Prediction of (residual stresses and) microstructural state after multi-pass GTA-Welding of X10CrMoVNb9-1 martensitic steel

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Industrial background and motivations

-Thick forged components
assembled by multipass GTAWelding

- Martensitic steel X10CrMoVNb9-1
a possible candidate for
Very High Temperature Reactors

- Numerical simulation of welding process

Numerical simulation of multi-pass GTAWelding

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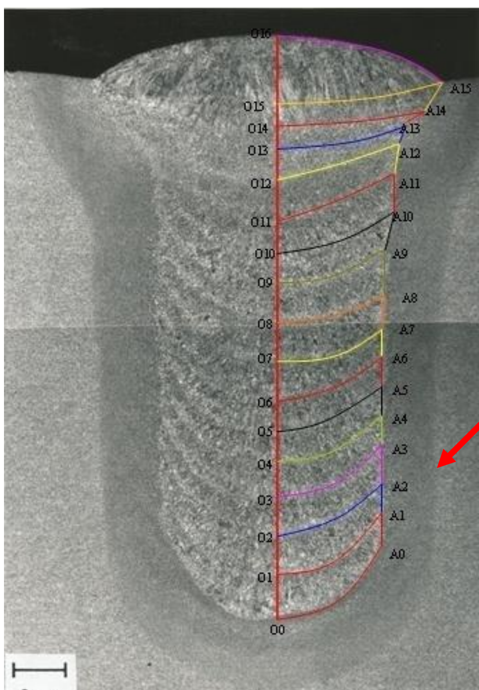
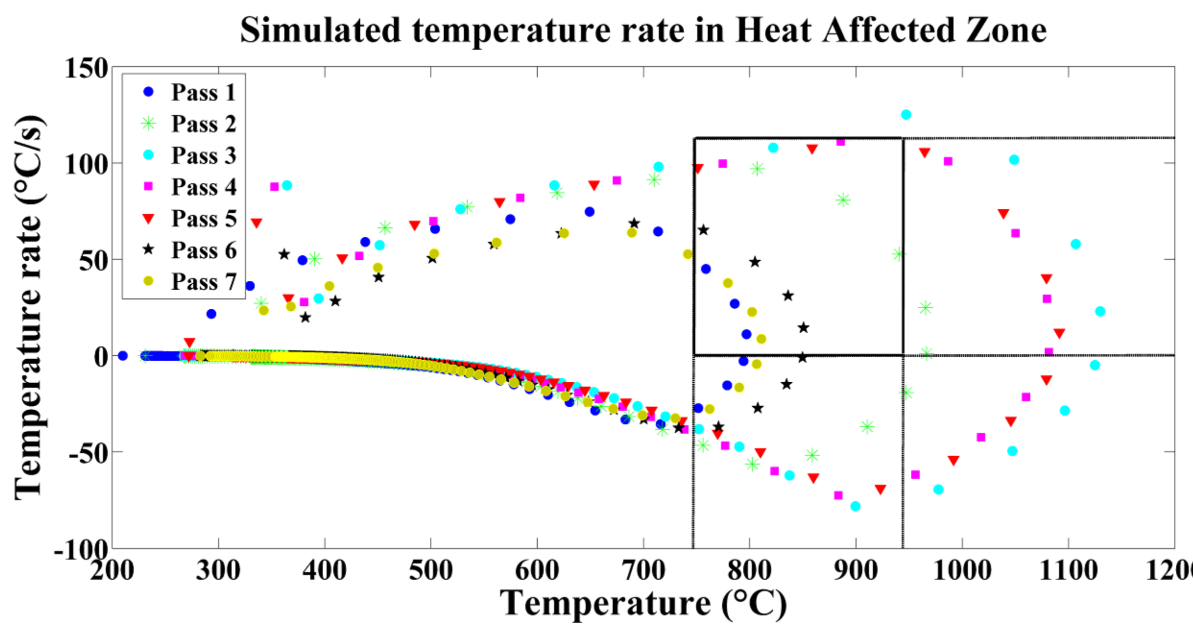
Initial state after welding (microstructure, residual stresses,…)



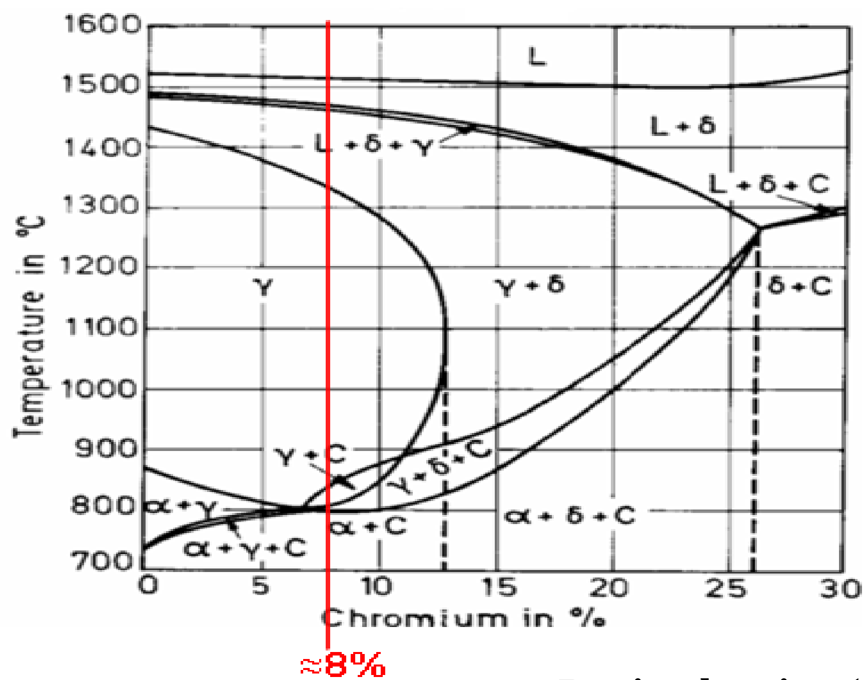


MUSICA test case

X10CrMoVNb9-1 steel - Phase changes

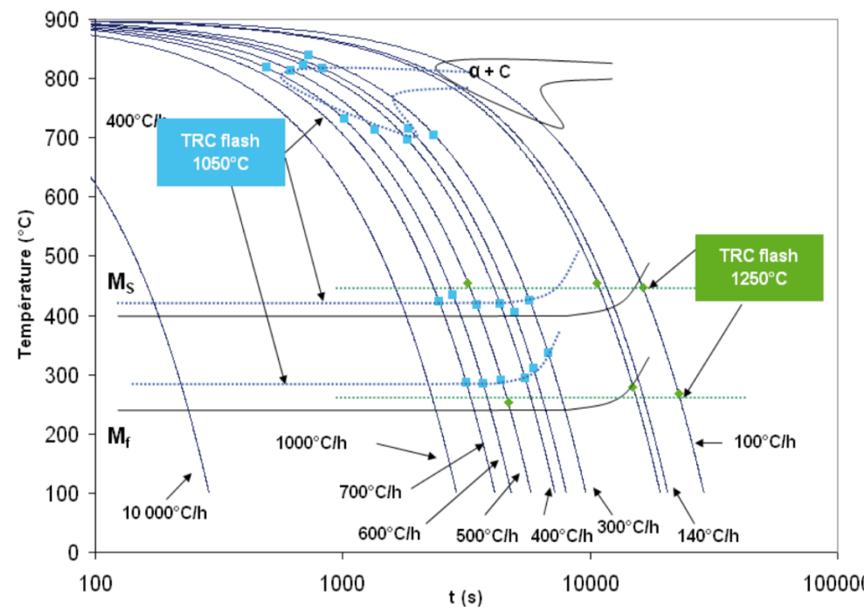
Pseudo-binary equilibrium diagram

Fe-Cr à 0.1% wt C [Easterling, 1992]



Continuous Cooling diagram

"T91" [Duthilleul, 2003]



During heating (1st pass)

Base material (tempered martensite) → Austenite → δ Ferrite → Liquid

During cooling

Liquid → δ Ferrite → Austenite → Quenched martensite

[Roux 2007]

[Roux 2006]

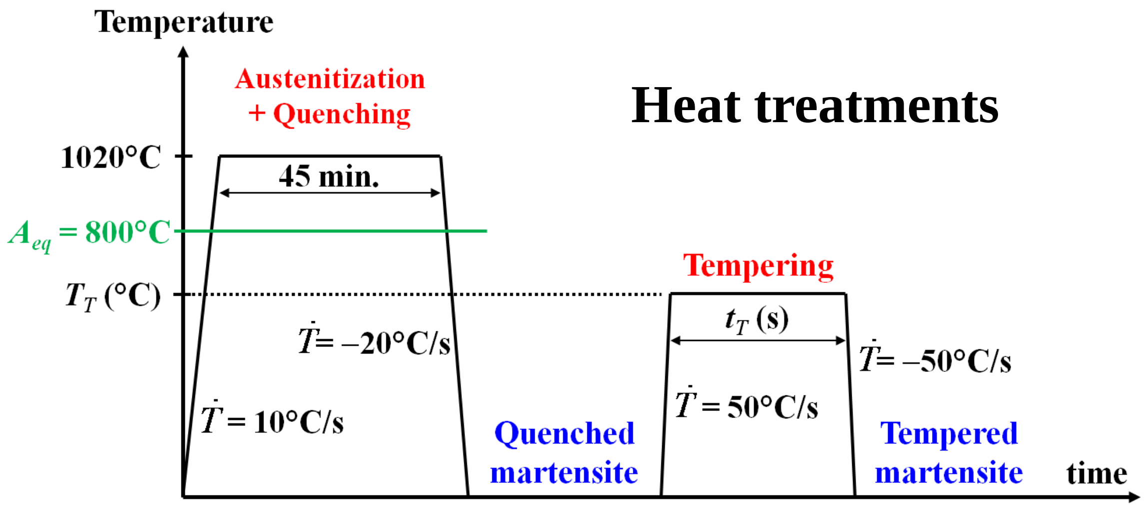
[Hanna 2009]

