Quench induced stresses considering precipitation in large industrial aluminum pieces

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and

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Competence Center for Materials Science and Technology (http://www.ccmx.ch/) project entitled

“Measurements and modelling of residual stress during quenching of thick heat treatable aluminium components in relation to their microstructure”

involving EPF Lausanne, Switzerland
Paul Scherrer Institute, Prof. H. Van Swygenhoven, PSI Villigen
Univ. South Brittany (D. Carron, LIMATB, Lorient, France)
Constellium CRV Voreppe, France
and ABB Turbo-Systems, Baden Switzerland.
Introduction: two industrial challenges

- Fabrication route for heat treatable (HT) aluminum alloys (AA)

  - AA7040 and AA7449 thick plates for aerospace applications

  - AA2618 large forgings for impellers

  - Hot forged pieces
Introduction: two industrial challenges

Heat treatment gives birth to internal stresses that are relaxed during machining of thick aluminium plates for aeronautic applications (buy to fly ratio is 10)

AA7040 and AA7449 thick plates for aerospace applications
Introduction: two industrial challenges

Heat treatment give birth to internal stresses that are relaxed during machining

AA2618 large forgings for impellers (turbo systems for marine industry)
Precipitation during quenching

- Problems arise for large components and quench sensitive AA7xxx (Al-Zn-Mg-Cu) alloys: precipitation should not occur during quenching.
- During the T6 heat treatment: SS → Guinier Preston(GP) (I) zones → η' → η (MgZn_{2(1-z)}Cu_zAl_z)

- Fast quench: high hardening potential (desirable) but high residual stresses (undesirable owing to distortions)
- Slow quench: lower residual stresses but decreased hardening potential by formation of quench-induced precipitates
- In thick products: quenching leads to a gradient of precipitation and thus of properties (trade-off residual stress/final yield strength).
Multi-scale & multi-physics approach

Internal stress formation during quenching of thick plates

Thermal gradients lead to RS

Residual stresses:

A FE model ignoring the change of yield strength associated with precipitation during quenching underestimates the RS.
Multi-scale & multi-physics approach

Precipitation model


FE model


Residual stresses:

RS predictions require a coupling with precipitation during quench
Outline

Residual stress analysis using neutrons and layer removal technique and FE modeling (N. Chobaut)

Precipitation during quench in AA7449: characterization and modeling (P. Schloth)

Gleeble interrupted quench tests to measure yield strength (D. Carron and N. Chobaut)
Residual stress analysis using neutrons and layer removal technique and FE modeling (N. Chobaut)
Neutron diffraction measurements

\[ \varepsilon = \left( d - d_0 \right) / d_0 \quad 2d_{hkl} \sin \theta = n\lambda \]

The lattice spacing acts as a kind of strain gauge. 
\( d_{hkl} \) is given by Bragg’s law (diffraction peak for (311) planes in aluminium). 
Peak shift (d-d_0) yields elastic strain and hence stress level. 
Measurements in 3 orthogonal directions are required to get stresses. 
Sample rotation are required to get shear components.

(311) Diffraction peak with a 3.8 mm collimator (55 mm³ gauge volume)

\[ Q = \frac{4\pi}{\lambda} \sin \theta \]
## Neutron sources

### Diffractometer

<table>
<thead>
<tr>
<th>Source:</th>
<th>Type</th>
<th>Flux</th>
<th>Source:</th>
<th>Type</th>
<th>Flux</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Spallation (pulsed)</td>
<td>$6 \times 10^6$ neutrons.cm$^{-2}$.s$^{-1}$</td>
<td></td>
<td>Nuclear (continuous)</td>
<td>$5 \times 10^7$ neutrons.cm$^{-2}$.s$^{-1}$</td>
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<tr>
<td></td>
<td>[Stuhr 2005]</td>
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<td>[Pirling 2006]</td>
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### Diffraction angle

<table>
<thead>
<tr>
<th></th>
<th>Fixed : $2\theta = 90^\circ$</th>
<th>Variable (measured)</th>
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### Wave length

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<tr>
<th></th>
<th>polychromatic</th>
<th>monochromatic</th>
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**Paul Scherrer Institut**
- PSI Villigen, Switzerland

**Institut Laue-Langevin**
- ILL Grenoble, France

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Stress in thick AA7040 and AA7449 plates

For an infinite plate, generalized plane stress situation

L rolling direction, ST short transverse, LT long transverse

\[ \begin{align*}
\sigma_{xx} &= \sigma_{yy} \\
\sigma_{xy} &= \sigma_{xz} = \sigma_{yz} = 0 \text{ no shear} \\
\text{div}(\sigma) &= 0 \Rightarrow \frac{\partial \sigma_{zz}}{\partial z} = 0 ; \\
\sigma_{zz}(-h) &= \sigma_{zz}(h) = 0 \Rightarrow \sigma_{zz}(z) = 0
\end{align*} \]

\[ \sigma = \begin{pmatrix}
\sigma_x(z) & 0 & 0 \\
0 & \sigma_x(z) & 0 \\
0 & 0 & 0
\end{pmatrix} \text{ is fully defined by } \sigma_x(z) \]
ND measurements

