Partitioning and austenite reversion in Mn steels


Max-Planck-Institut
für Eisenforschung GmbH
Düsseldorf, Germany
WWW.MPIE.DE
d.raabe@mpie.de

Symposium Atomistic Effects in Migrating Interphase Interfaces in Mn steels
13. March 2012
Dierk Raabe
TMS Annual Meeting, Orlando, USA
- Design of complex steels

- Nanostructuring by lattice defect decoration and selective phase transformation

- Theoretical treatment

- Summary and conclusions
From atomistic understanding towards designing new materials

Inverse strength-ductility relation

Design strain hardening only where needed
- Design of complex steels

- Nanostructuring by lattice defect decoration and selective phase transformation

- Theoretical treatment

- Summary and conclusions
Effect of aging on ductility

Engineering Stress (MPa)

Engineering Strain (%)

1. as-quenched
2. aged 450°C/48h

strain 0%
strain 15%

Precipitation hardening
increase of austenite fraction during aging

α-Fe (Martensite)
γ-Fe (Austenite), vol. fraction 15-20%

<table>
<thead>
<tr>
<th>C</th>
<th>Ni</th>
<th>Mo</th>
<th>Ti</th>
<th>Al</th>
<th>Mn</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>2.0</td>
<td>1.0</td>
<td>1.0</td>
<td>0.15</td>
<td>12</td>
<td>bal.</td>
</tr>
</tbody>
</table>

D. Raabe et al. Scripta Materialia 60 (2009) 1141
Effect of cold rolling after aging

12MnPH X-Ray

Why so much austenite 120 K below equilibrium transformation?

\[ \gamma \rightarrow \alpha' \text{ (TRIP)} \]

Fraction of Austenite (%)
Cold Rolling Reduction, %
quenched
aged (450°C/48h)
formation during aging
450°C/48h
quenched
APT results: Atomic map (12\%Mn, aged 450°C/48h)

Mn atoms
Ni atoms
Mn iso-concentration: 18 at.\%

<table>
<thead>
<tr>
<th>C</th>
<th>Ni</th>
<th>Mo</th>
<th>Ti</th>
<th>Al</th>
<th>Mn</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>2.0</td>
<td>1.0</td>
<td>1.0</td>
<td>0.15</td>
<td>12</td>
<td>bal.</td>
</tr>
</tbody>
</table>

70 million ions Laser mode (0.4nJ, 54K)
APT results: Atomic map (12MnPH aged 450°C/48h)

Martensite decorated by precipitations

Mn atoms
Ni atoms
Mn iso-concentration: 18 at.%

<table>
<thead>
<tr>
<th>C</th>
<th>Ni</th>
<th>Mo</th>
<th>Ti</th>
<th>Al</th>
<th>Mn</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>2.0</td>
<td>1.0</td>
<td>1.0</td>
<td>0.15</td>
<td>12</td>
<td>bal.</td>
</tr>
</tbody>
</table>

70 million ions Laser mode (0.4nJ, 54K)
Aging-induced austenite reversion

Thermo-Calc $\Rightarrow$
equilibrium Mn-conc.:
27 at. % Mn in austenite (A)
3 at. % Mn in ferrite (martensite) (M)

Mn iso-concentration (18 at.% Mn)

Mn layer 1
Mn layer 2
nominal 12 at.% Mn
depletion zone

M  A

Manganese content, at. %
Boundary profile (Martensite to Austenite), nm

precipitates in $\alpha$'

\[ x_{\text{Diff}} \approx 2\sqrt{Dt} \approx 30\text{nm} \]

no precipitates in austenite

\[ x_{\text{Diff}} \approx 2\text{nm} \]


Max-Planck-Institut für Eisenforschung, Düsseldorf, Germany

stem [ STEM BF ]
TEM 200kV x400k 50%
Thermo-Calc ⇒
equilibrium Mn-conc.:
27 at. % Mn in austenite (A)
3 at. % Mn in ferrite (martensite) (M)

Excellent agreement between experiment & simulation!
Hierarchy of maraging TRIP / TWIP steels

TEM M
estacking faults DF
Print Mag: 49500x @ 100 mm
TEM Mode: Imaging
Growth of retained austenite 450°C/48h. 12MnPH

Mn profile

<table>
<thead>
<tr>
<th>C</th>
<th>Ni</th>
<th>Mo</th>
<th>Ti</th>
<th>Al</th>
<th>Mn</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>2.0</td>
<td>1.0</td>
<td>1.0</td>
<td>0.15</td>
<td>12</td>
<td>bal.</td>
</tr>
</tbody>
</table>
Martensite relaxation & aging & nanoscale austenite reversion

650 MPa to 2 GPa

400°C aging: Ms-relaxation + prec. (aging) + austenite reversion

Fe-13.6Cr-0.44C (wt.%)
at 5.45 at.% C, austenite forms at 400°C
at 5.45 at.% C, austenite forms at 400°C
Microstructure development

400° C
1 min

200 nm
Microstructure development

400° C
1 min

Prior Austenite Grain Boundary

[111]α

[110]γ

1 μm
Self-repair steels

Retained austenite

Reversed austenite
Self-repair steels
- Design of complex steels

- Nanostructuring by lattice defect decoration and selective phase transformation

- Theoretical treatment

- Summary and conclusions
Equilibrium carbon concentration in austenite

Nanoscale austenite reversion in Fe-C system

Distance from grain boundary (nm)

at.%C

Graph showing the equilibrium carbon concentration in austenite at different times:
- $t = 0.01\,\text{ms}$
- $t = 0.1\,\text{ms}$
- $t = 1\,\text{ms}$
- $t = 10\,\text{ms}$
- Design of complex steels
- Nanostructuring by lattice defect decoration and selective phase transformation
- Theoretical treatment
- Summary and conclusions