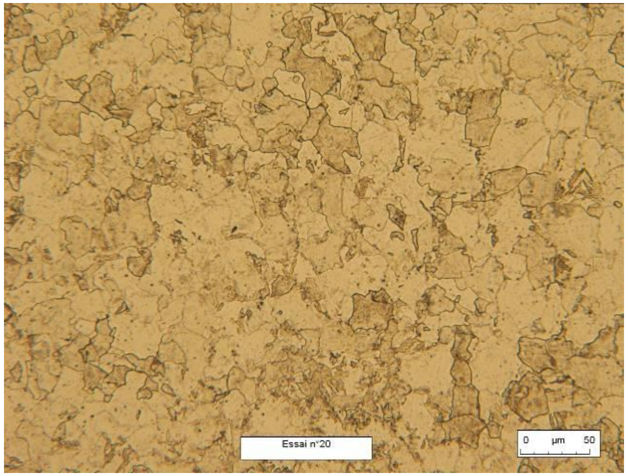
During subsequent heating (2nd and following passes)

Quenched martensite → Tempered martensite → Austenite → …

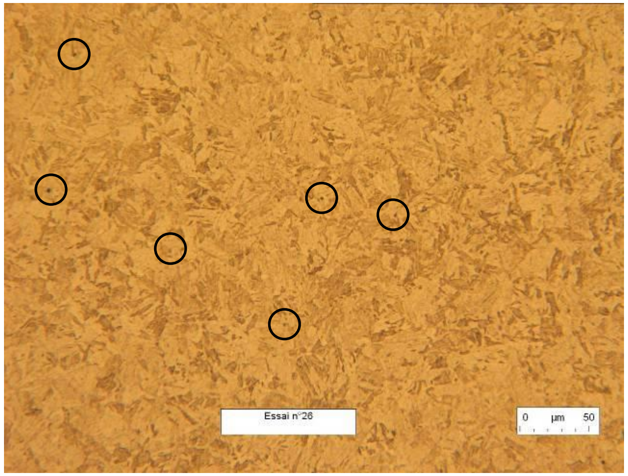
[Hanna 2010]

Martensite tempering

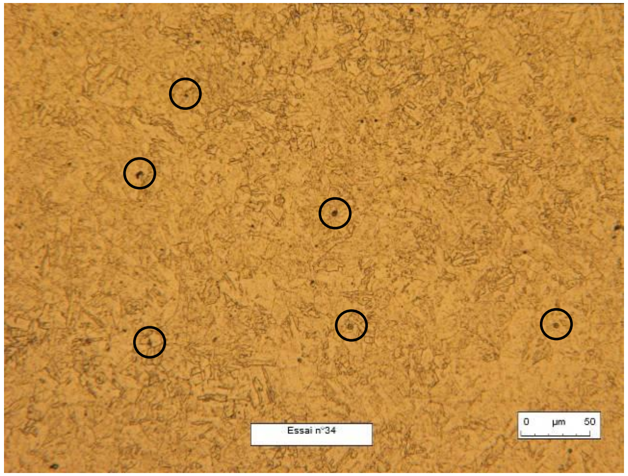




Tempered @ 500°C for 6 min.



Tempered @ 500°C for 1h



Tempered @ 750°C for 5h30

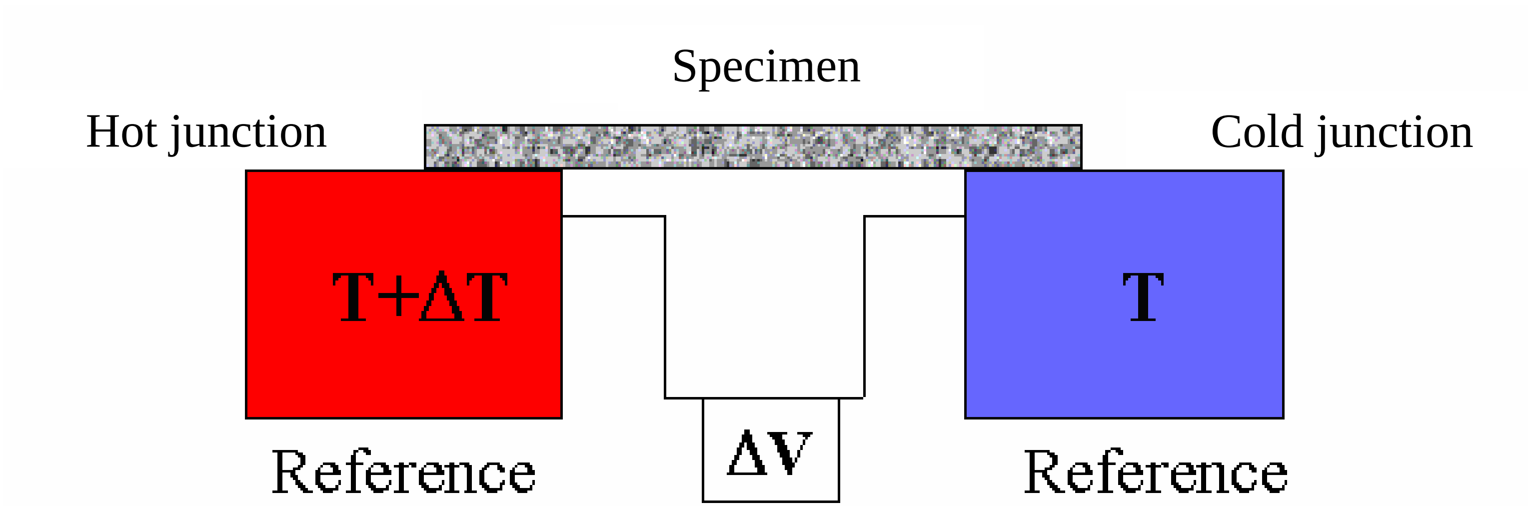
Martensite tempering → Carbides precipitation

Measurement of carbides precipitation

Indirect measurement of carbides precipitation

through the percentage of free carbon in the matrix

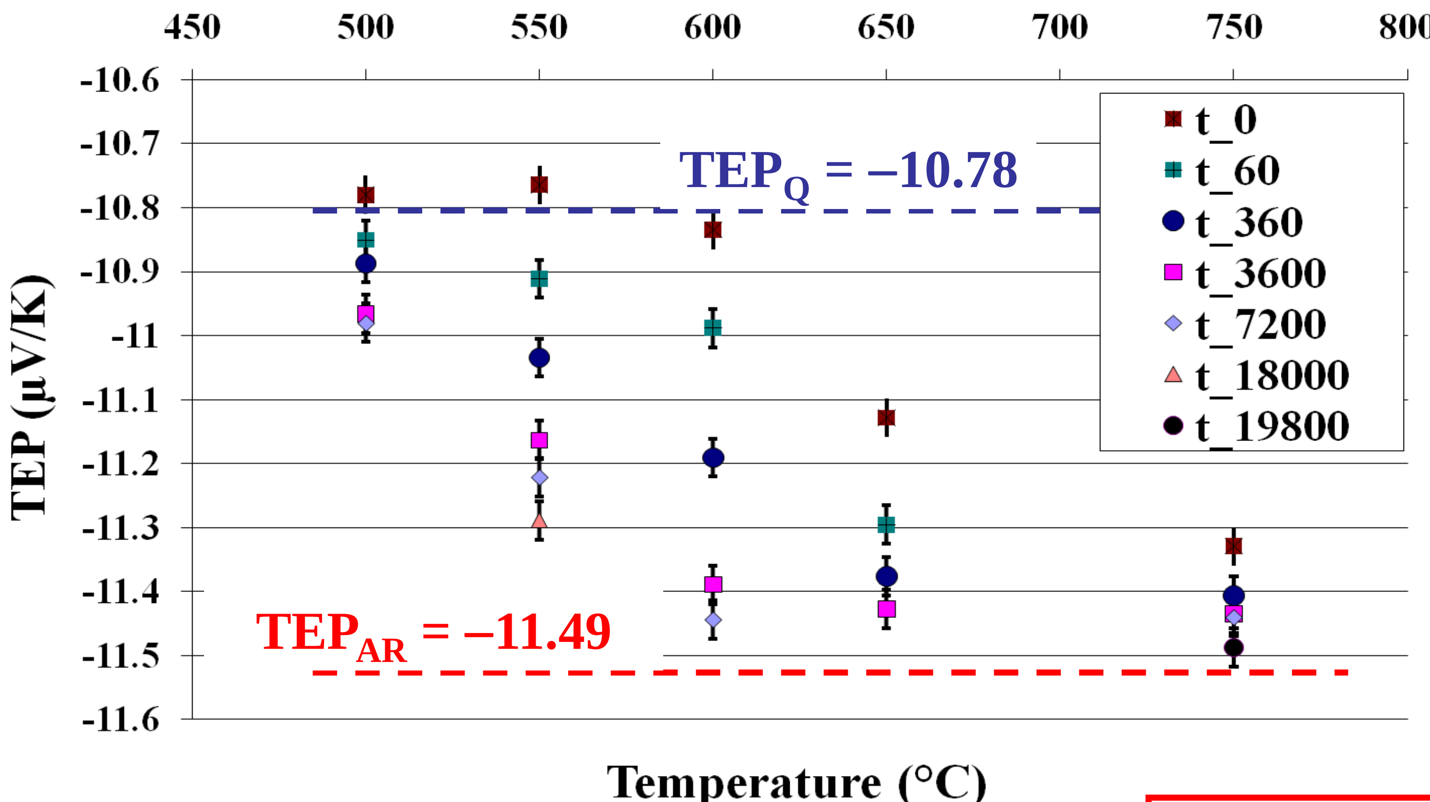
by Thermo-Electric Power measurements (Seebeck effect)



$$S_{specimen} = S_{ref} - \frac{\Delta V(chemical\ composition)}{\Delta T}$$

Measurement of carbides precipitation

TEP measurements after different tempering heat treatments (T_T, t_T)



