Quench induced stresses considering precipitation in large industrial aluminum pieces

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and

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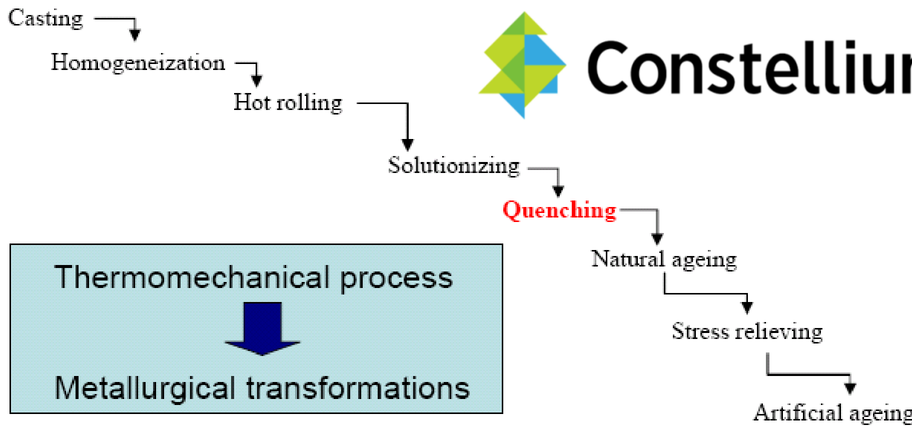
Competence Center for Materials Science and Technology (http://www.ccmx.ch/) project entitled

"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)

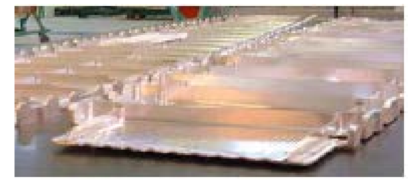


Thermomechanical process

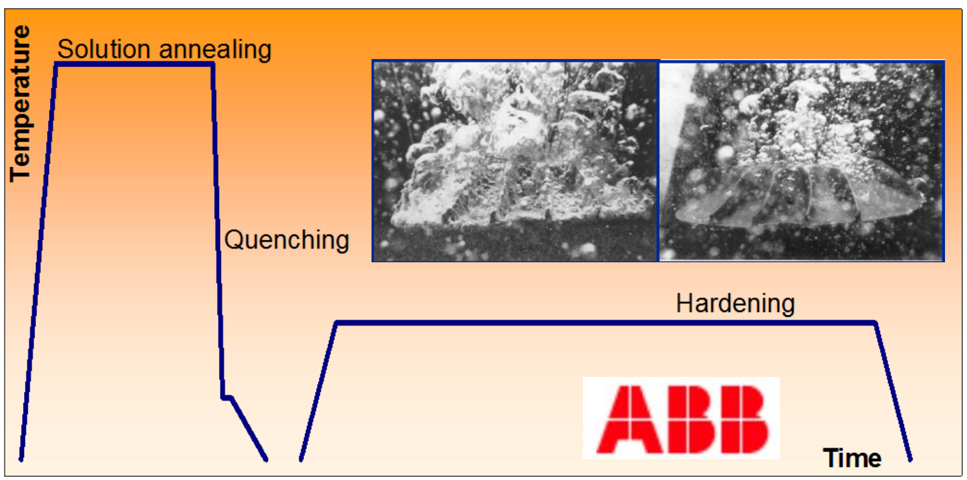
Metallurgical transformations

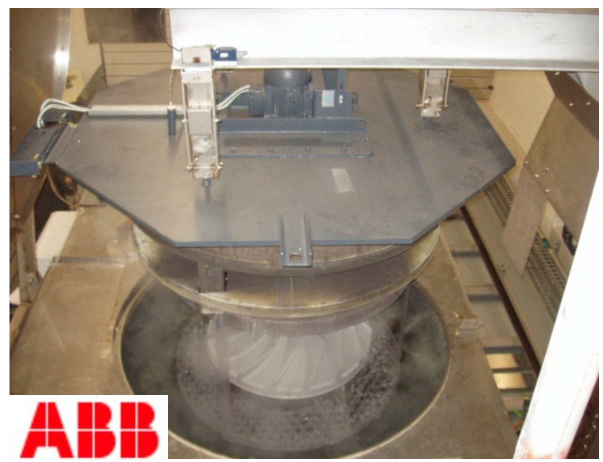
Constellium

AA7040 and AA7449 thick plates for aerospace applications



- Hot forged pieces

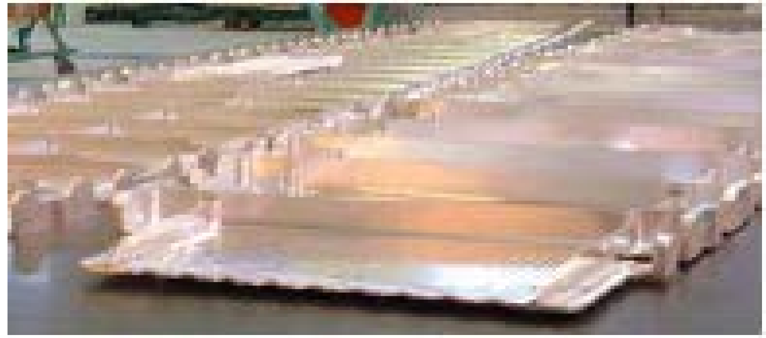




AA2618 large forgings for impellers

Introduction: two industrial challenges

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

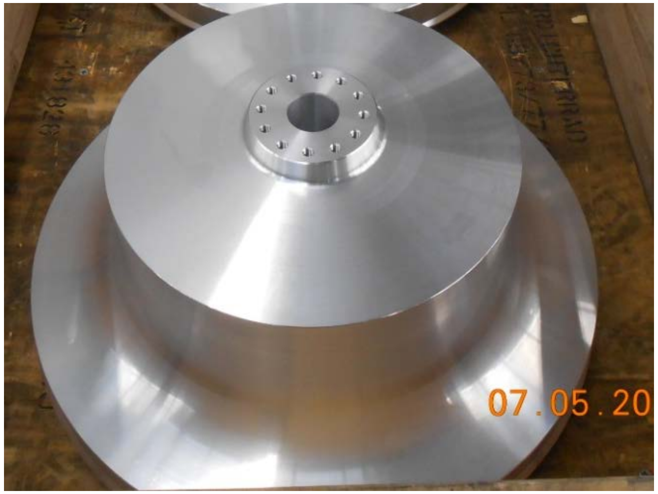


AA7040 and AA7449 thick plates for aerospace applications

machining of thick aluminium plates for aeronautic applications (buy to fly ratio is 10)

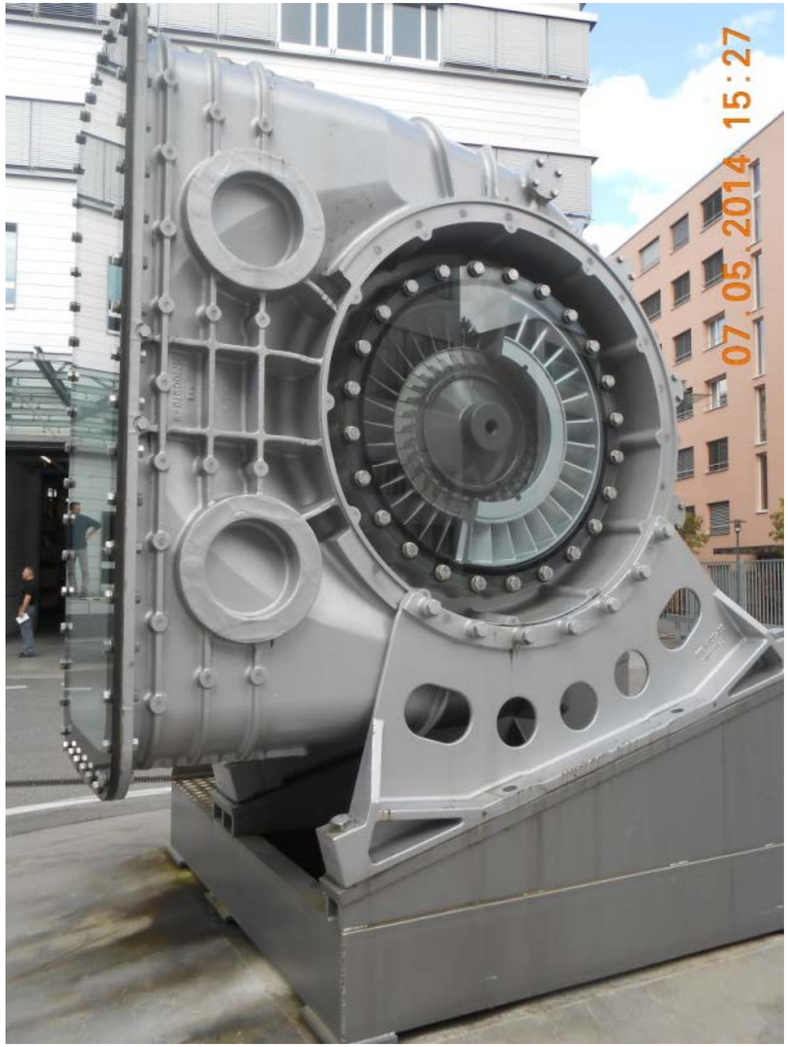
Introduction: two industrial challenges

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



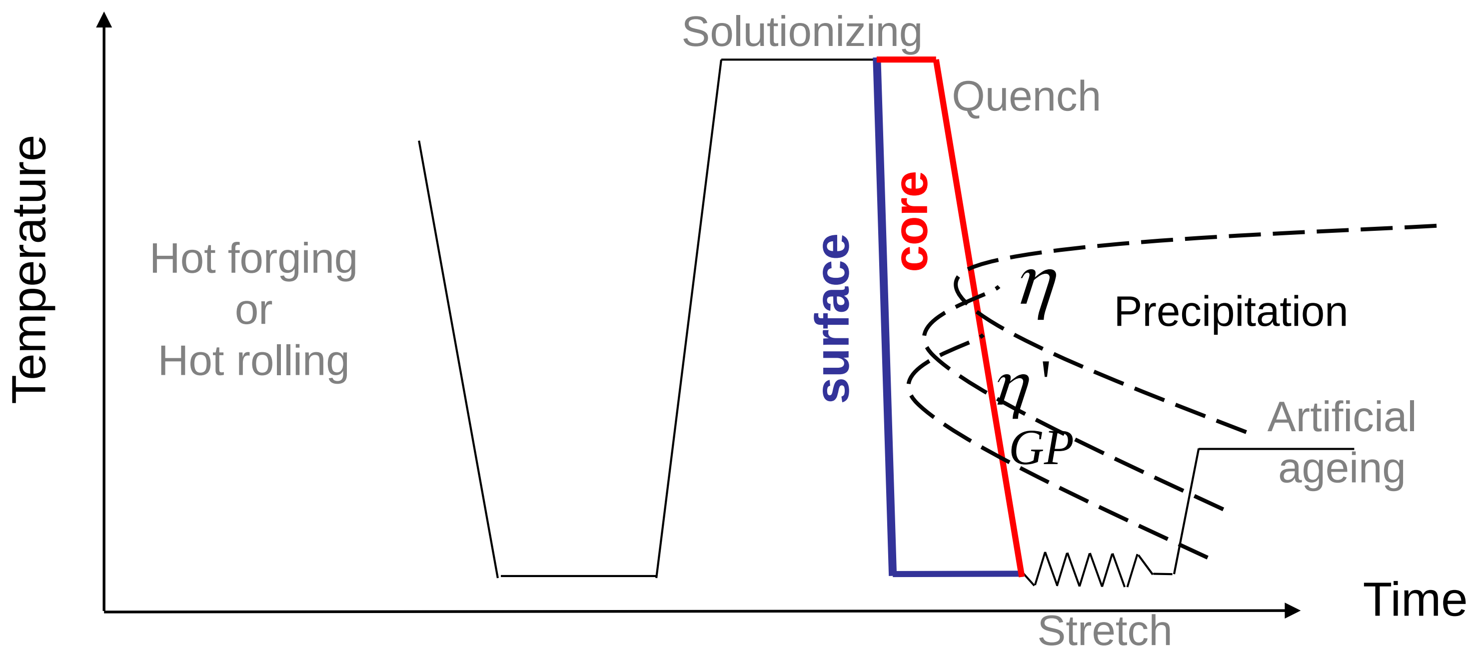
AA2618 large forgings for impellers (turbo systems for marine industry)