As-quenched hot rolled 7xxx alloy plates 75 mm in thickness measured at Salsa-ILL and Poldi-PSI (cold water quenched by Constellium CRV in a laboratory device)

Large plates: 700 mm (L) x 525 mm (TL)
Small plates: 310 mm (L) x 310 mm (TL)

No side effect if plane dimensions > 4 times thickness (checked by FE modelling)
Residual stress in 75 mm thick AA7449 cold water quenched plates

In-plane stresses, skin core effect
Good agreement between the two diffractometers
Residual stress in 75 mm thick AA7449 cold water quenched plates

Comparison with a FE model ignoring precipitation, i.e. considering temperature dependant mechanical properties (solid solution properties)

Precipitation during quench in AA7449: characterization and modeling (P. Schloth)
Perfect quench:
- Freeze supersaturated solid solution
- Maintain high vacancy density

→ Maximum hardening potential

Quenching large components:
- Different cooling rates through thickness
- Possible precipitation during quench
- and associated solute loss

→ Reduced hardening potential for aging
→ Affects RS formation

Main precipitation sequence for 7xxx Al. alloys:
SS (solid solution) → VRC/GP zones → metastable $\eta'$ → stable $\eta$ ($\sim\text{MgZn}_{2(1-x)}\text{Cu}_{x}\text{Al}_x$)

Quench induced precipitation in AA7449
As-quenched nanostructure: heterogeneous precipitation

- Intergranular η precipitates
- Intragranular η precipitates

@ plate center

Al₃Zr
As-quenched nanostructure: homogeneous precipitation

@ plate center (as quenched but also naturally aged)

High angle annular dark field
HAADF

Selected area diffraction pattern
SADP

homogeneously distributed Guinier Preston zones and η′
Mechanical influence of precipitation

![Graph showing temperature over time with legend: surface, 1/4 thickness, center.](image)

**Softening effect**
(heterogeneous $\eta$

$$\sigma_{sol} = \left(\sum k_jc_j\right)^{2/3}$$

**Hardening effect**
(homogeneous $\eta'/GPZ$

$$\sigma_P = \frac{MF}{bL}$$

Shearing for small radii
Orowan for larger radii

$$\sigma_y = \sigma_0 + \sigma_{ss} + \sigma_P = 10 + 805 \times C_{ss}^{2/3} + \begin{cases} 
0.013 \times M \mu \sqrt{f_v R/b} & (ua) \\
29 + 0.59 \times M \mu b \sqrt{f_v / R} & (oa) 
\end{cases}$$

In situ c-SAXS characterisation of precipitation

TCC (transf. during continuous cooling) diagram for the AA7449 based on in situ SAXS measurements: clusters and GP zones always form even at high cooling rates. AA7449 is particularly quench sensitive.

Gleeble interrupted quench tests to measure precipitation dependent yield strength  (N. Chobaut)

An alternative to full coupling with precipitation ....
Gleeble measurements

Gleeble machine at UBS-Lorient: mechanical testing + heating by Joule effect and cooling by air or water.

Interrupted quenching test requires a good temperature control
Yield stress is measured at high strain rate to reduce time for any further precipitation

Specimen geometry equipped with 3 TCs
Gleeble measurements: interrupted quenched tests

Surface coolings are imposed to the Gleeble specimens and tensile loading is applied.
Stress-strain curves are fitted using:

\[ \bar{\sigma} = \sigma_0 + H \left( \bar{\varepsilon}_p \right)^n + K \left( \dot{\bar{\varepsilon}}_p \right)^m \]
FE computations using Abaqus

(a) AA7449
75 mm plate

Measurements:
- Layer Removal
- neutrons SALSA
- neutrons POLDI

(b) AA7040
75 mm plate

FE simulation:
- without precipitation
- with precipitation

(c) AA7449
20 mm plate

(d) AA7040
140 mm plate

in-plane stress $\sigma_{yy}$ (MPa)

Normalised position through plate thickness

50 MPa

110 MPa

70 MPa

90 MPa

75 MPa
Conclusion

• Precipitation during quenching has a strong influence on internal stress generation in thick AA2xxx and AA7xxx components.

• At least two different precipitate families have to be considered due to their opposing effects on yield strength (hardening and softening phases).

• Real precipitation sequence is very complex and delicate to model (VRC, GPZ and $\eta'$ phase, no thermodynamic descriptions, importance of frozen vacancies).

• Gleeble interrupted tests is an interesting alternative to characterize the impact of VRC/GPZ on the yield strength at the plate surface and thus to correctly model the stress generation.

• The same methodology is being applied to the ABB forgings.
At ABB, 3 machining steps are carried out. How to optimize the machining sequence with respect to internal stresses?

Outlook

3D FE model with cyclic boundary conditions
Special thanks to Constellium CRV, France and ABB Turbo Systems, Baden, for the provision of samples and results using the layer removal technique, to the Swiss Spallation Neutron Source at PSI and the International neutron source at ILL-Grenoble, France, for the provision of beam time.

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Thank you for your attention
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