Precipitation evolution →Tempering evolution

$TEP_Q = -10.78$

$TEP_{AR} = -11.49$

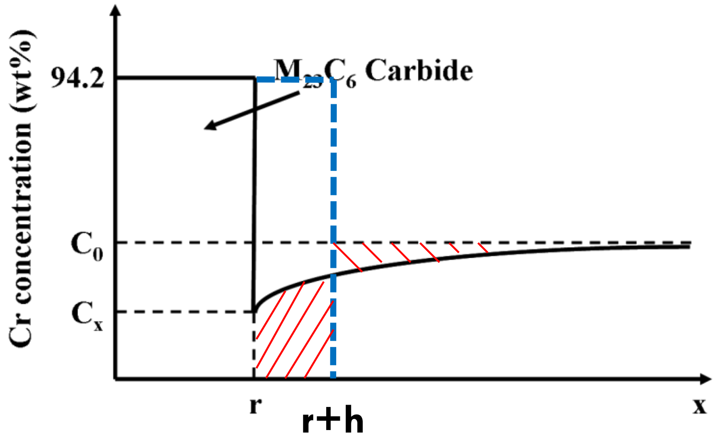
Definition of the "tempering factor"

$$x_T = \frac{TEP - TEP_Q}{TEP_{AR} - TEP_Q}$$

Modelling of martensite tempering

Fick law

$$\vec{J} = -D\,\overrightarrow{grad}\,C \xrightarrow{\text{1D}} J = -D\,\frac{\partial C}{\partial x}$$



Conservation law

$$\frac{\partial C}{\partial t} = -div\,\vec{J} \xrightarrow{\text{1D}} \frac{\partial C}{\partial t} = -\frac{\partial J}{\partial x}$$

Isothermal case

$$x = \sqrt{D\,t}$$

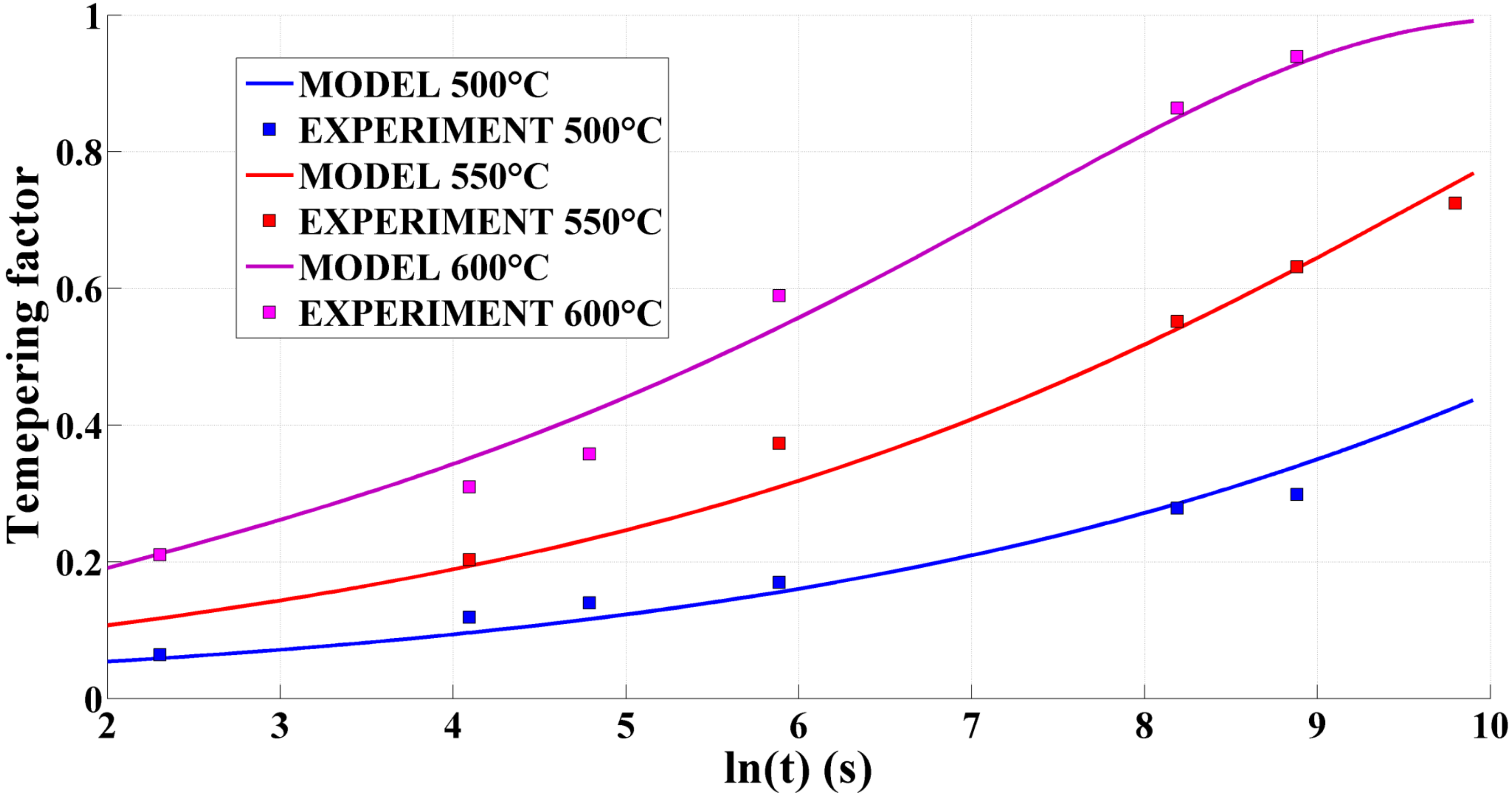
Temperature dependence of the diffusion coefficient and generalisation

$$x = \left[D_0 \exp\left(-\frac{\Delta H}{R\,T} \right) t \right]^{\frac{1}{n}} \longleftarrow \dot{x} = \frac{1}{n} D_0 \exp\left(-\frac{\Delta H}{R\,T} \right) x^{1-n}$$

Proposed evolution law for tempering factor x_T

$$\dot{x}_T = \frac{1}{n} D_0 \exp\left(-\frac{\Delta H}{R\,T} \right) x_T^{\,1-n} \left(1 - x_T \right) H\left[T - T_{TTh} \right]$$

Identification of tempering model



$$\dot{x}_T = \frac{1}{n} D_0 \exp\left(-\frac{\Delta H}{R\,T}\right) x_T^{\,1-n} \left(1 - x_T\right)\ H(T - T_{TTh})$$

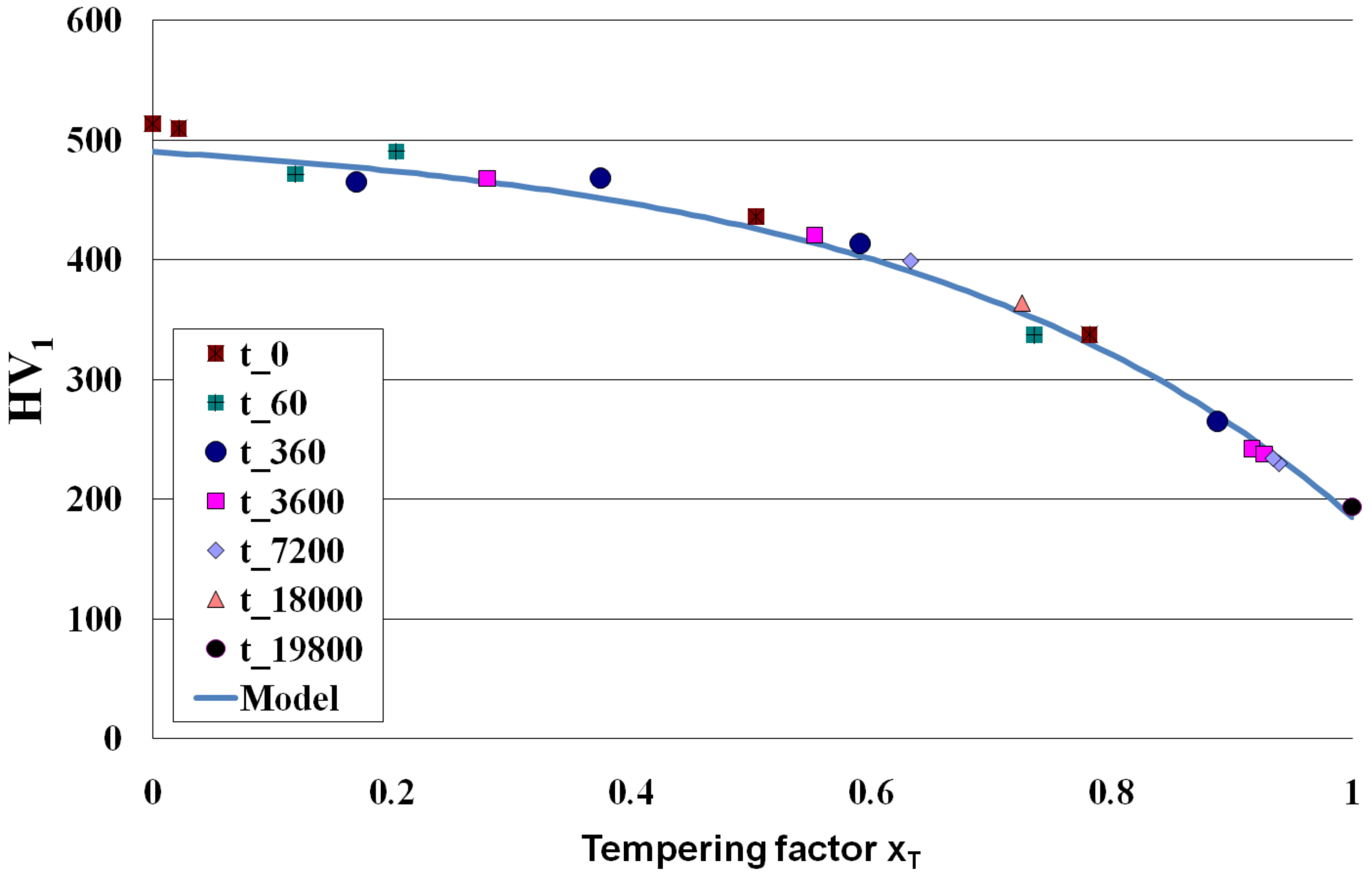
$D_0 = 2.4\,10^{13}$

$\Delta H = 278.2\ \text{KJ/mol}$

$n = 3.61$

- coherent with Cr bulk diffusion and carbides growth-coalescence
- not applicable to tempering at T < 475°C (with long holding times) (secondary ageing, embrittlement)