ABB



Precipitation during quenching

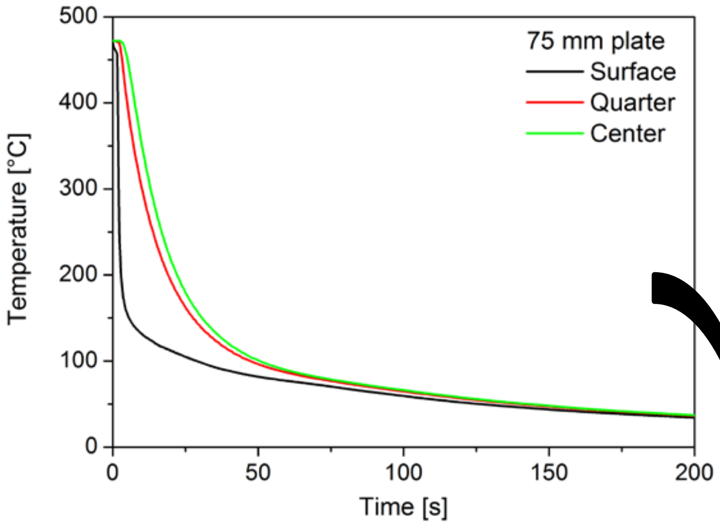
- Problems arise for large components and quench sensitive AA7xxx (Al-Zn-Mg-Cu) alloys: precipitation should not occur during quenching.
- During the T6 heat treatment: SS → Guinier Preston(GP) (I) zones → η' → η ($MgZn_{2(1-z)}Cu_zAl_z$)

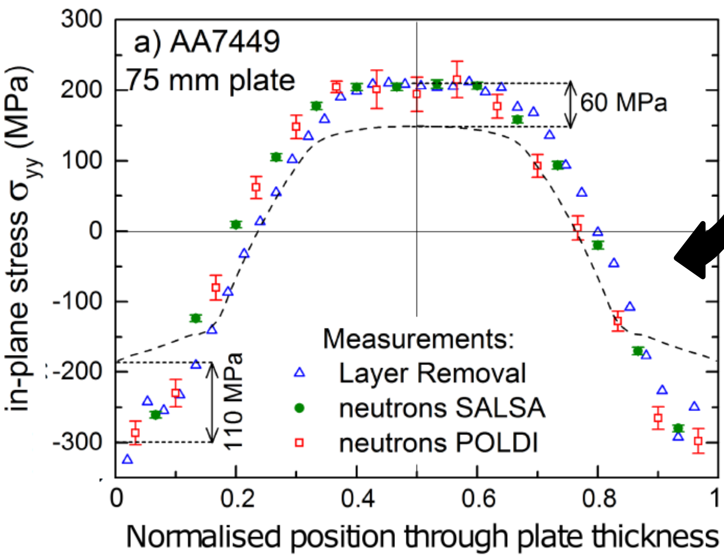


- **Fast quench:** high hardening potential (desirable) but high residual stresses (undesirable owing to distortions)
- **Slow quench:** lower residual stresses but decreased hardening potential by formation of quench-induced precipitates
- **In thick products:** quenching leads to a gradient of precipitation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

Multi-scale & multi-physics approach

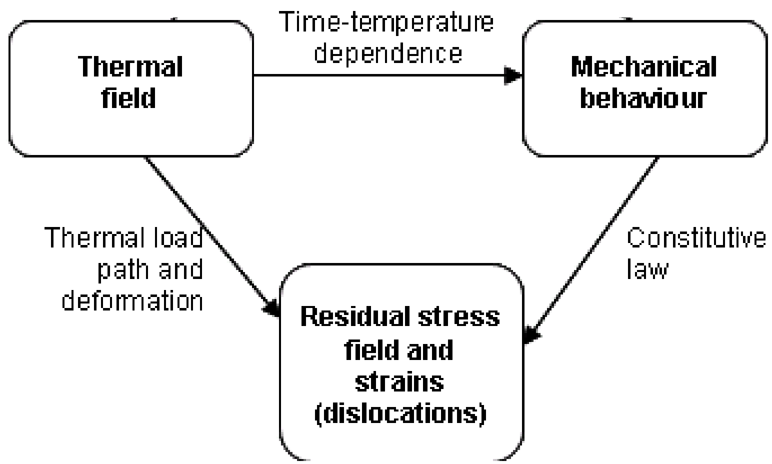
Internal stress formation during quenching of thick plates





Thermal gradients

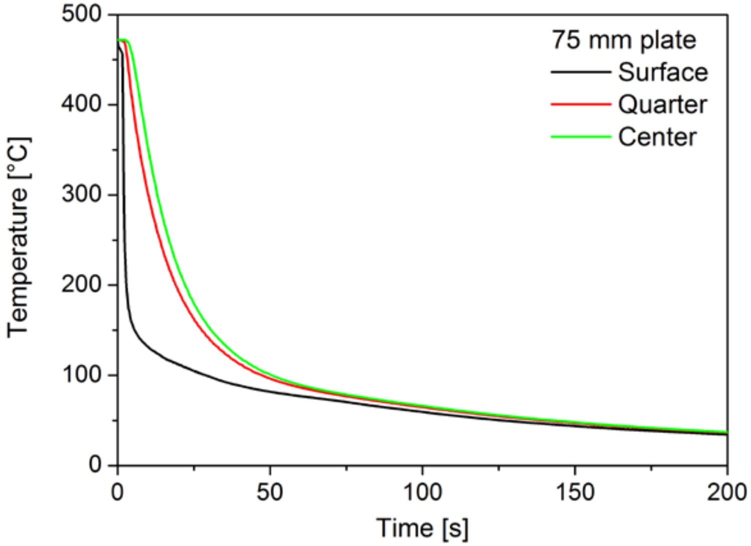
lead to RS

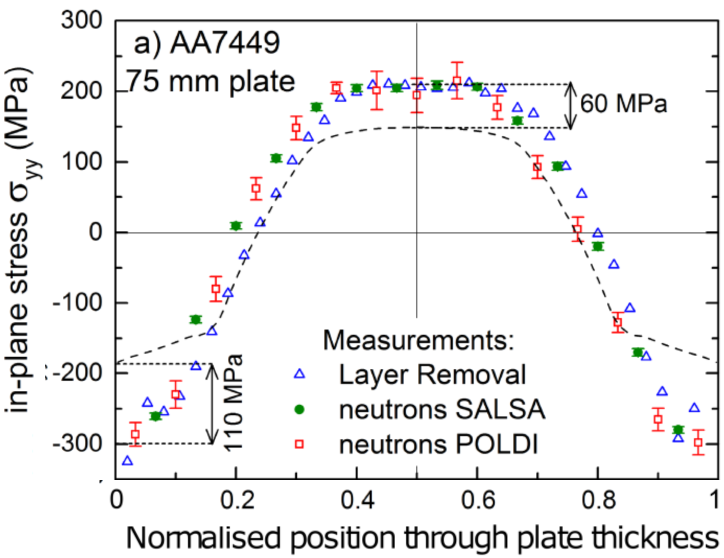


<u>Residual stresses:</u>

A FE model ignoring the change of yield strength associated with precipitation during quenching **underestimates** the RS.

