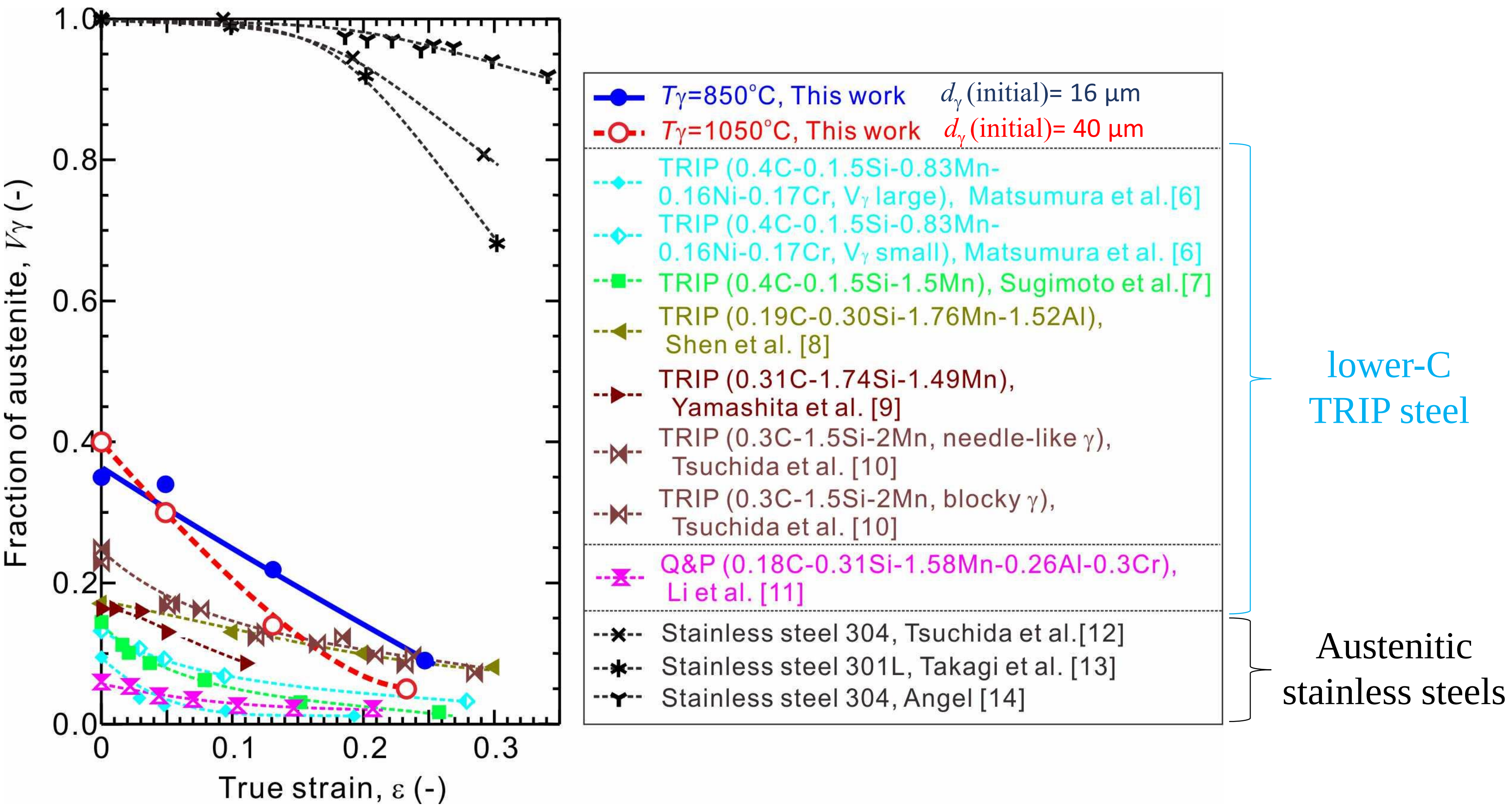


Figure 5. Fraction of retained austenite in various steels as a function of true strain.