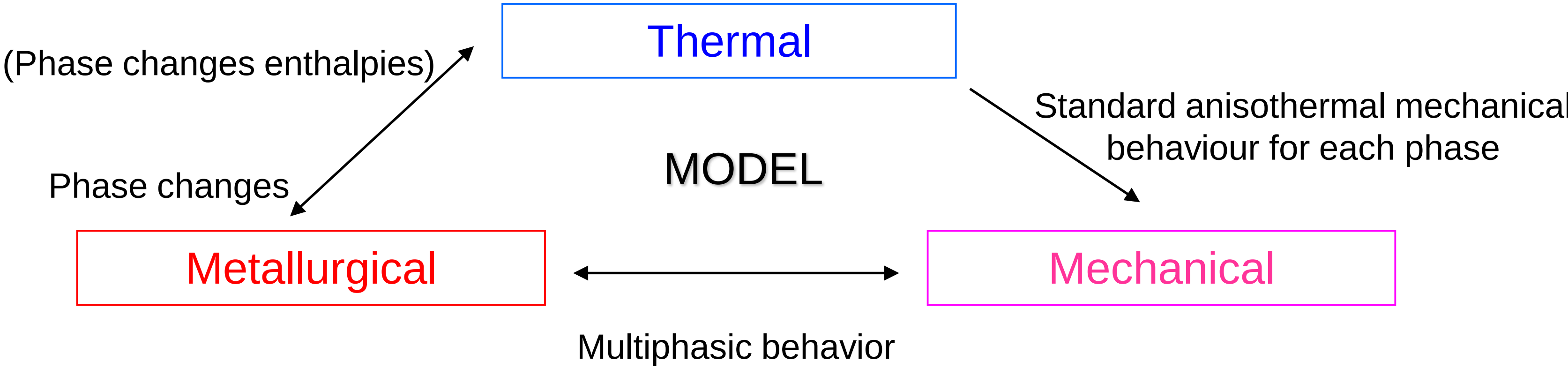
Hardness vs. tempering factor



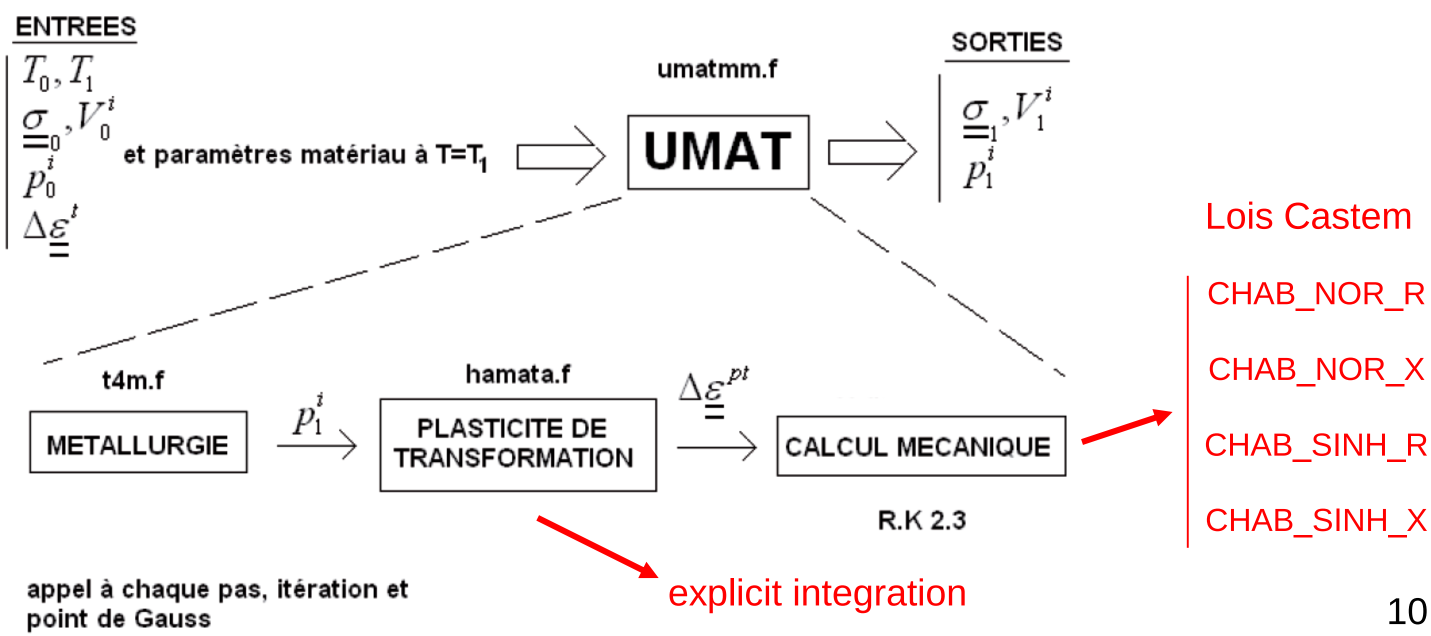
$$HV_{TM} = HV_Q - \left(HV_Q - HV_{AR}\right)\exp\left(\frac{x_T - 1}{x_0}\right)$$

$$HV_{AR} = 185 \qquad HV_Q = 513 \qquad x_0 = 0.374$$

Modelling the thermo-metallurgical-mechanical behaviour



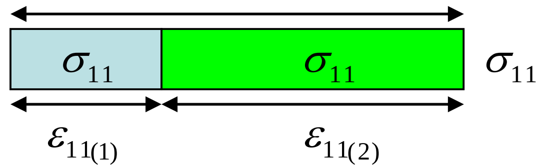
UMAT formalism integration



Modelling the multiphasic behaviour

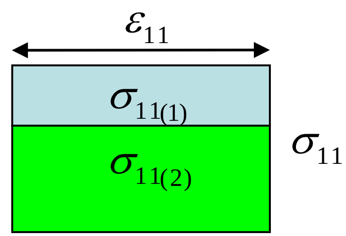
<u>Two scale mixing mechanical law</u>:

•Reuss approach



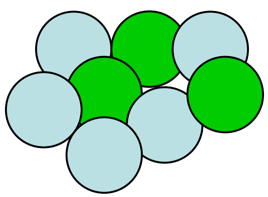
$$\underline{\underline{\varepsilon}} = x_{(1)} C_{(1)}^{-1} \underline{\underline{\sigma}} + x_{(2)} C_{(2)}^{-1} \underline{\underline{\sigma}}$$

•Voigt approach
[Goth 2002]



$$\underline{\underline{\sigma}} = x_{(1)} C_{(1)} \underline{\underline{\varepsilon}} + x_{(2)} C_{(2)} \underline{\underline{\varepsilon}}$$

•Hill & Berveiller-Zaoui type approach [Cailletaud, 87] [Pilvin, 90]



[Robert 2007] for welding

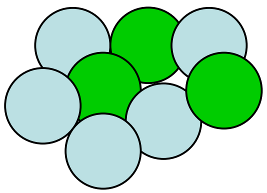
Intergranular accommodation variables

$$\underline{\underline{\sigma}}_i = \underline{\underline{\Sigma}} + C\left(\underline{\underline{\beta}} - \underline{\underline{\beta}}_i\right) \text{ avec } \underline{\underline{\beta}} = \sum_{i=0}^{N} Z_i \underline{\underline{\beta}}_i$$

$$\dot{\underline{\underline{\beta}}}_i = \dot{\underline{\underline{\varepsilon}}}_i^p - D_i \frac{2}{3} J_2\left(\dot{\underline{\underline{\varepsilon}}}_i^p\right) \underline{\underline{\beta}}_i$$

Modelling the multiphasic behaviour

•Hill & Berveiller-Zaoui type approach [Cailletaud, 87] [Pilvin, 90]



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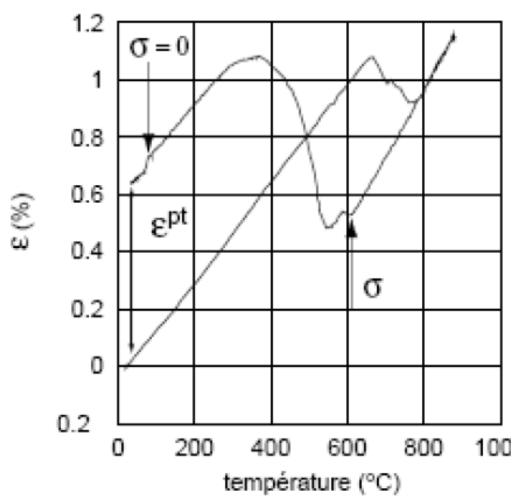
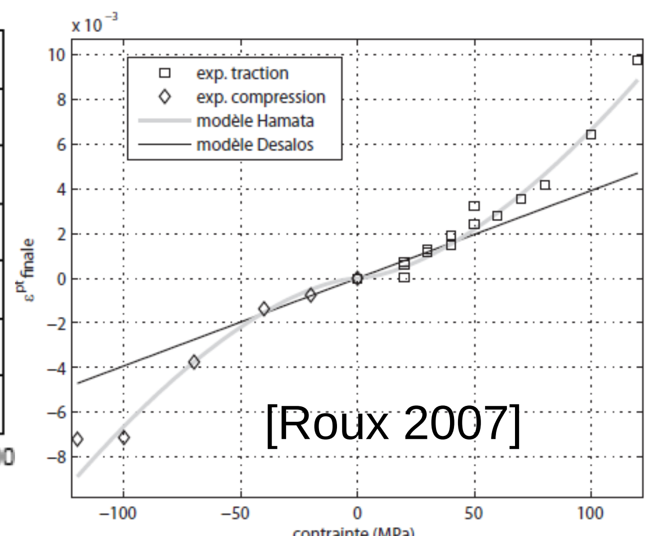
TRIP (Transformation Induced Plasticity): $\varepsilon^t = \varepsilon^e + \varepsilon^{vp} + \varepsilon^{met} + \varepsilon^{pt}$

$$\dot{\underline{\underline{\varepsilon}}}^{pt} = \frac{3}{2}\left(\frac{J_2\left(\underline{\underline{s}} - \underline{\underline{X}}\right)}{\lambda}\right)^N \frac{\underline{\underline{s}}}{J_2\left(\underline{\underline{s}} - \underline{\underline{X}}\right)}\dot{z}$$