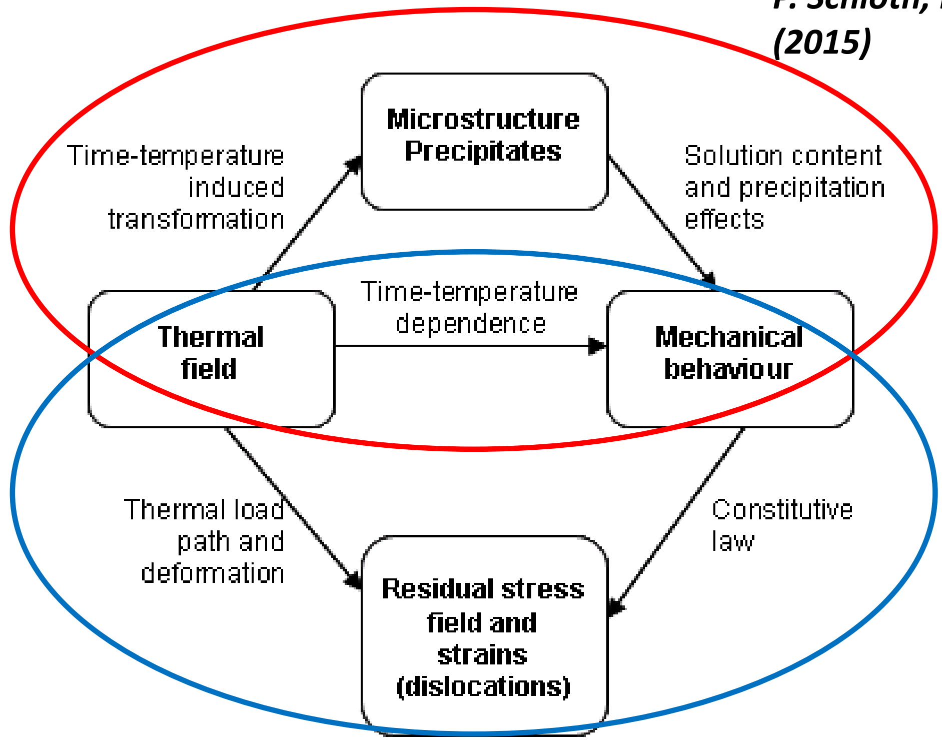
Multi-scale & multi-physics approach





Precipitation model

P. Schloth, PhD thesis, EPFL (2015)



FE model

N. Chobaut, PhD thesis, EPFL (2015)

<u>Residual stresses:</u>

RS predictions require a coupling with precipitation during quench

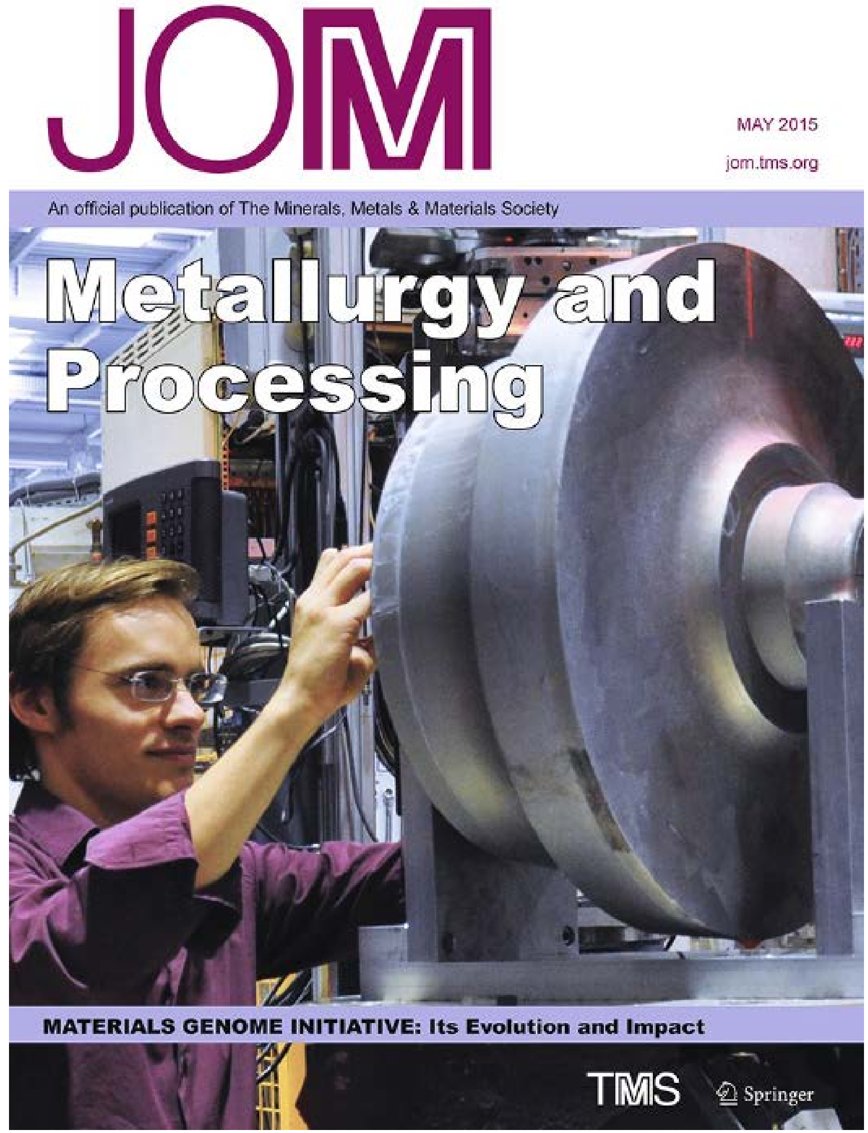
Outline

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)

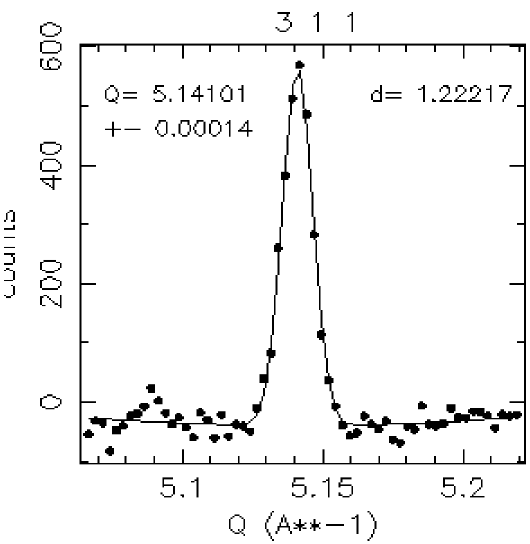
Residual stress analysis using neutrons and layer removal technique and FE modeling (N. Chobaut)



Neutron diffraction measurements

$$\varepsilon = (d - d_0) / d_0 \qquad 2d_{hkl} \sin\theta = n\lambda$$

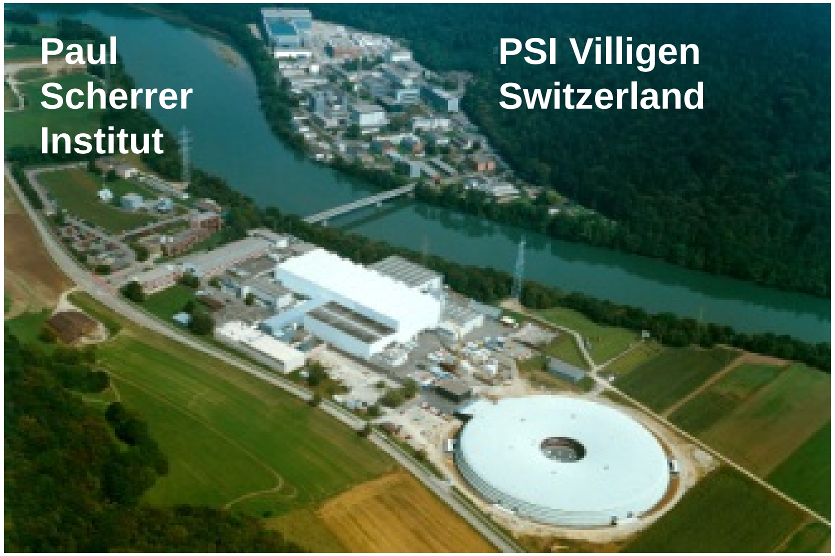
The lattice spacing acts as a kind of strain gauge
d_{hkl} is given by Bragg's law (diffraction peak for (311) planes in aluminium)
Peak shift (d-d_0) yields elastic strain and hence stress level
Measurements in 3 orthogonal directions are required to get stresses
Sample rotation are required to get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



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

$$Q = \frac{4\pi}{\lambda} \sin\theta$$

Neutron sources



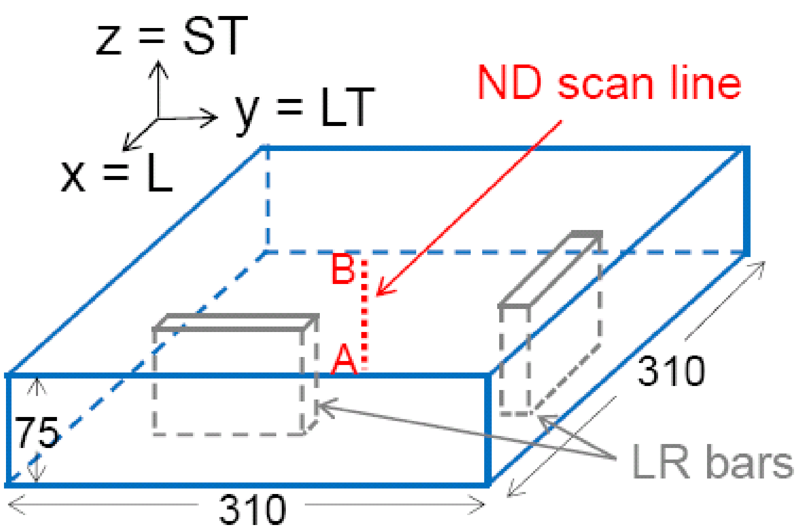
Diffractometer	POLDI (Pulse-OverLap Diffractometer)	SALSA (Strain Analyser for Large and Small scale engineering Applications)
Source: - Type - Flux	Spallation (pulsed) 6.10^{6} neutrons.$cm^{-2}.s^{-1}$ [Stuhr 2005]	Nuclear (continuous) 5.10^{7} neutrons.$cm^{-2}.s^{-1}$ [Pirling 2006]
Diffraction angle	Fixed : 2θ = 90°	Variable (measured)
Wave length	polychromatic	monochromatic

U. Stuhr *et al.*, Nuclear Instruments and Methods in Physics Research A, 545 (2005) 330-338
T.Pirling, G.Bruno and P.J.Withers, Mat. Sci. Eng. A, 437 (2006) 139-144

Stress in thick AA7040 and AA7449 plates

For an infinite plate, generalized plane stress situation

L rolling direction, ST short transverse, LT long transverse



$$\sigma_{xx} = \sigma_{yy} \quad (1)$$

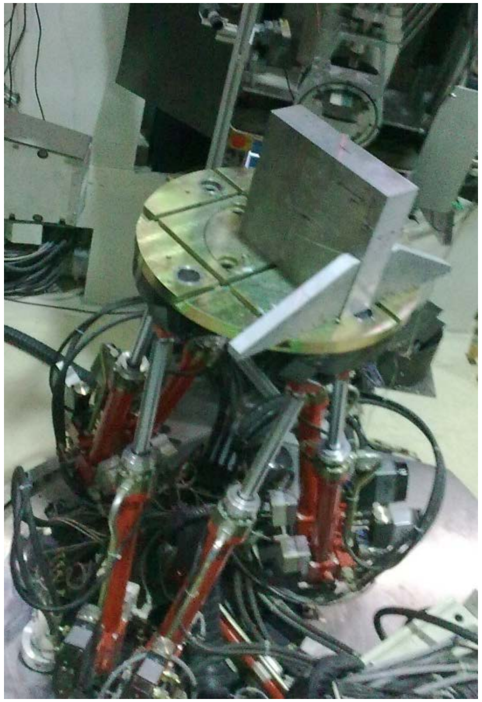
$$\sigma_{xy} = \sigma_{xz} = \sigma_{yz} = 0 \text{ no shear} \quad (2)$$

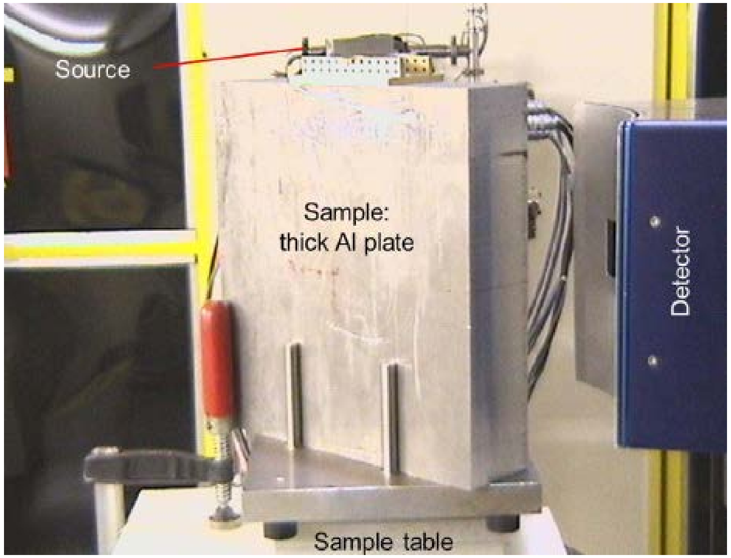
$$\underline{div}(\underline{\underline{\sigma}}) = \underline{0} \Rightarrow \frac{\partial \sigma_{zz}}{\partial z} = 0\ ;$$