$$-\frac{dV_\gamma}{d\varepsilon}\,(low-C) < -\frac{dV_\gamma}{d\varepsilon}\,(high-C) \quad \Longleftrightarrow \quad -\frac{dV_\gamma}{d\varepsilon} \cong k_1 \Delta G^{\alpha'/\gamma} \cdot \varepsilon$$

less stable γ

Sherif et al., Mater. Sci. Tech., 20(2004) 319

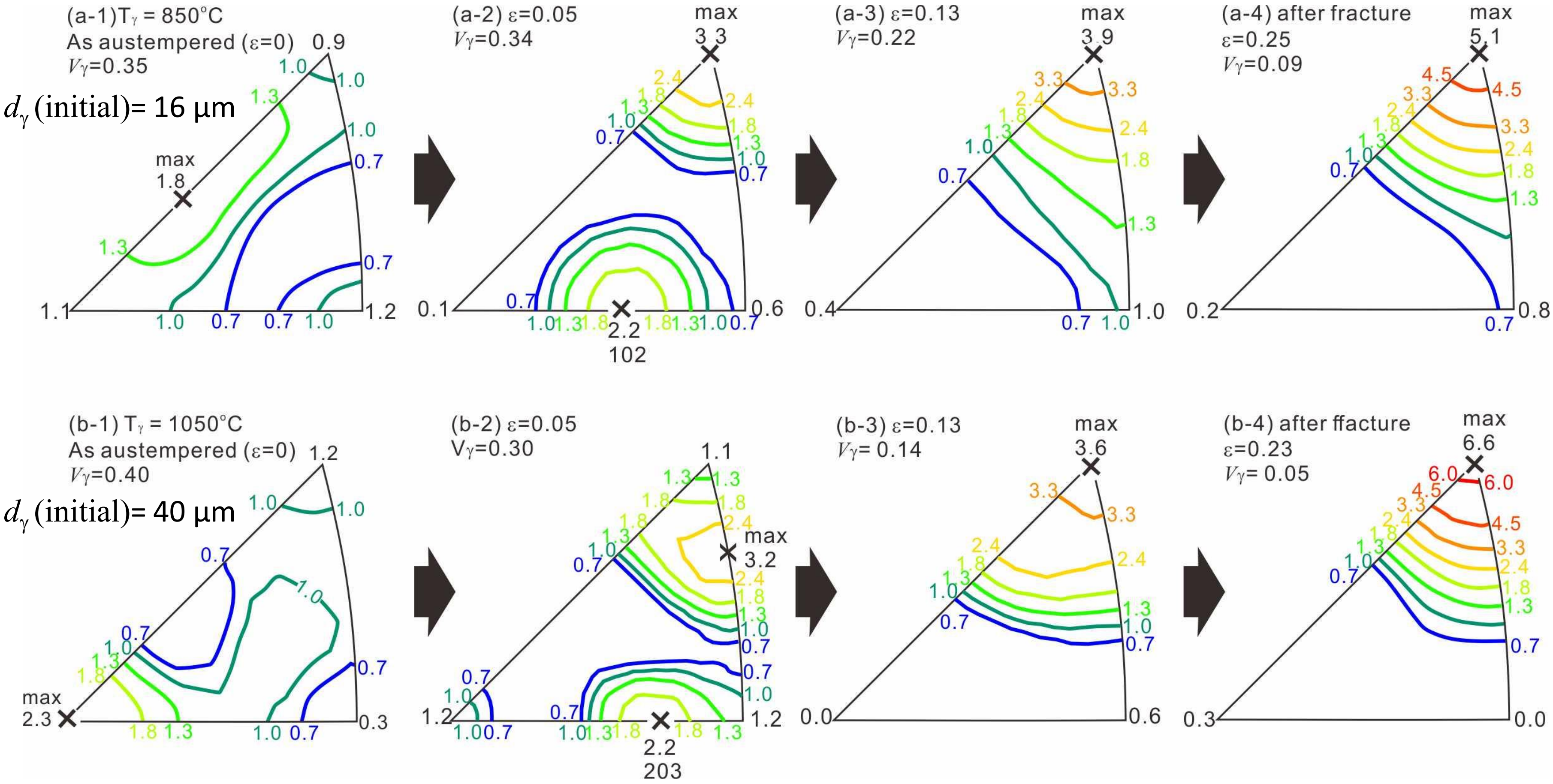


Figure 6. Inverse pole figures showing intensity of crystallographic orientation parallel to the tensile axis in the FCC phase of the steels austenitized at 850 ° C (a1-4) or 1050 ° C (b1-4) followed by austempering (a1,b1) and tensile deformation (a2-4, b2-4).

- The deformation-induced martensitic transformation occurs more preferentially in the grains in which the tensile orientation is around **<001>** than in those around <111>.
- The preferable orientation, <001> is not dependent with the mean prior-austenite grain size.

Discussion: the reason for the preferential orientation (tensile orientation // <001>)