[Hamata 1992]



[Coret 2001]



[Roux 2007]

Mechanical behaviour of each phase

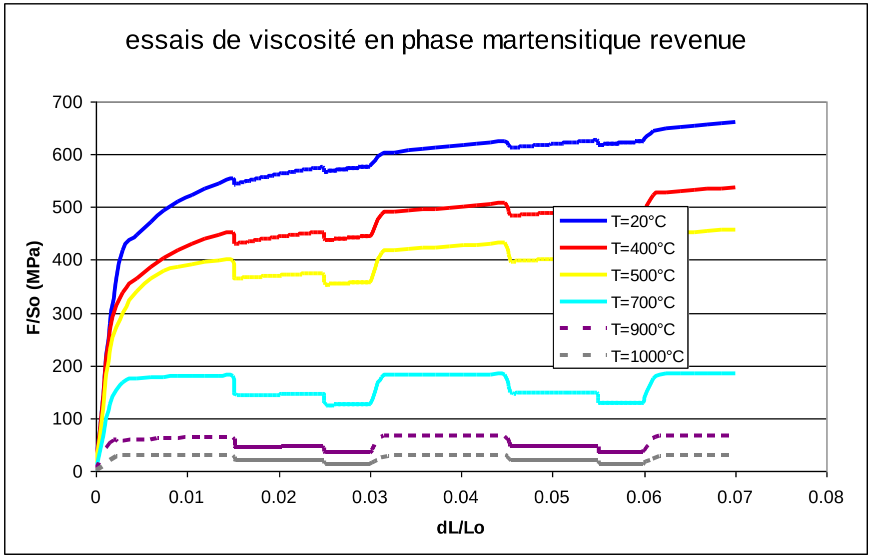
Anisotropic elastoviscoplastic mechanical behaviour

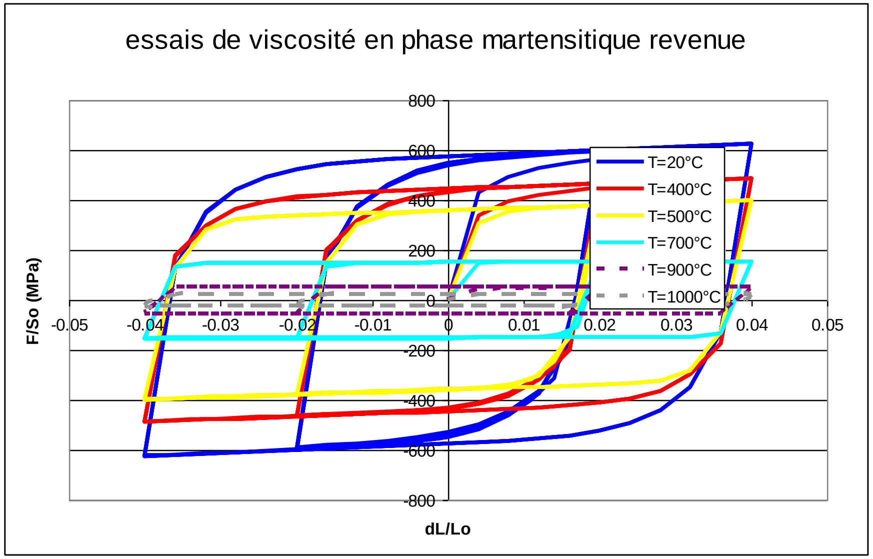
Norton Law $\Phi_i^{*VP}\left(\underline{\underline{\sigma}}_i, R_i, \underline{\underline{X}}_i; T, x_i\right) = \frac{K_i(T)}{1+N_i(T)}\left\langle\left\langle\frac{f^p}{K}\right\rangle\right\rangle^{1+N_i(T)}$

Isotropic hardening $\dot{r} = (1 - br)\dot{p}$ avec $R = bQr$

Linear and non-linear Kinematic hardening $\dot{\underline{\underline{\alpha}}} = \dot{\underline{\underline{\varepsilon}}}^p - \dot{p}\frac{3}{2}\frac{d}{C}\underline{\underline{X}}$ avec $\underline{\underline{X}} = \frac{2}{3}C\underline{\underline{\alpha}}$

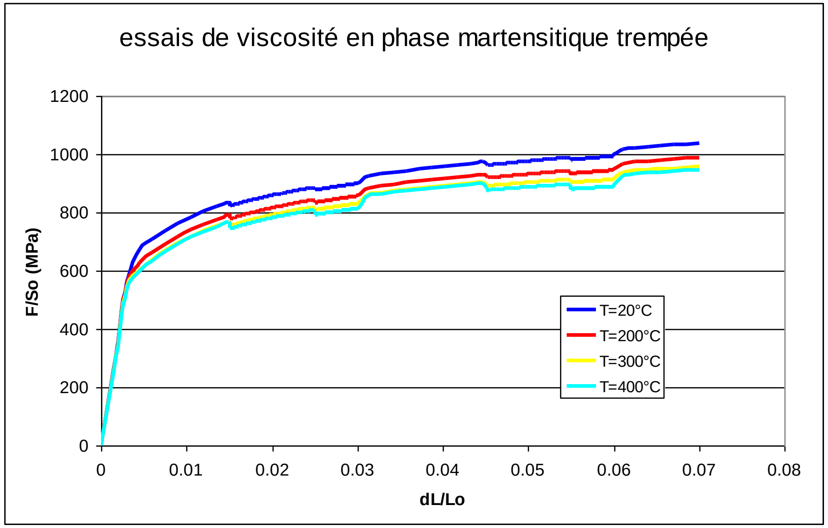
Tempering martensite (reception state)