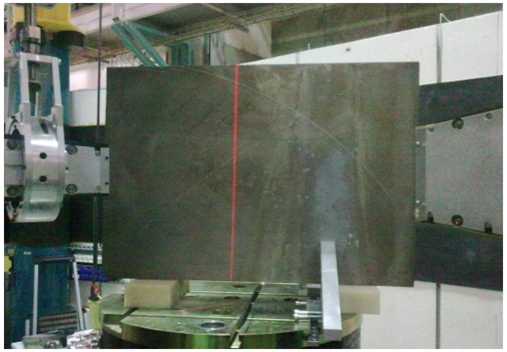
$$\sigma_{zz}(-h) = \sigma_{zz}(h) = 0 \Rightarrow \sigma_{zz}(z) = 0 \quad (3)$$

$$\sigma = \begin{pmatrix} \sigma_x(z) & 0 & 0 \\ 0 & \sigma_x(z) & 0 \\ 0 & 0 & 0 \end{pmatrix} \text{is fully defined by } \sigma_x(z)$$

ND measurements





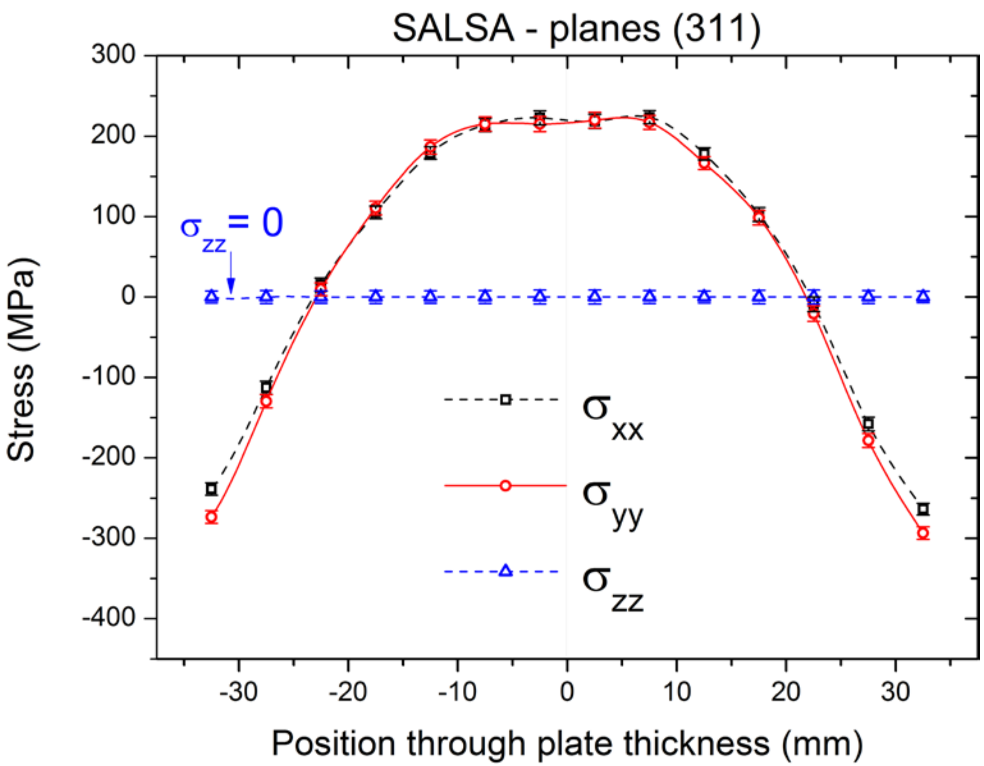


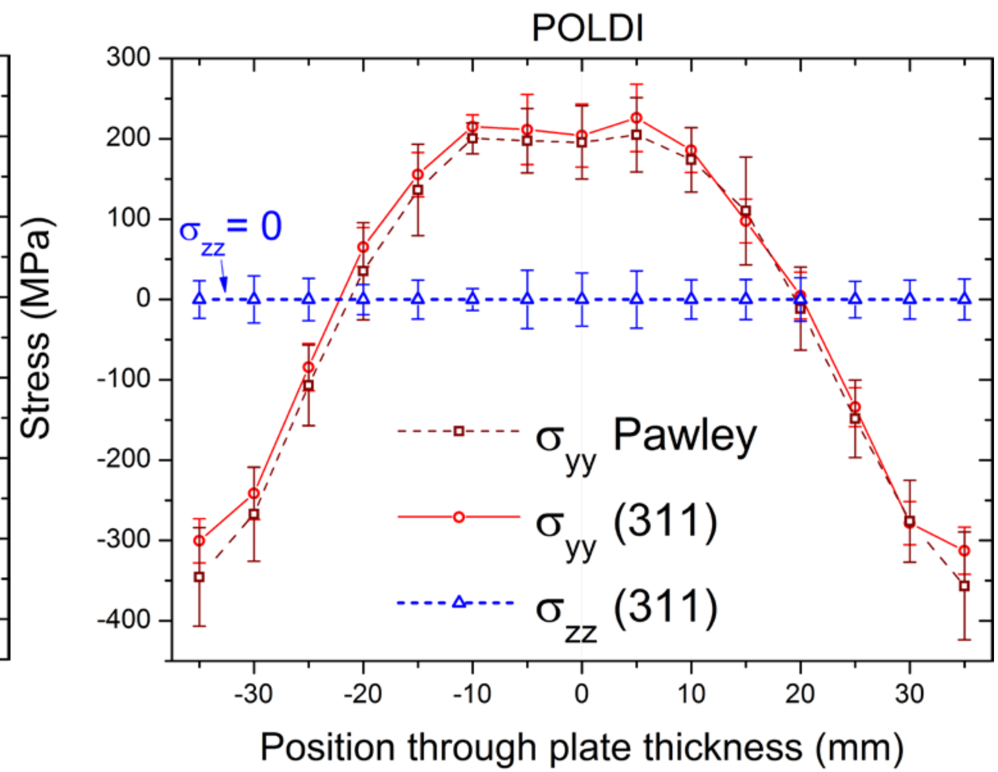
As-quenched hot rolled 7xxx alloy plates 75 mm in thickness measured at Salsa-ILL and Poldi-PSI (cold water quenched by Constellium CRV in a laboratory device)

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

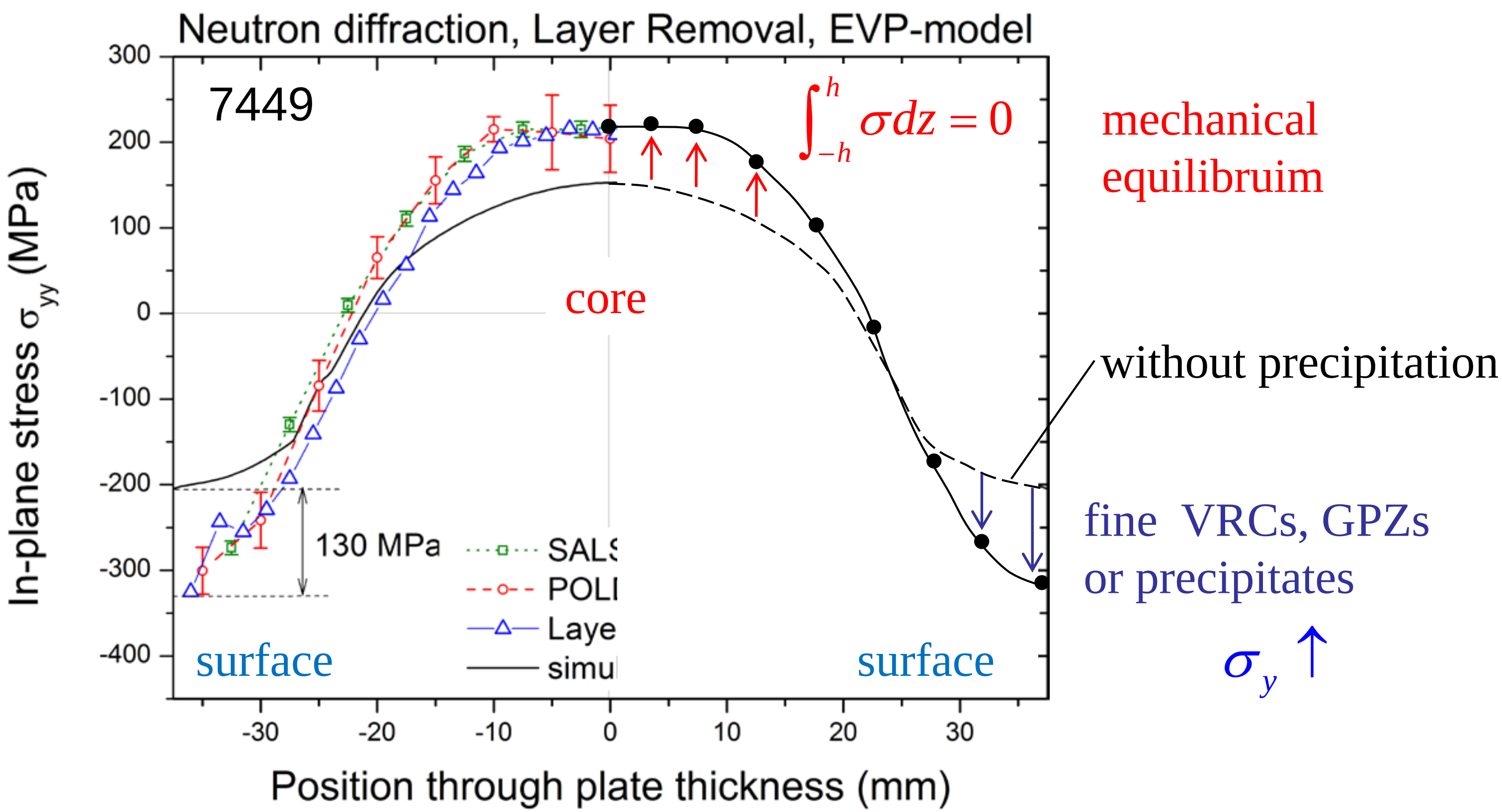




In-plane stresses, skin core effect
Good agreement between the two diffractometers

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)



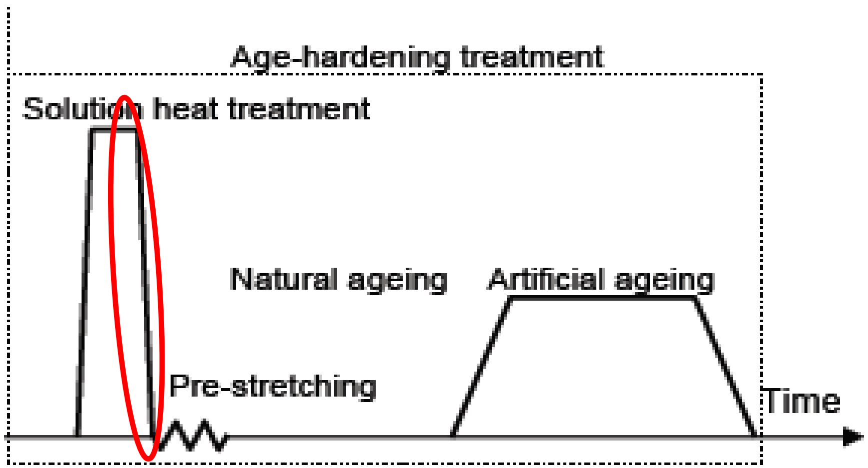
N. Chobaut, J. Repper, T. Pirling, D. Carron and J-M. Drezet, 13th Int. Conf. on Aluminum Alloys (ICAA13), Edited by H. Weiland, A. D. Rollett and W. A. Cassada, TMS, 2012, p. 285-291.

