Plastic Strain and Variant Selection during Diffusional Transformation in Steels

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Reviews: *Variant selection in displasive transformation*

The interaction energy $U$ between the stress and the plate of martensite:

$$U = \sigma N \zeta + \tau \delta$$

100-pole figure of martensite for the transformation of Cube oriented austenite grains. (b) is the experimental result and (c) shows favored variants of martensite and (d) shows all possible variants.*

- Shape deformation model (J.R. Pater et al., 1953) : Maximum work (Stress-Displacive shear)
- Active slip system model (J. Nutting et al, 1967) : Maximum resolved shear stress
- Bain strain model (Furubayashi et al., 1988) : Maximum work (Stress-Bain strain)

Reviews: *Variant selection in reconstructive transformation*

(a) is ODF(\(\Phi=45^\circ\)) of ferrite obtained in hot rolled 0.12C-1.47Mn-0.05Nb steel.
(b) was calculated result from KS orientation relationship*

‘Complicated metallurgical variables’ (H. J. Bunge, 1983)

*Acta Metall. 24 (1976), 159*
Research Aim

Un-deformed sample

Phase transformation by reconstructive mechanism

G.B plane orientation, Interfacial energy minimization

Deformed sample

Strain energy by dislocation field in each grains

Orientation relationship between $\gamma$ and $\alpha$, Variants selection of precipitations
### Experimental procedures

(covering wt.%)

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Al</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.595</td>
<td>0.98</td>
<td>1.01</td>
<td>1.50</td>
<td>Balance</td>
</tr>
</tbody>
</table>

- **BHAR DIL-805**
- **EBSD**: Scanning Electron Microscope (ZEISS SUPRA™ (Step size: 0.2 μm))
- **Software**: OIM data collection, analysis 5.0
Results: *Un-deformed sample*

- $\alpha_1 \sim \alpha_7$: group 1 (precipitated at $\gamma_1/\gamma_2$ grain boundary)
- $\alpha_8 \sim \alpha_{15}$: group 2 (precipitated at $\gamma_3/\gamma_4$ grain boundary)

IQ map (a), Phase map (b) and Inverse pole figure (c) of scanned area.
## Results: *Un-deformed sample*

<table>
<thead>
<tr>
<th>Grain</th>
<th>Deviation angle from KS relationship</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>With respect to $\gamma^1$</td>
<td>With respect to $\gamma^2$</td>
</tr>
<tr>
<td>Group 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\alpha^1$</td>
<td>$1.73^\circ$</td>
<td>$17.3^\circ$</td>
</tr>
<tr>
<td>$\alpha^2$</td>
<td>$1.50^\circ$</td>
<td>$18.3^\circ$</td>
</tr>
<tr>
<td>$\alpha^3$</td>
<td>$4.37^\circ$</td>
<td>$18.4^\circ$</td>
</tr>
<tr>
<td>$\alpha^4$</td>
<td>$2.05^\circ$</td>
<td>$19.8^\circ$</td>
</tr>
<tr>
<td>$\alpha^5$</td>
<td>$3.30^\circ$</td>
<td>$18.1^\circ$</td>
</tr>
<tr>
<td>$\alpha^6$</td>
<td>$2.13^\circ$</td>
<td>$19.3^\circ$</td>
</tr>
<tr>
<td>$\alpha^7$</td>
<td>$4.89^\circ$</td>
<td>$19.8^\circ$</td>
</tr>
<tr>
<td>$\gamma^1$</td>
<td></td>
<td>$41.7^\circ$</td>
</tr>
<tr>
<td>$\gamma^2$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Group 2</th>
<th>With respect to $\gamma^3$</th>
<th>With respect to $\gamma^4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha^8$</td>
<td>$27.6^\circ$</td>
<td>$7.9^\circ$</td>
</tr>
<tr>
<td>$\alpha^9$</td>
<td>$2.02^\circ$</td>
<td>$27.8^\circ$</td>
</tr>
<tr>
<td>$\alpha^{10}$</td>
<td>$28.2^\circ$</td>
<td>$2.19^\circ$</td>
</tr>
<tr>
<td>$\alpha^{11}$</td>
<td>$28.3^\circ$</td>
<td>$2.87^\circ$</td>
</tr>
<tr>
<td>$\alpha^{12}$</td>
<td>$28.1^\circ$</td>
<td>$1.74^\circ$</td>
</tr>
<tr>
<td>$\alpha^{13}$</td>
<td>$17.5^\circ$</td>
<td>$1.22^\circ$</td>
</tr>
<tr>
<td>$\alpha^{14}$</td>
<td>$4.30^\circ$</td>
<td>$25.3^\circ$</td>
</tr>
<tr>
<td>$\alpha^{15}$</td>
<td>$13.4^\circ$</td>
<td>$6.24^\circ$</td>
</tr>
<tr>
<td>$\gamma^3$</td>
<td>$38.0^\circ$</td>
<td></td>
</tr>
<tr>
<td>$\gamma^4$</td>
<td></td>
<td>$38.0^\circ$</td>
</tr>
</tbody>
</table>
Results: *Deformed sample*