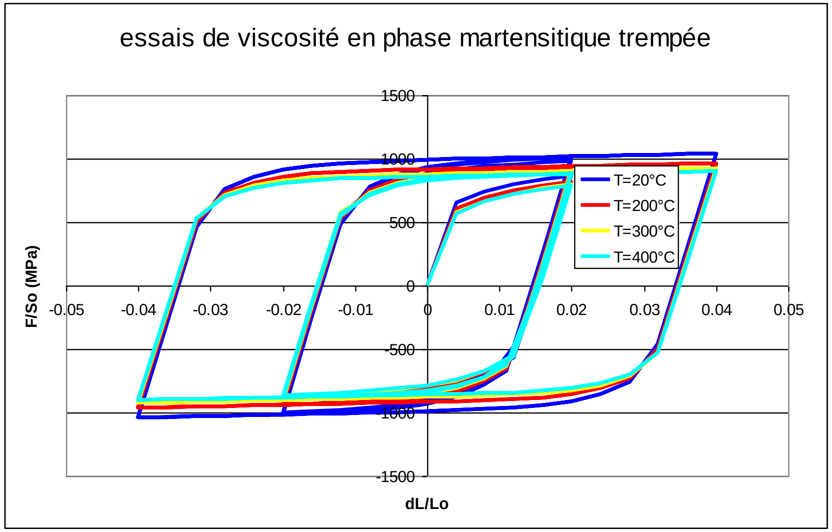




Mechanical behaviour of each phase

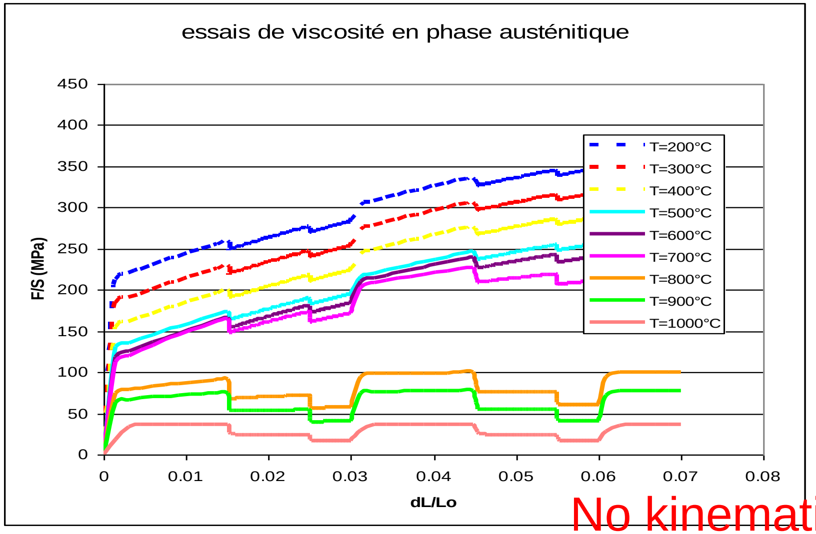
Quenched martensite

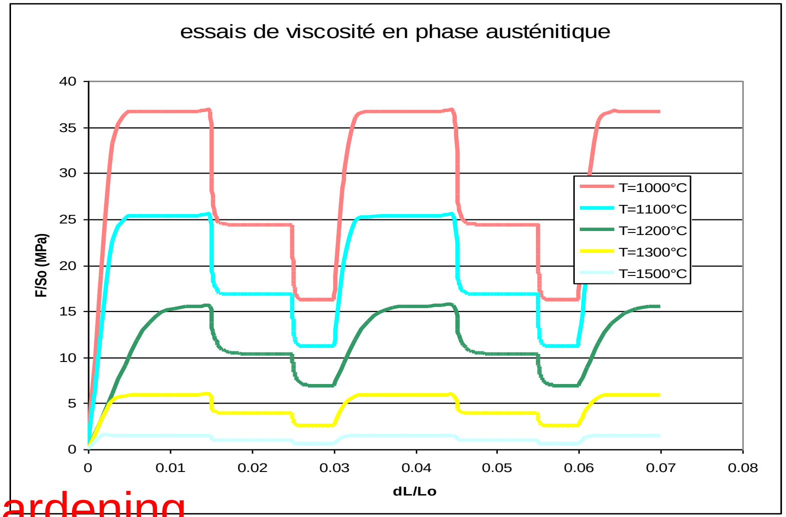




Tempering occurs for T> 400°C

Austenite





No kinematic hardening

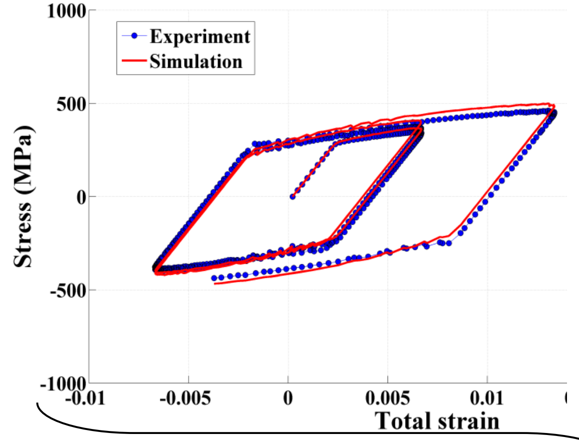
Mixing tempered and quenched martensites

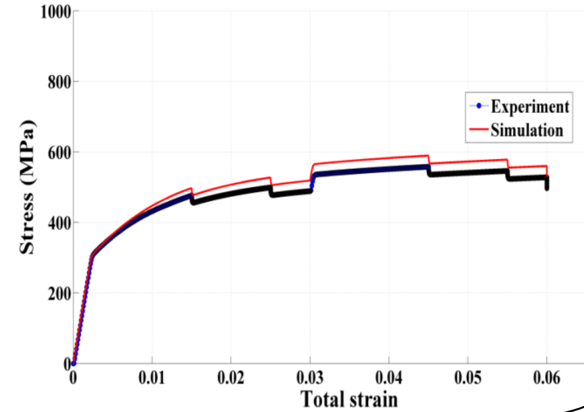
Experimental procedure

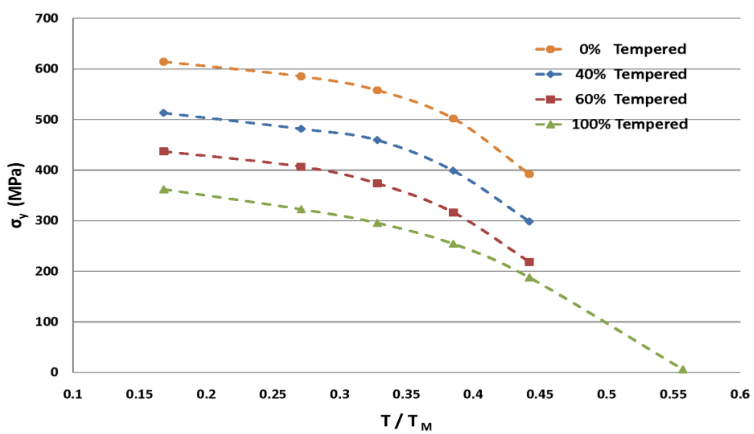
experiments at x_t=0.6 (500°C)

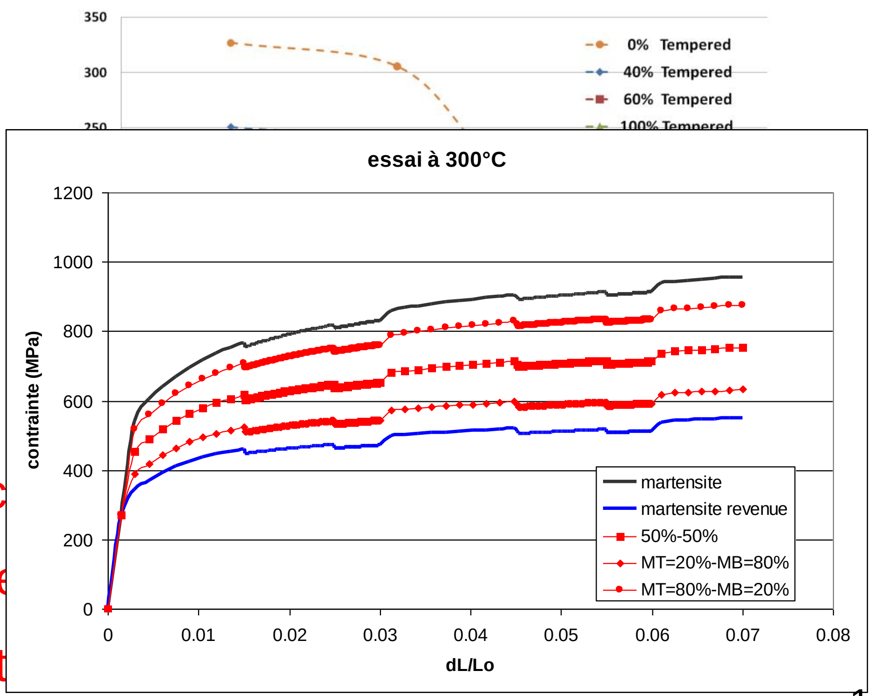
Model for quenched
+
tempered martensite

+





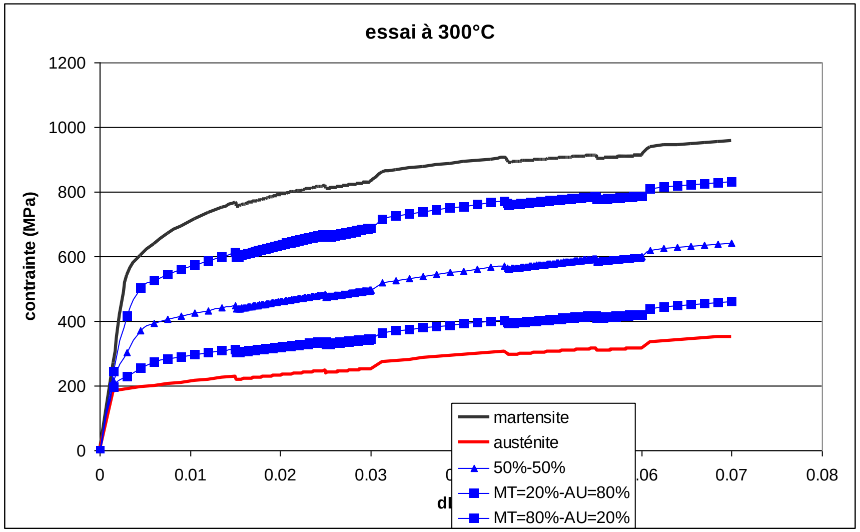




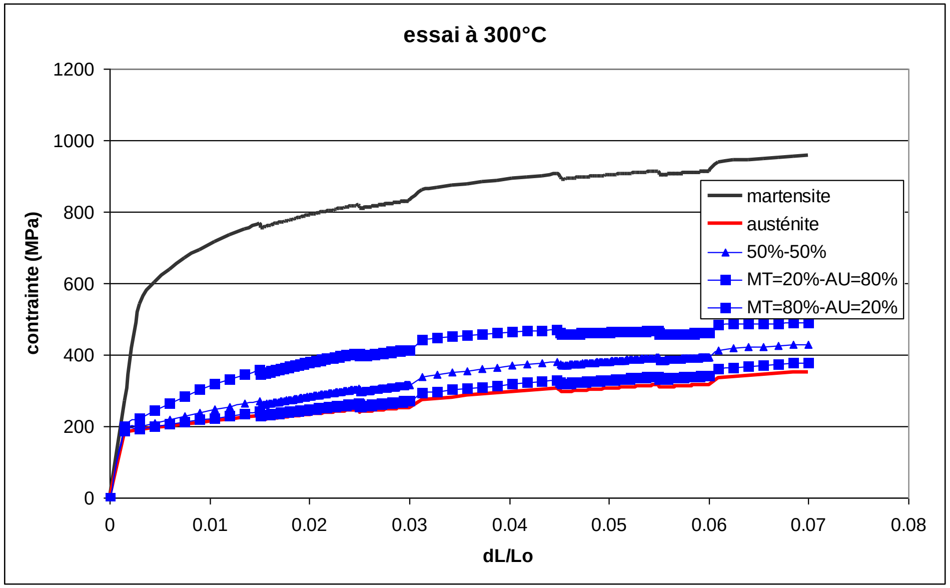
- Tempering has a softening effect on elastic
- No dependance of temperature on mixing e
- Linear dependance of mechanical paramet approach)

Mixing austenite and quenched martensite

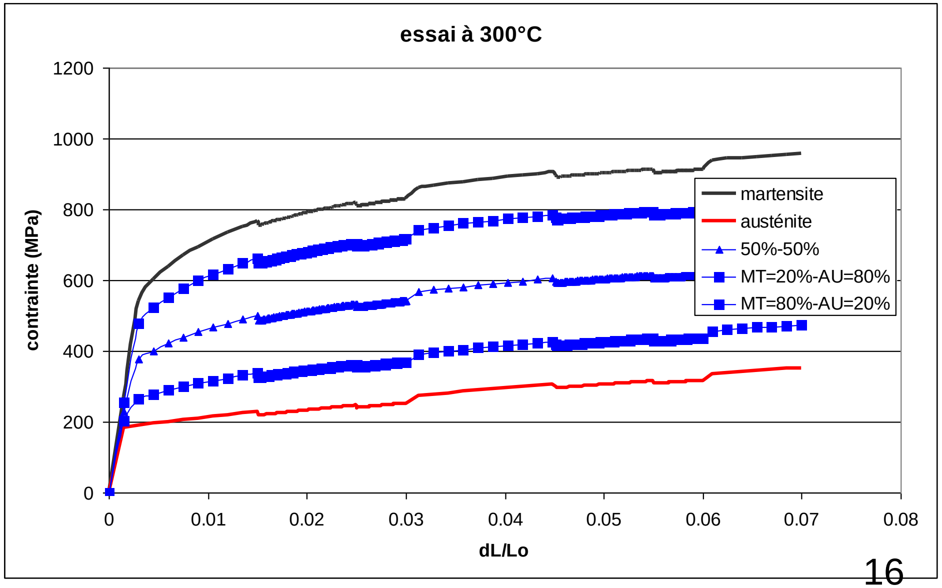
βeta model:



Reuss approach:

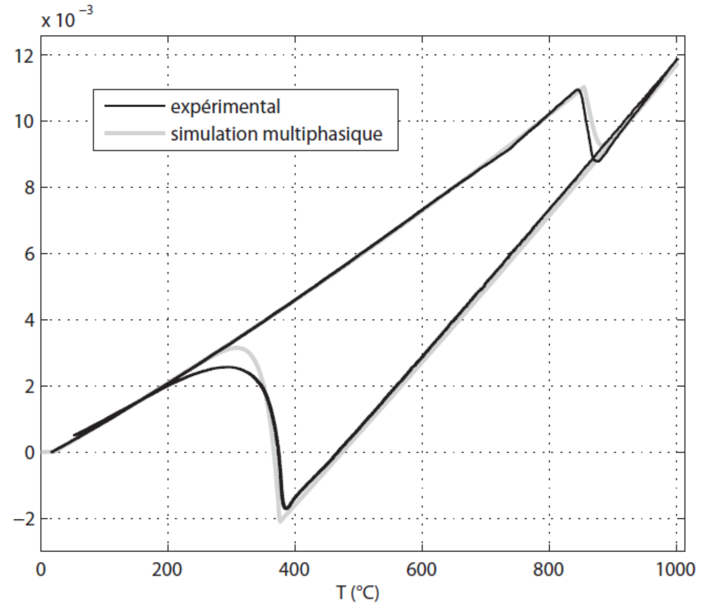


Voigt approach:

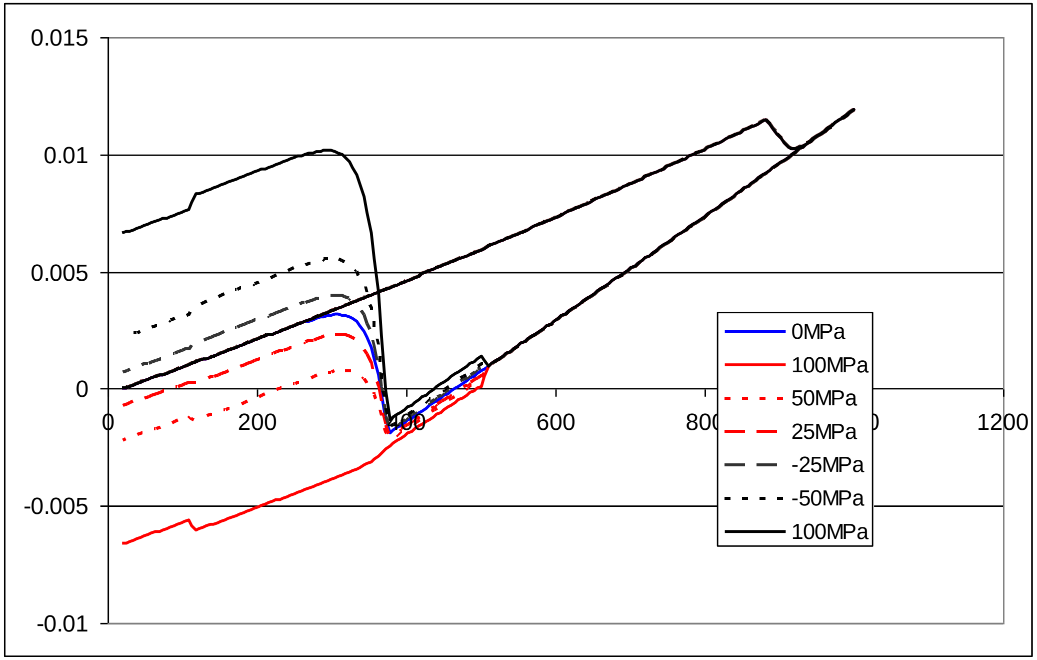


Simulation of dilatometry tests

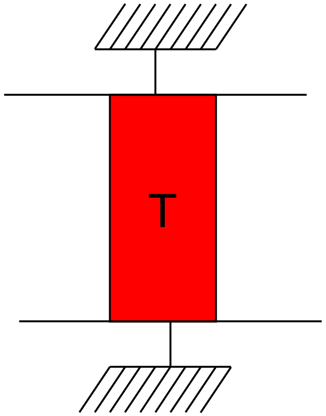
Free dilatometry curve:

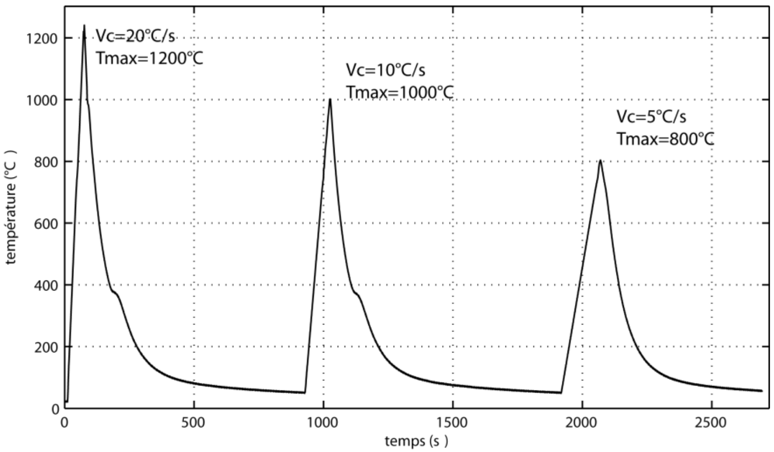


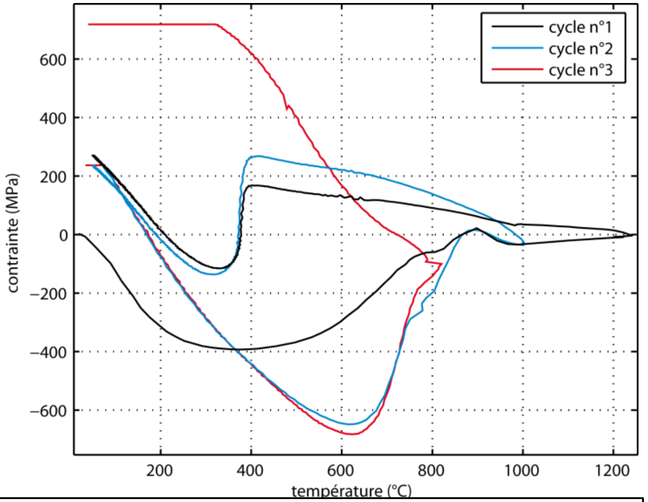
TRIP experiments:



Simulation of Satoh experiment







Overestimation of TRIP effect

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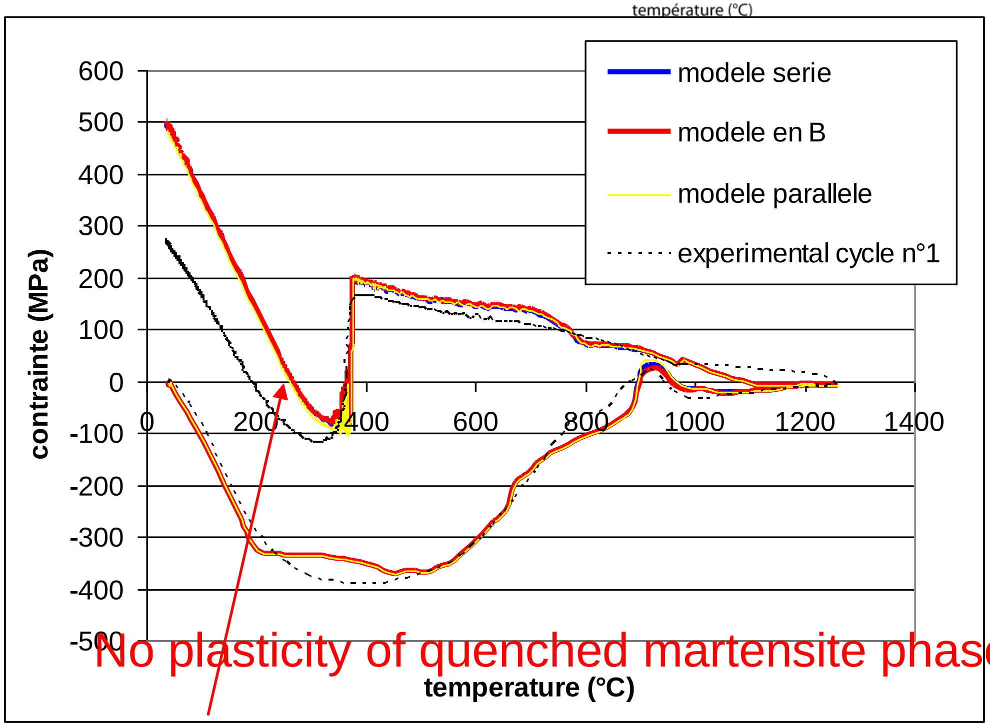
Coupling between hardening of mother and daughter phases and TRIP