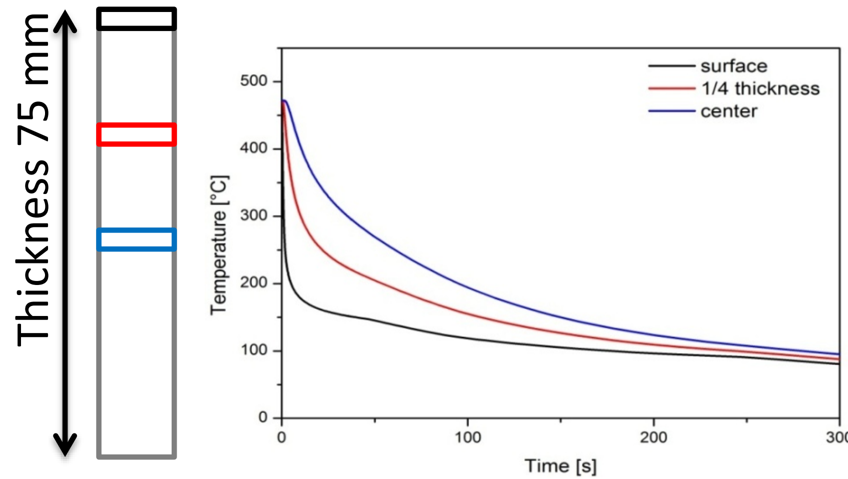
Precipitation during quench in AA7449: characterization and modeling (P. Schloth)

Quench induced precipitation in AA7449

Main precipitation sequence for 7xxx Al. alloys :

SS (solid solution) → VRC/GP zones → metastable η' → stable η (~$MgZn_{2(1-x)}$,Cu_xAl_x)





Perfect quench:

- Freeze supersaturated solid solution
- Maintain high vacancy density

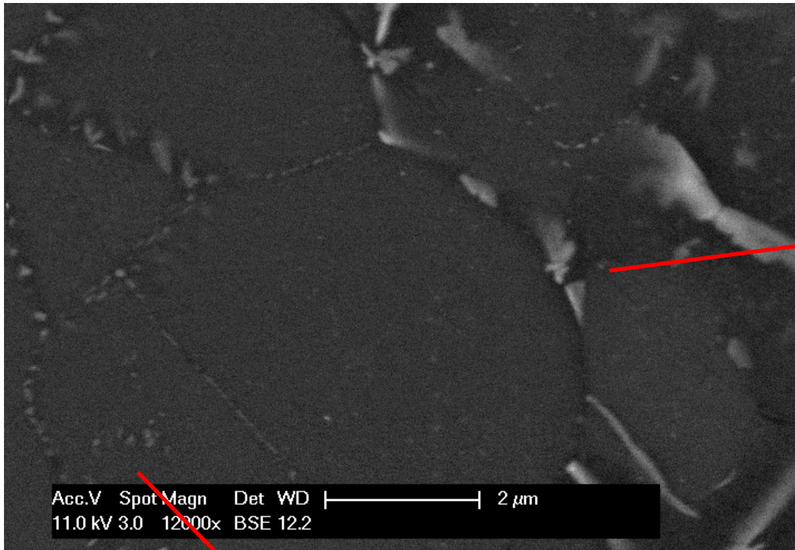
→ Maximum hardening potential

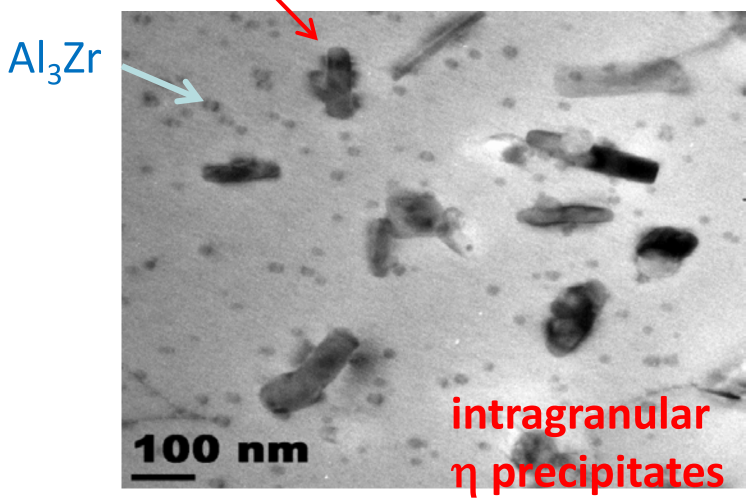
Quenching large components:

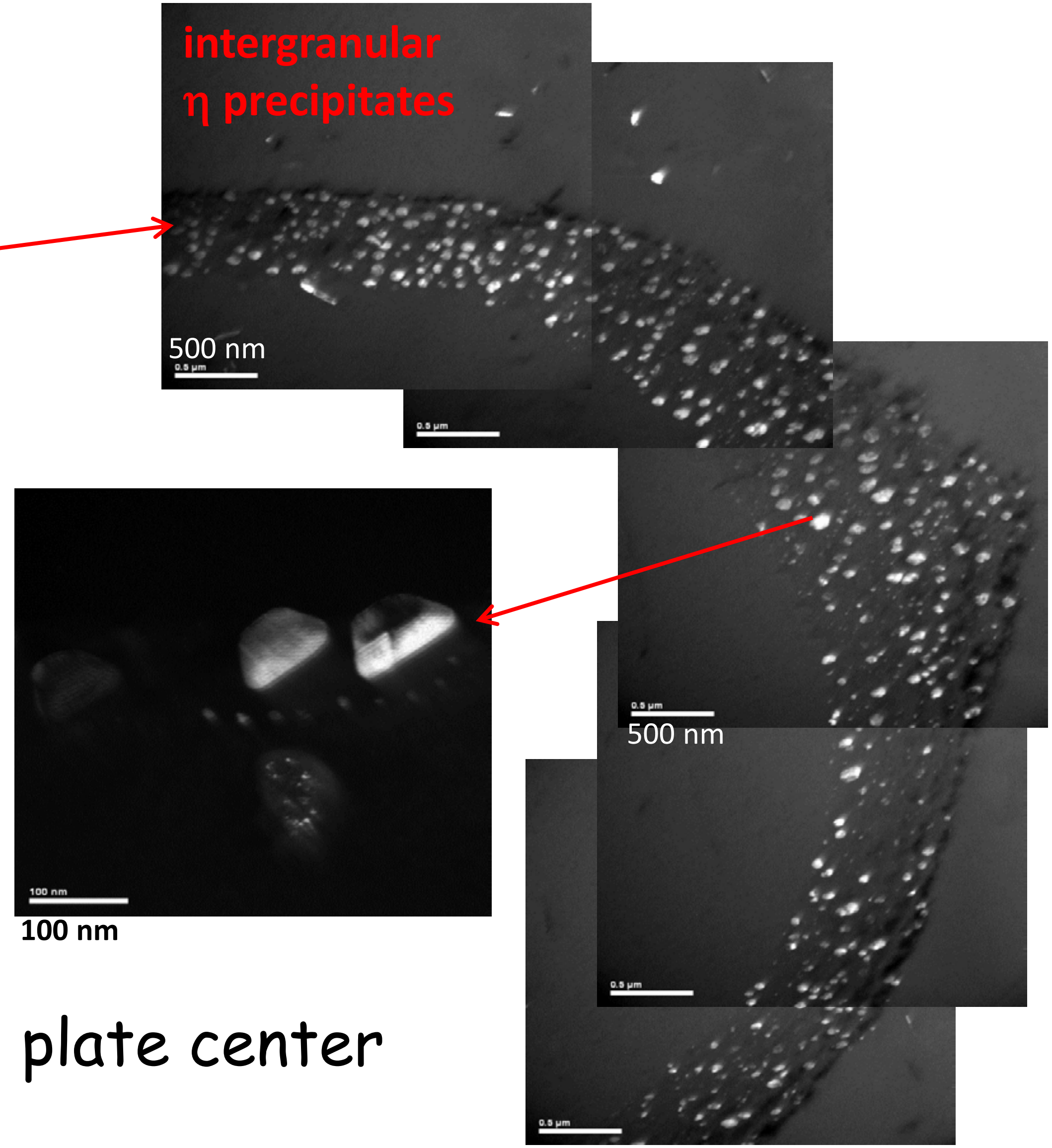
- Different cooling rates through thickness
- Possible precipitation during quench
- and associated solute loss