Controlling mechanism of deformation-induced martensitic transformation

Bogers-Burgers model

1st primitive shear = $\{1\text{-}11\}_{fcc}\langle 121\rangle_{fcc}$

Kato and Mori (Acta metall. 24(1976)853) successfully explained the orientation dependence in single crystals.

Resolved elastic shear strain for {1-11}<121>, γ_b can be evaluated with **Schmid factor, S_F** if the **elastic strain parallel to tensile orientation [hkl], ε_{hkl}** is known.

$$\gamma_b = \varepsilon_{hkl}\, S_F$$

Elastic strain conditions in each grains in polycrystal due to elastic anisotropy

Nearly average condition between stress-constant and strain-constant conditions.

according to the in-situ neutron diffraction studies. (e.g. A.J. Allen et al., Int. Conf. on Residual Stress, Elsevior, (1989) 78 .)

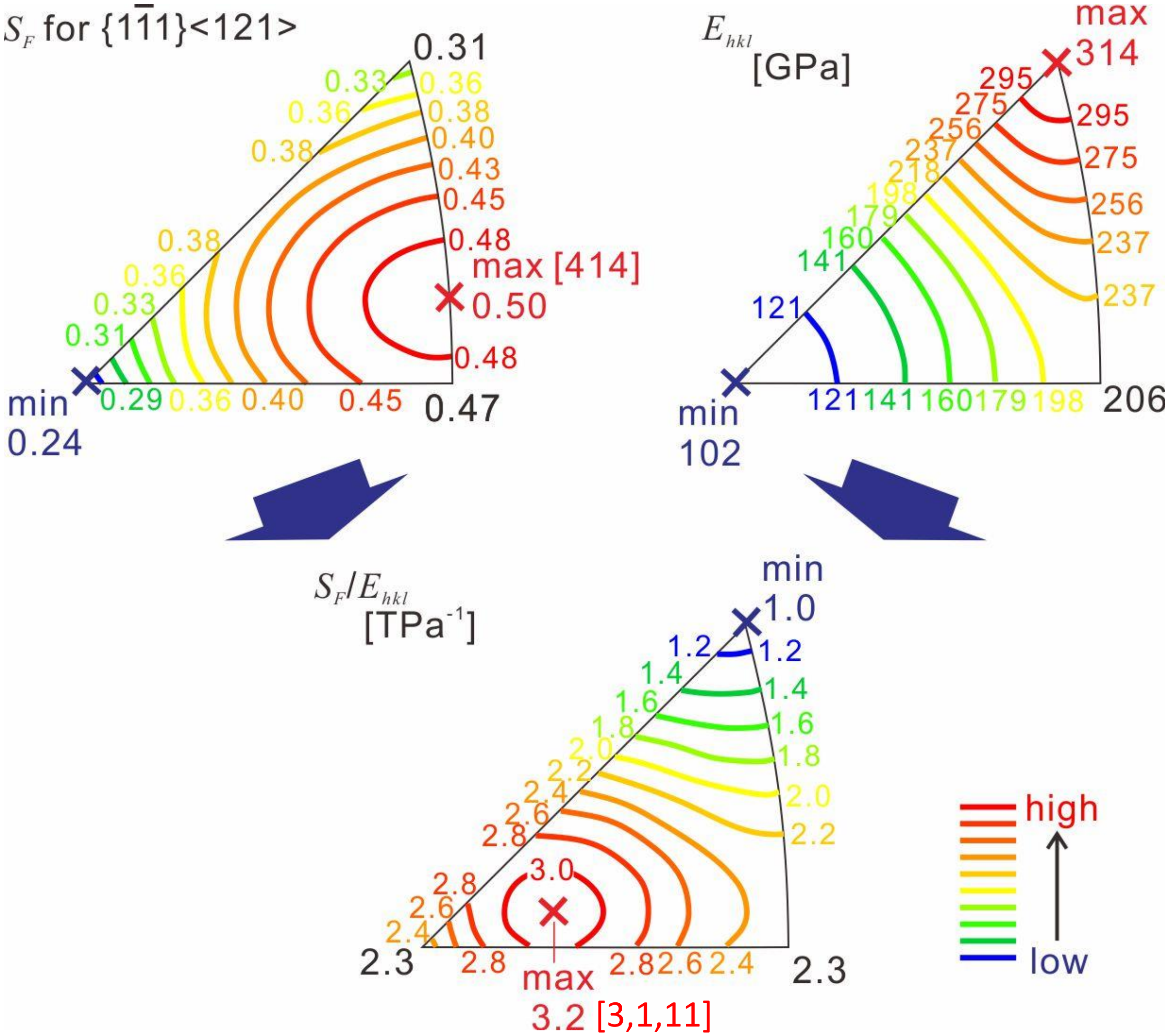
ε_{hkl} is roughly estimated with **the effective Young's modulus, E_{hkl}**. and **applied stress, σ**.