IQ image (a), Inverse pole figure (b) and Taylor factor map (c)
Results: *Deformed sample*

(a) 110 and 111 pole figure of austenite 1 and 2
(b) 110 pole figure of ferrite group
(c) 111 pole figure of ferrite group

\{111\} of $\gamma_1$ // Grain boundary plane

All ferrite has KS-type with $\gamma_2$
Discussion: *Grain boundary plane orientation*

\[ \Delta G^* = \frac{-1}{4 \Delta G_V} \frac{E^2}{V} \]

\( \Delta G_V \): volume free energy change  
\( E \): changes of an interface energy  
\( V \): volume of the critical nucleus

Activation energy according to the tilt angle (\( \theta \)) for nucleation (*)

Low energy interface (facetted) // Matrix grain boundary

* Acta metal. 23:799, 1979
Discussion: Dominant factor in strained sample

At high energy boundaries and incoherent boundaries when  

\[
\frac{\Delta G^1_s - \Delta G^2_s}{\Delta G_s} \gg 0
\]

Why not?

Case I: ‘Nucleation selection’ dominant

\[
\Delta G = -\frac{4\pi}{3} r^3 (\Delta G_v + W) + 4\pi r^2 \sigma_{\gamma\alpha} \\
\Delta G^* = \frac{\Gamma \sigma_{\gamma\alpha}^3}{(\Delta G_v + W)^2}
\]

Benefit by Strain E ↑ >> Loss of Interfacial E ↑

→ Ferrite should have KS with \(\gamma_1\)

(Austenite free energy increase: \(\gamma_1 > \gamma_2\))

Case II: ‘Growth selection’ dominant

Existence of very small ferrite which have KS-type with \(\gamma_1\)

→ All possible nuclei conditions in early stage of nucleation

High E
{111} plane // Grain boundary

Low E
{111} plane ≠ Grain boundary

Low energy orientation relationship → Random orientation relationship

Austenite 1

Austenite 2

Why not?
Discussion: **Growth selection**

Case (b) is more advantageous in activation minimization, however!

- **growth rate ↑↑**
  - (high dislocation density, high boundary mobility)

- **growth rate ↓**
  - (low dislocation density)

- **growth rate ↓**
  - (low boundary mobility)

KS with $\gamma_1$ and $\gamma_2$.
- ‘Double orientation relationship’ irrespective of Taylor factor
- $\gamma/\gamma$ boundary $E \downarrow$ (Very stable)
- Boundary mobility $\downarrow$ (Both semi-coherent boundaries)
→ Invisible difference in growth rate between both sides
Summary

Un-deformed sample

{111} of $\gamma_1$ parallel to $\gamma_1$-$\gamma_2$ grain boundary

Nucleation selection

Low energy O.R with $\gamma_1$

Deformed sample

At high energy boundaries

At CSL boundaries

Coherent boundaries

Incoherent boundaries

$\frac{\Delta G_s^1 - \Delta G_s^2}{\Delta G_s} \gg 0$

$\frac{\Delta G_s^1 - \Delta G_s^2}{\Delta G_s} \approx 0$

Growth Selection

Nucleation selection

Low energy O.R with $\gamma_1$

Low energy O.R with $\gamma_2$

Low energy O.R with $\gamma_1$

Low energy O.R with $\gamma_1$ and $\gamma_2$
Thank you for your listening!