→ Reduced hardening potential for aging
→ Affects RS formation

As-quenched nanostructure: heterogeneous precipitation

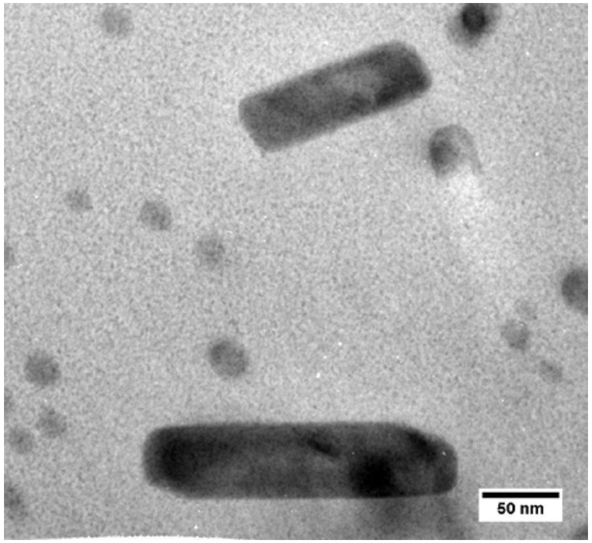


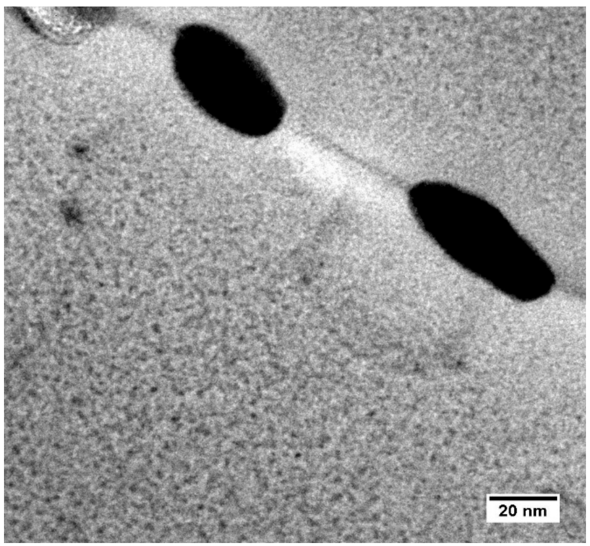




@ plate center

As-quenched nanostructure: homogeneous precipitation

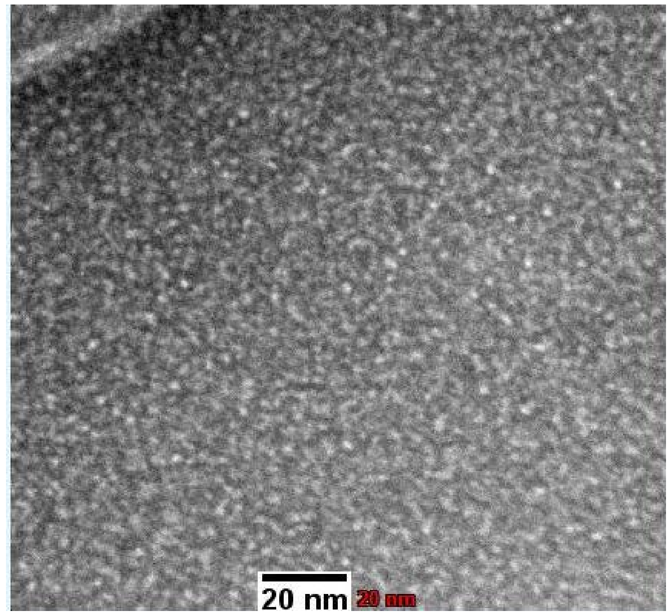




@ plate center (as quenched but also naturally aged)

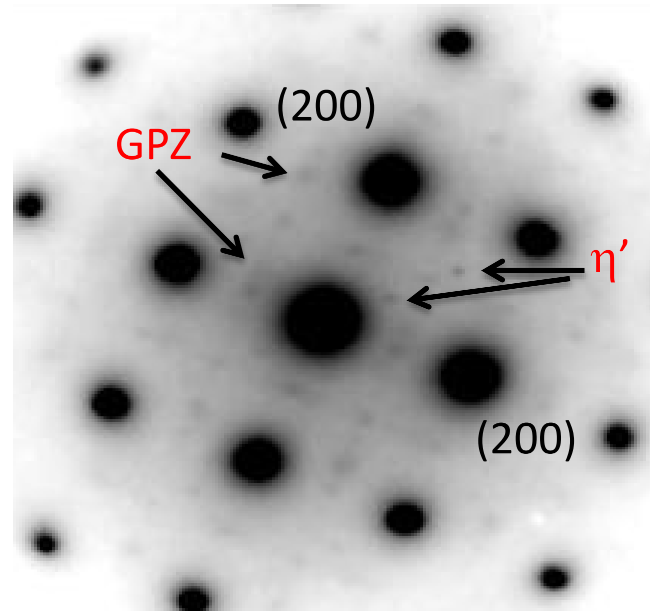
High angle annular dark field

HAADF



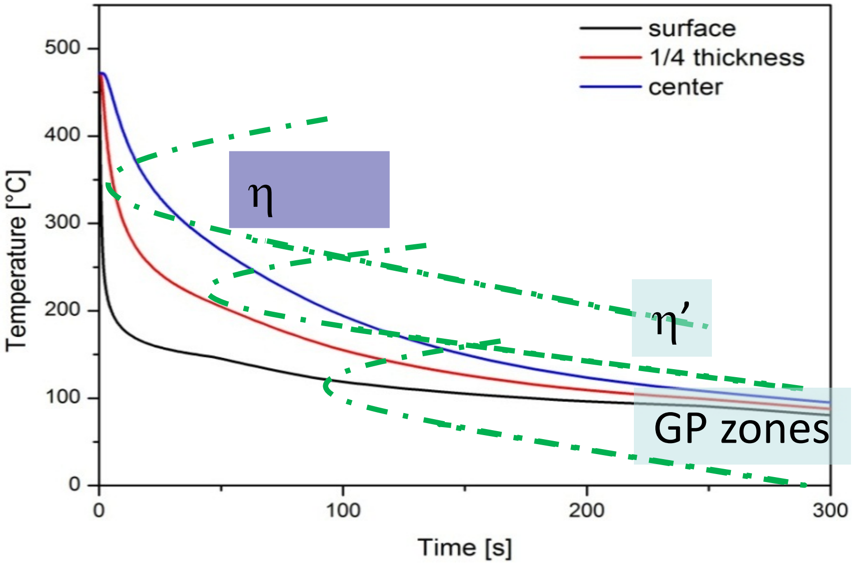
Selected area diffraction pattern

SADP



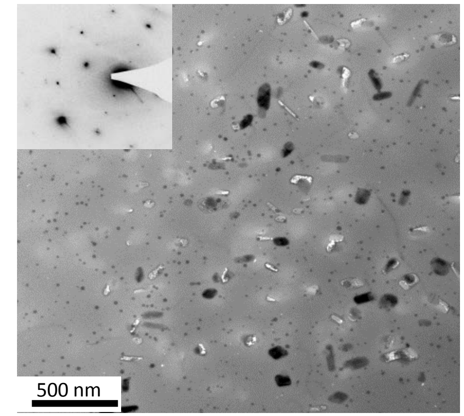
homogeneously distributed Guinier Preston zones and η'

Mechanical influence of precipitation



Softening effect
(heterogeneous η)

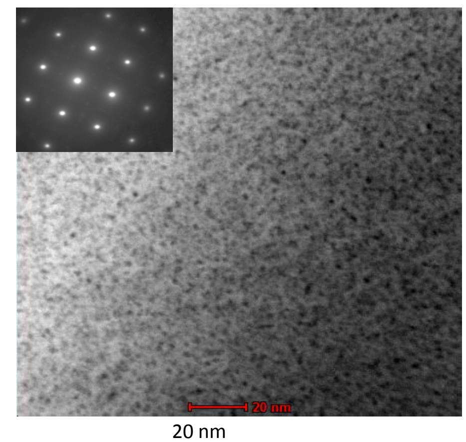
$$\sigma_{sol} = \left(\sum k_j c_j\right)^{2/3}$$



Hardening effect
(homogeneous η'/GPZ)

$$\sigma_P = \frac{M\bar{F}}{bL}$$

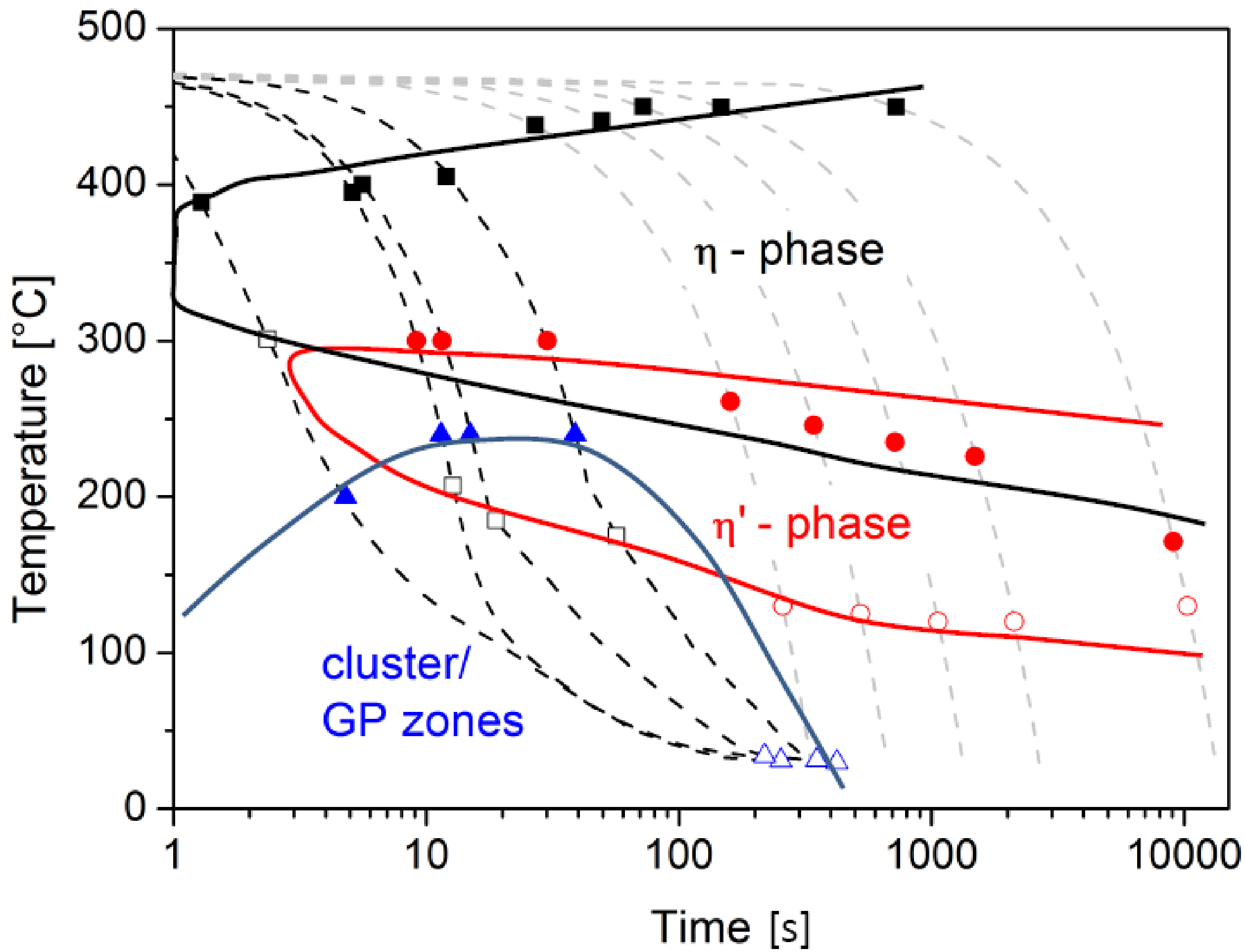
Shearing for small radii
Orowan for larger radii



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

G. Fribourg, PhD Thesis, INPG, 2009

In situ c-SAXS characterisation of precipitation



P. Schloth, J.N. Wagner, J.L. Fife, A. Menzel, J.-M. Drezet and H. Van Swygenhoven: Early precipitation during cooling of an Al-Zn-Mg-Cu alloy revealed by in situ small angle X-ray scattering, Applied Physics Letters, APL, 105, 101908, (2014). http://dx.doi.org/10.1063/1.4894768

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.