$$\varepsilon_{hkl} = \sigma / E_{hkl}$$

$$S_F/E_{hkl} = \gamma_b/\sigma$$

Elastically normalized Schmid factor, S_F/E_{hkl} implies the apparent magnitude of the resolved elastic shear strain supporting the Bogers-Burgers 1st shear deformation in polycrystal.

Evaluation of S_F/E_{hkl} *(Ueji et al., Scr. mater., 194(2021)113666)*



E_{hkl}

$= 1/\{ s_{11} + (2s_{12} - 2s_{11} + s_{44})A_{hkl} \}$

A_{hkl}

$= (h^2k^2+k^2l^2+l^2n^2)/(h^2+k^2+l^2)^2$

Elastic constant of austenitic steel

s_{11} = 9.84 TPa^{-1}

s_{44} = 7.92 TPa^{-1}

s_{12} = -3.74 TPa^{-1}

(M.Kikuchi, Trans. JIM, 12(1971)417)

The orientation with larger S_F/E_{hkl} is approximately consistent with the preferential orientation for the deformation-induced martensitic transformation.

{1-11}<121> **transformation shear**
(Bogers-Burgers)

✚

Elastic strain difference in polycrystals
due to **elastic anisotropy**

Summary

The deformation-induced martensitic transformation in the high carbon bainitic steel (0.6%C-2.0%Si-1%Cr-Fe) with two different mean diameters of prior-austenite grains (16 µm, 40 µm) was studied. The high-carbon bainitic steels show high strength with large ductility.

(1) The retained austenite decreases relatively faster with the tensile deformation due to the deformation-induced martensitic transformation.

(2) According to the prior-austenite grain size effect, the significant influence cannot be found in the tensile deformation behaviors.

(3) The deformation-induced martensitic transformation occurs preferentially in the retained austenite grains having the tensile orientation nearly parallel to <001>. 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.

(4) The orientation dependence can be explained by the elastically normalized Schmid factor, S_F/E_{hkl} for the {1-11}<121> transformation shear with the consideration of the elastic anisotropy of austenite.