Chemical gradients across martensite/austenite phase boundaries in precipitation hardened TRIP steel studied by atom probe tomography

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- Motivation and alloy design
- Atom probe tomography
- Mechanical properties and microstructure
- Mn partitioning and simulations
- Conclusions
Fe-Mn based maraging TRIP steel development

- **TRIP**: deformation-stimulated transformation of unstable austenite into martensite and accommodation plasticity (e.g. Mn, Ni, low C)

- **Maraging effect**: hardening of heavily strained martensite via nano-sized (intermetallic) precipitates (Ni, Al, Ti, Mo)

(see also conventional Maraging steels)

**What is maraging-TRIP?**

Quenched austenite: ductile low carbon martensite
Retained austenite (TRIP or TWIP)
Aging: austenite reversion (increase TRIP / TWIP volume)
Aging: controlled precipitation hardening

* TRIP: transformation-induced plasticity
* Maraging: martensite aging
### Compositions in mass%

<table>
<thead>
<tr>
<th>Steel</th>
<th>C</th>
<th>Ni</th>
<th>Co</th>
<th>Mo</th>
<th>Ti</th>
<th>Al</th>
<th>Mn</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maraging</td>
<td>0.01</td>
<td>18</td>
<td>12</td>
<td>4</td>
<td>1.6</td>
<td>0.15</td>
<td>0.05</td>
<td>Balance</td>
</tr>
<tr>
<td>09MnPH</td>
<td>0.01</td>
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<td>-</td>
<td>1</td>
<td>1.0</td>
<td>0.15</td>
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<tr>
<td>12MnPH</td>
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<td>2</td>
<td>-</td>
<td>1</td>
<td>1.0</td>
<td>0.15</td>
<td>12</td>
<td>Balance</td>
</tr>
<tr>
<td>15MnPH</td>
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<td>2</td>
<td>-</td>
<td>1</td>
<td>1.0</td>
<td>0.15</td>
<td>15</td>
<td>Balance</td>
</tr>
</tbody>
</table>

**Low carbon: ductile martensite**

**Precipitation Hardenable**

**Mn (+Ni): austenite (TRIP)**

Martensite aging after quenching at 450°C
- Motivation and alloy design
- Atom probe tomography
- Mechanical properties and microstructure
- Mn partitioning and simulations
- Conclusions
Atom Probe Tomography (APT)

**Tip-shaped sample** initiated evaporation by ± ~ 10 kV

**Detector**

**Counts**

**Mass to charge ratio**

**3D atom map**

**APT**: Time of flight measurement (chemical identification) + Ion projection microscopy (determination of position)
- Motivation and alloy design
- Atom probe tomography
- Mechanical properties and microstructure
- Mn partitioning and simulations
- Conclusions
Precipitation-hardening of martensite → "maraging"

TRIP effect: hardness + ductility

Specimen [ STEM BF ]
JEOL-TEM 200KV x400K 50%
Motivation and alloy design
Atom probe tomography
Mechanical properties and microstructure
Mn partitioning and simulations
Conclusions
APT results: Atomic map (12MnPH aged 450°C/48h)

Martensite decorated by precipitations

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

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<td>12</td>
<td>bal.</td>
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</table>

70 million ions
Laser mode
(0.4nJ, 54K)
Thermo-Calc ⇒
equilibrium Mn-conc.:
27 at. % Mn in austenite (A)
3 at. % Mn in ferrite (martensite) (M)

Mn iso-concentration (18 at.% Mn)

nominal 12 at.% Mn depletion zone

12MnPH after aging (48h 450°C)

precipitates in $\alpha'$

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

no precipitates in austenite

$$x_{\text{Diff}} \approx 2\text{nm}$$
Aging-induced austenite reversion

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

Excellent agreement between experiment & simulation!

Kinetic freezing and associated austenite reversion!
Mean diffusion path of Mn in austenite (aging 450 °C/48h) ≈ 2 nm

APT results and simulation: DICTRA/ThermoCalc

- Motivation and alloy design
- Atom probe tomography
- Mechanical properties and microstructure
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Conclusions

- Maraging-TRIP as a new GPa steel design approach

- Unexpected simultaneous increase in strength and elongation

- Mn partitioning, predicted by ThermoCalc/DICTRA

- Austenite stability predicted using ab initio methods (see talk of T. Hickel)

- B2 and L21 nano-precipitates

- Next steps: lean composition, interstitials, alloy variants, equilibrium partitioning, nano-precipitates