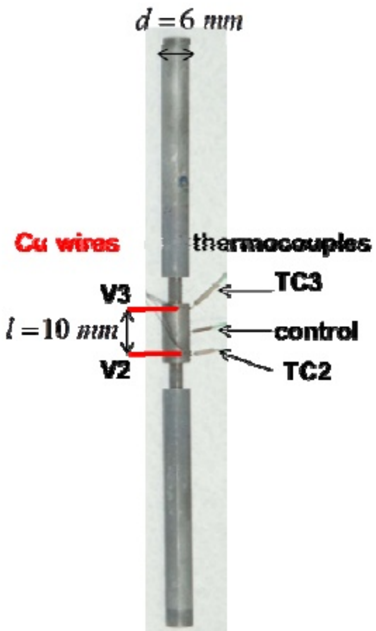
Gleeble interrupted quench tests to measure precipitation dependent yield strength (N. Chobaut)

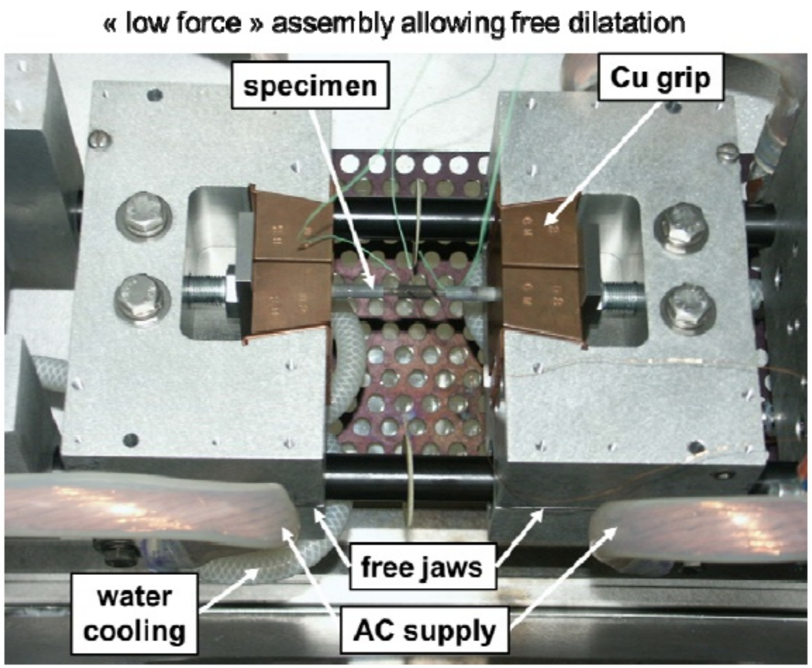
An alternative to full coupling with precipitation ....

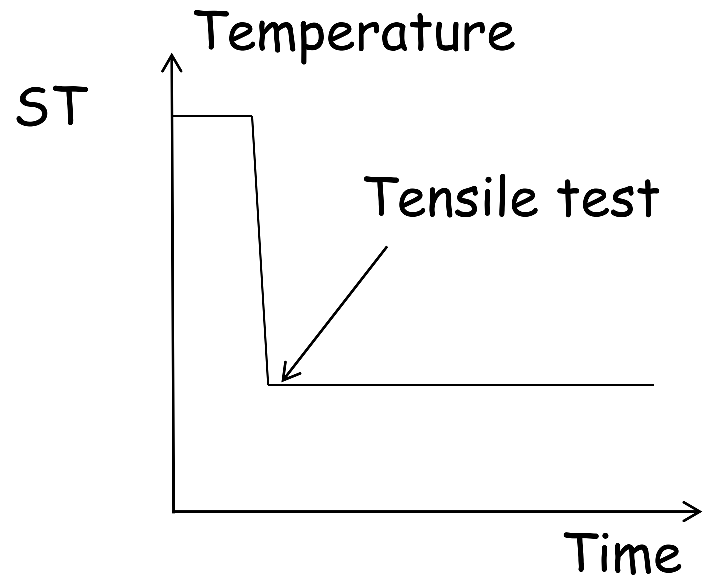
Gleeble measurements

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

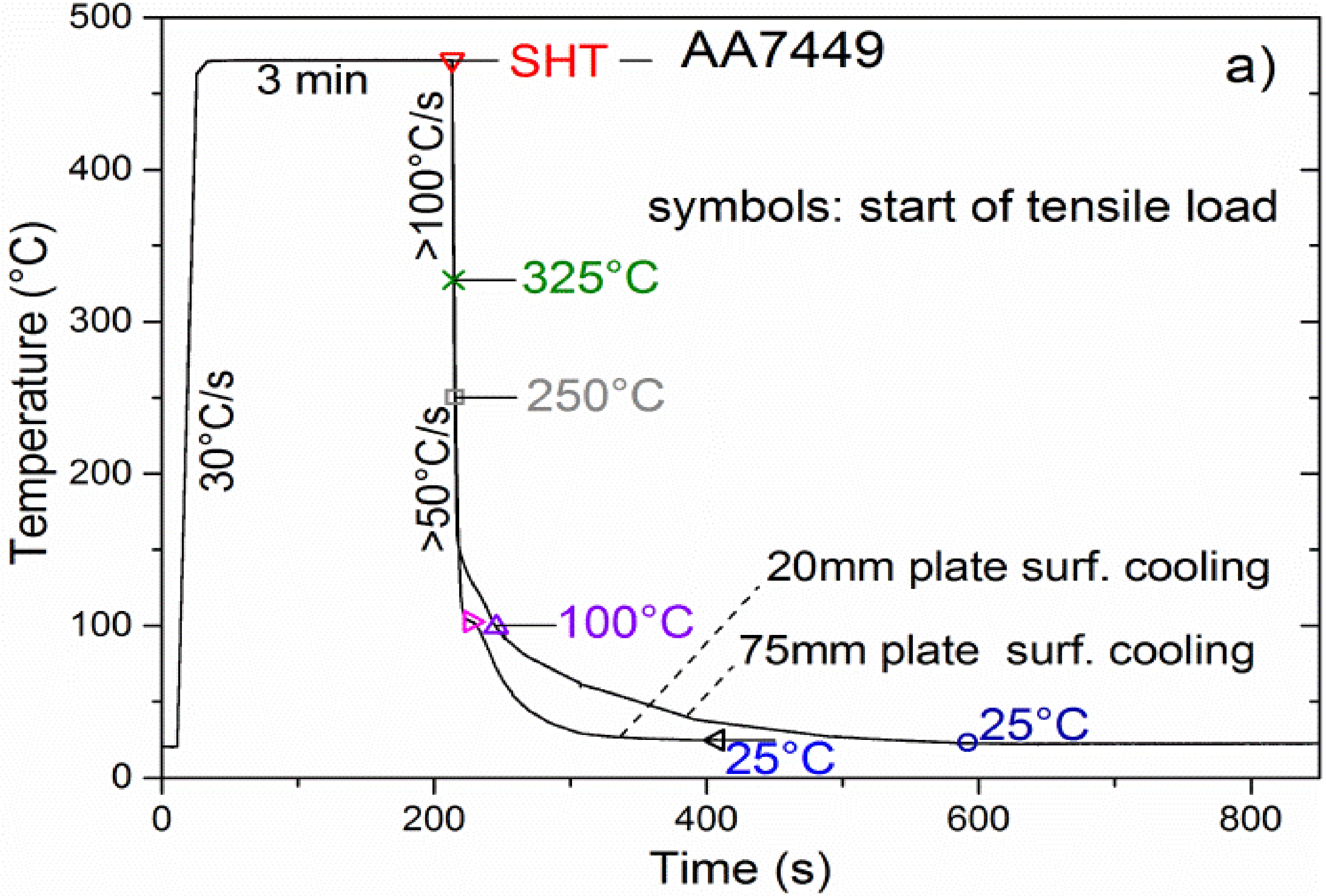






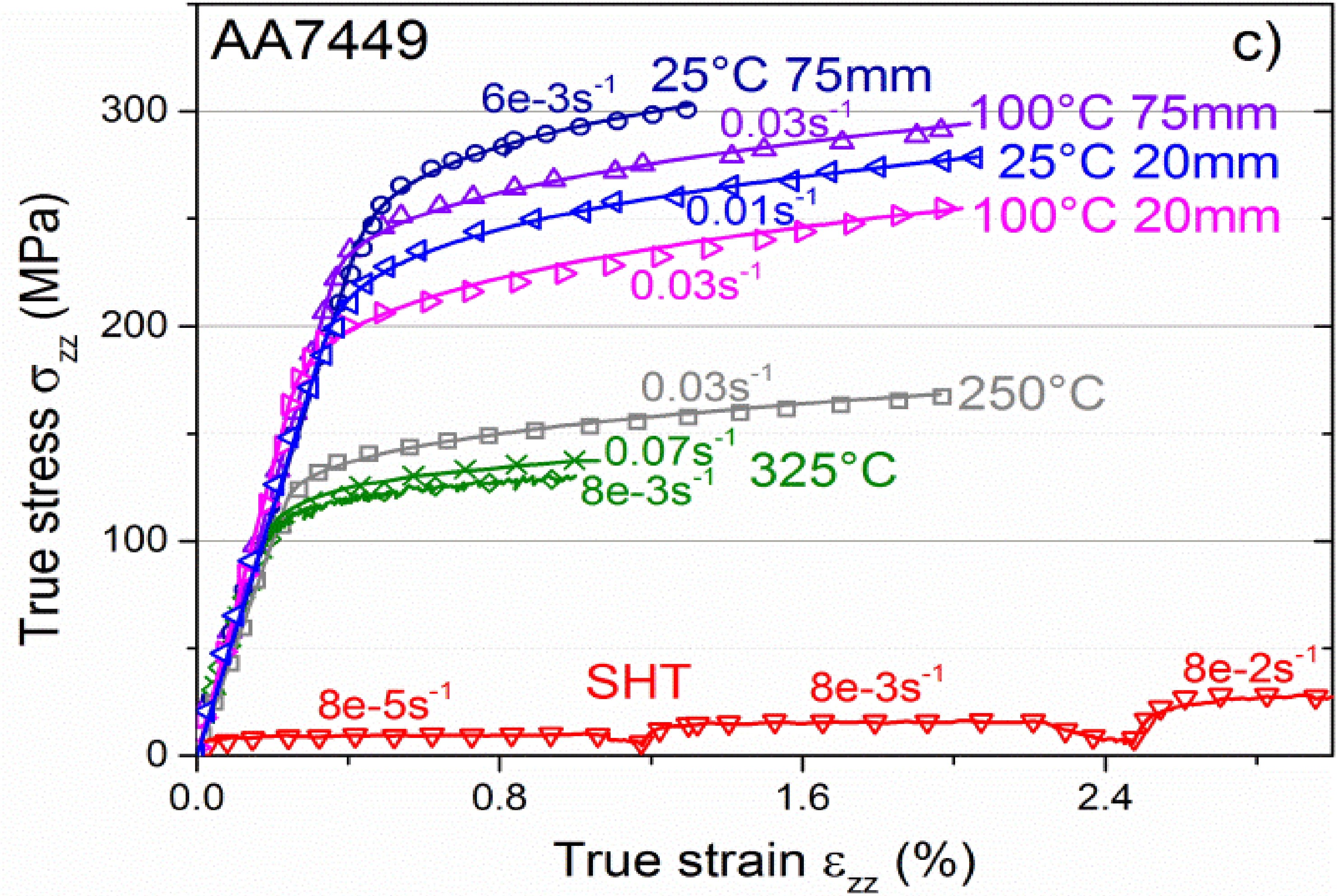
Specimen geometry equipped with 3 TCs

Gleeble measurements: interrupted quenched tests



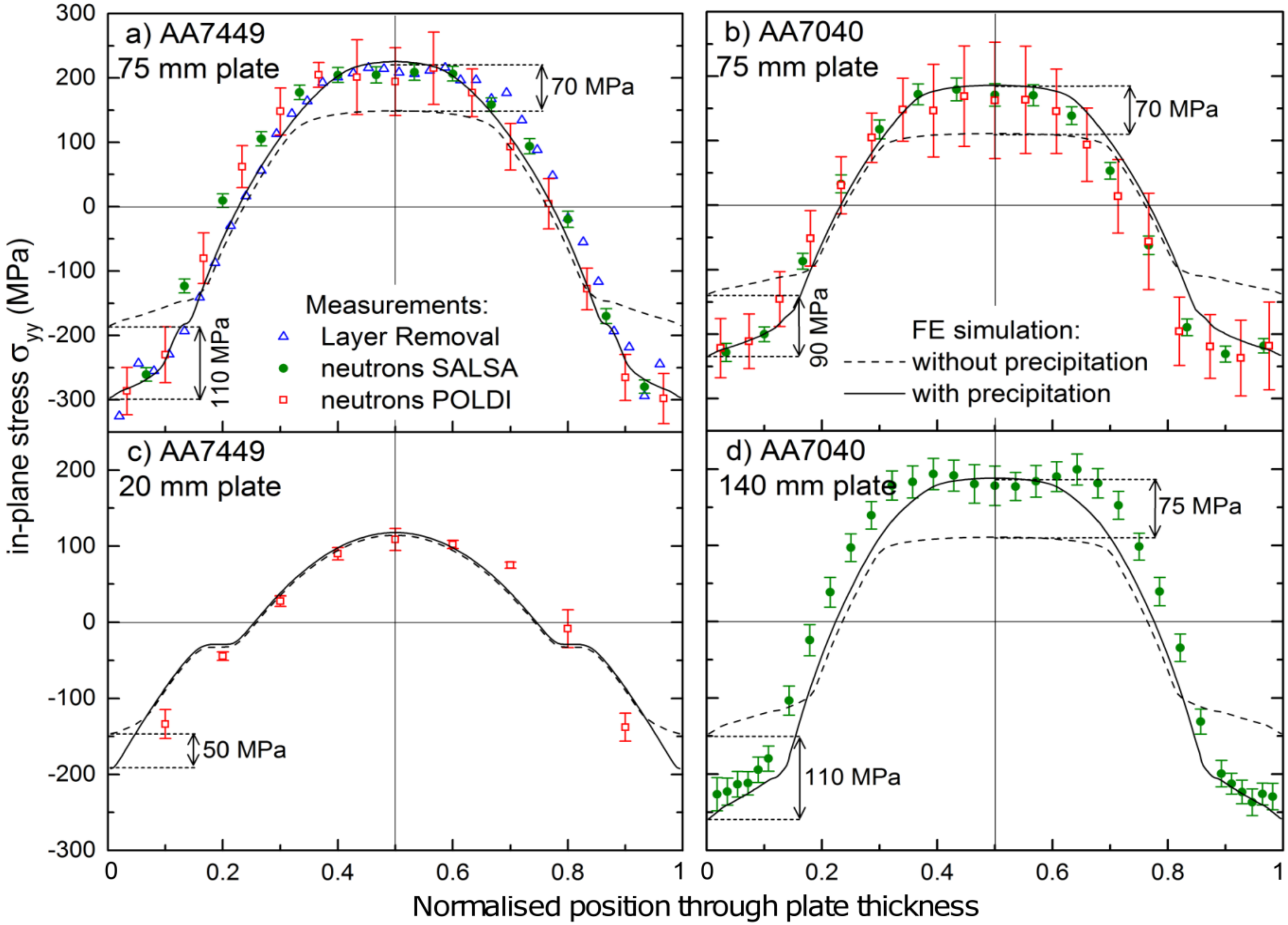
Surface coolings are imposed to the Gleeble specimens and tensile loading is applied

Gleeble measurements



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



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).

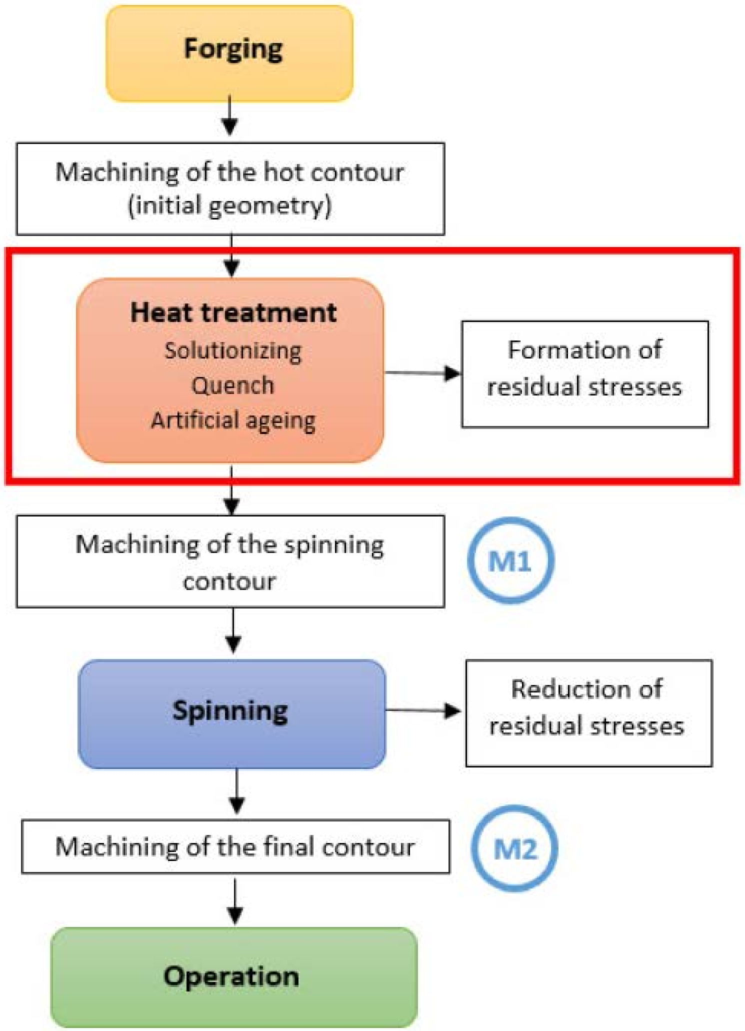
- Real precipitation sequence is very complex and delicate to model (VRC, GPZ and η' phase, no thermodynamic descriptions, importance of frozen vacancies).

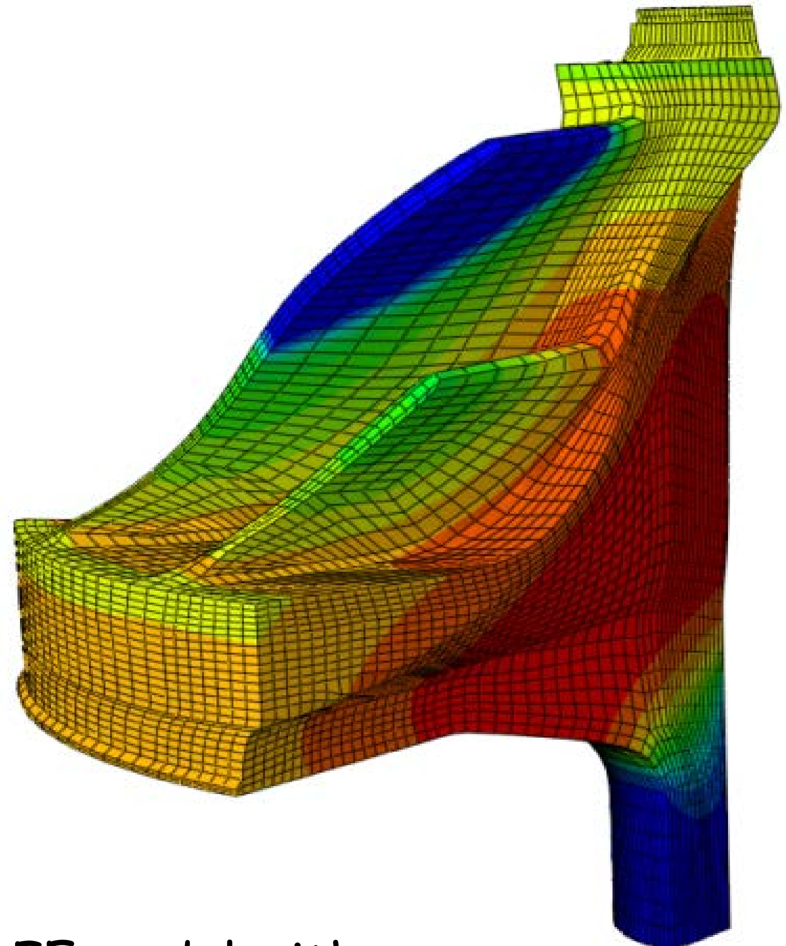
- Gleeble interrupted tests is an interesting alternative to characterize the impact of VRC/GPZ on the yield strength at the plate surface and thus to correctly model the stress generation.

- The same methodology is being applied to the ABB forgings.

Outlook

- At ABB, 3 machining steps are carried out. How to optimize the machining sequence with respect to internal stresses ?





3D FE model with cyclic boundary conditions

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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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http://infoscience.epfl.ch/record/205768
http://infoscience.epfl.ch/record/208831

Thank you for your attention

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