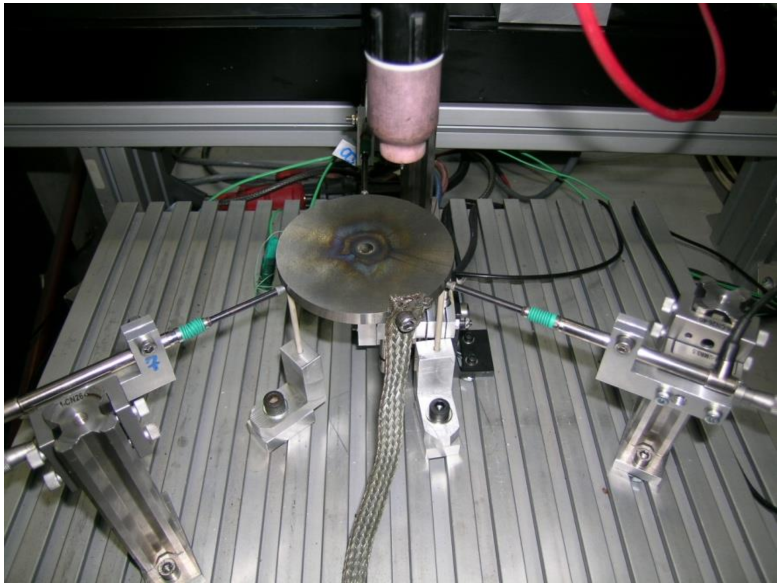
[Petit-Grotabussiat 2000] for 16MND5 alloy



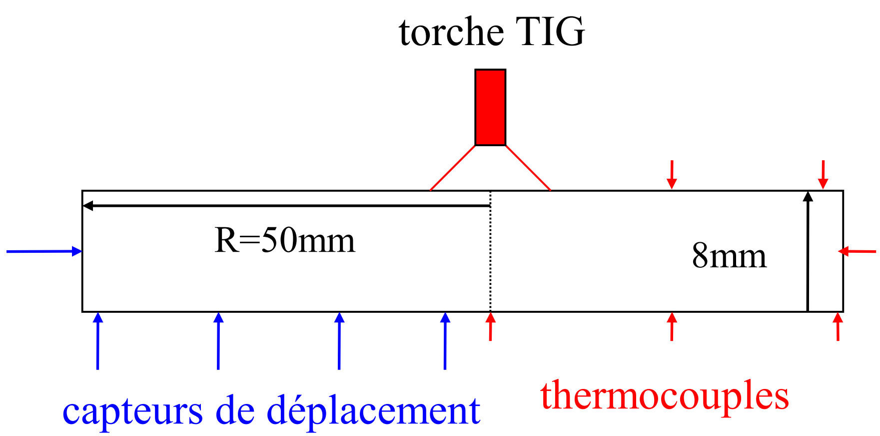
→ Very low influence of homogenization rule

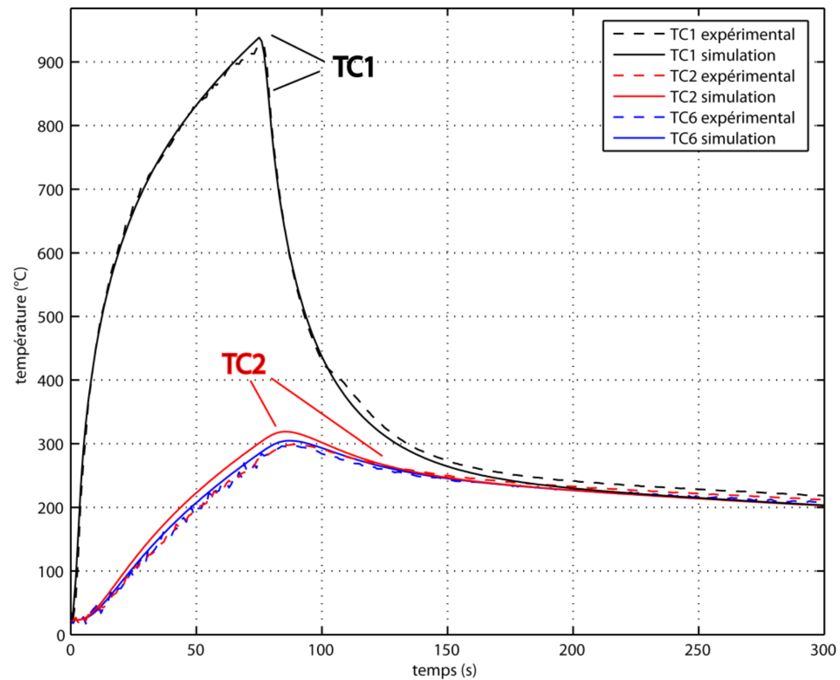
Simulation of Disk Spot experiment

Experimental set-up : [Cavallo 1998] [Cano 1999]



Test at DEN/DM2S/SEMT/LTA

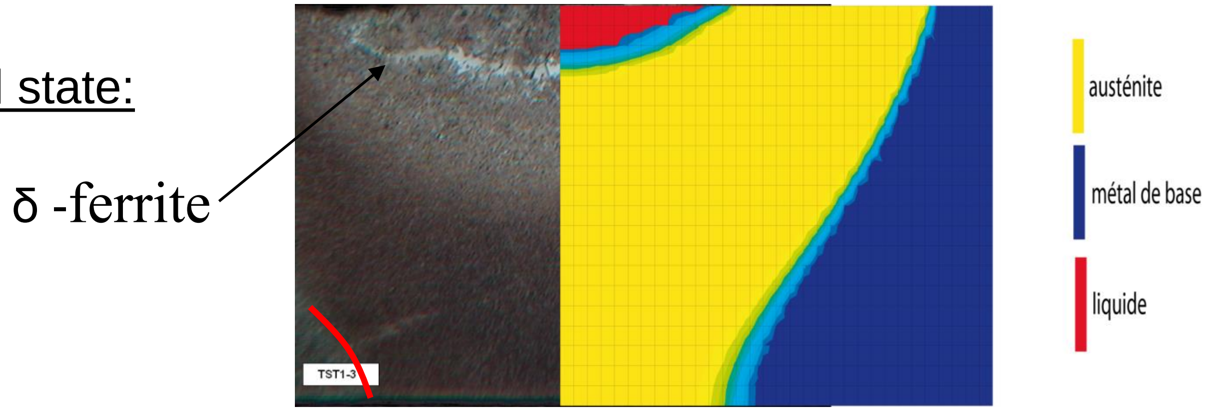




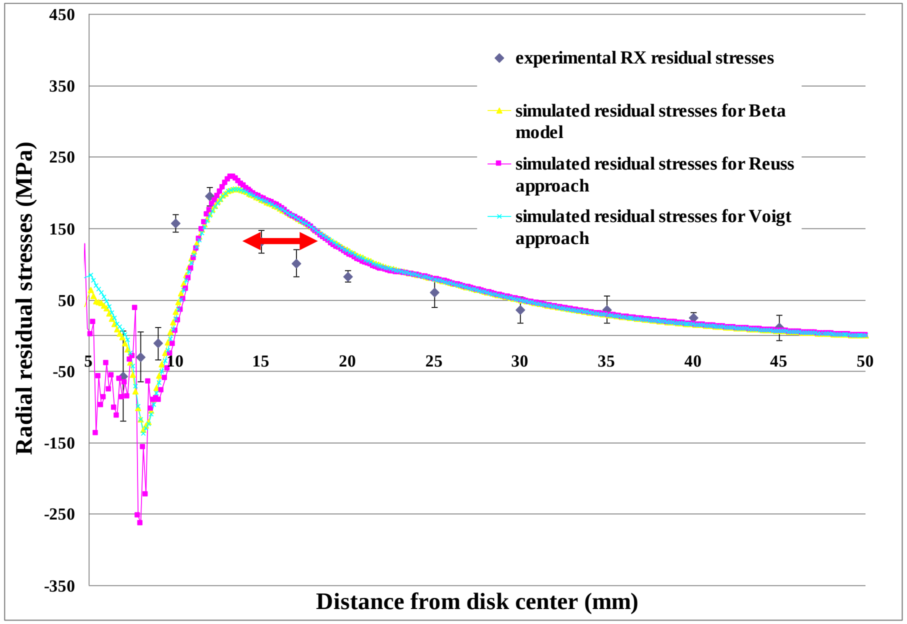
→ Inverse analysis identification of heat source intensity and spatial distribution [Roux 2006]

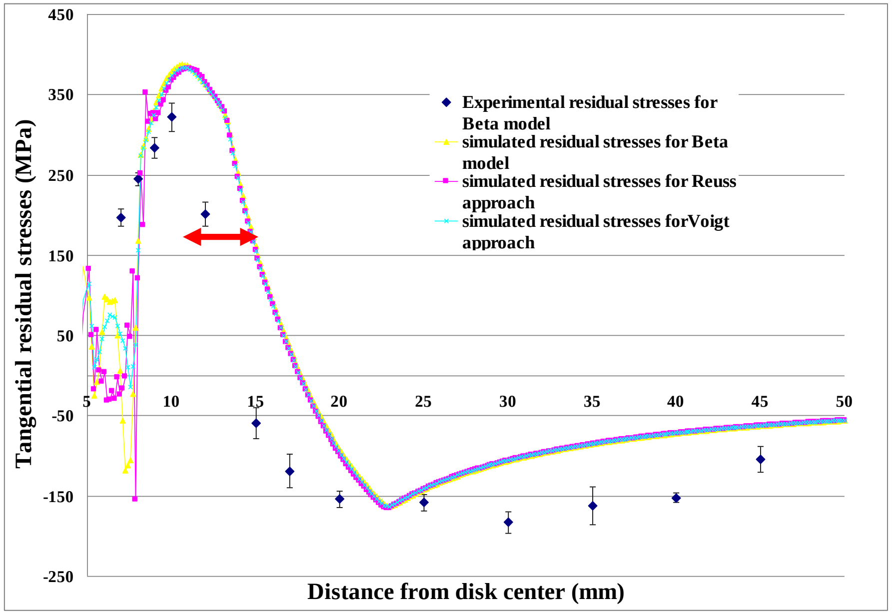
Simulation of Disk Spot experiment

Prediction of final metallurgical state:



Residual stresses on upper surface (X ray diffraction measurements):

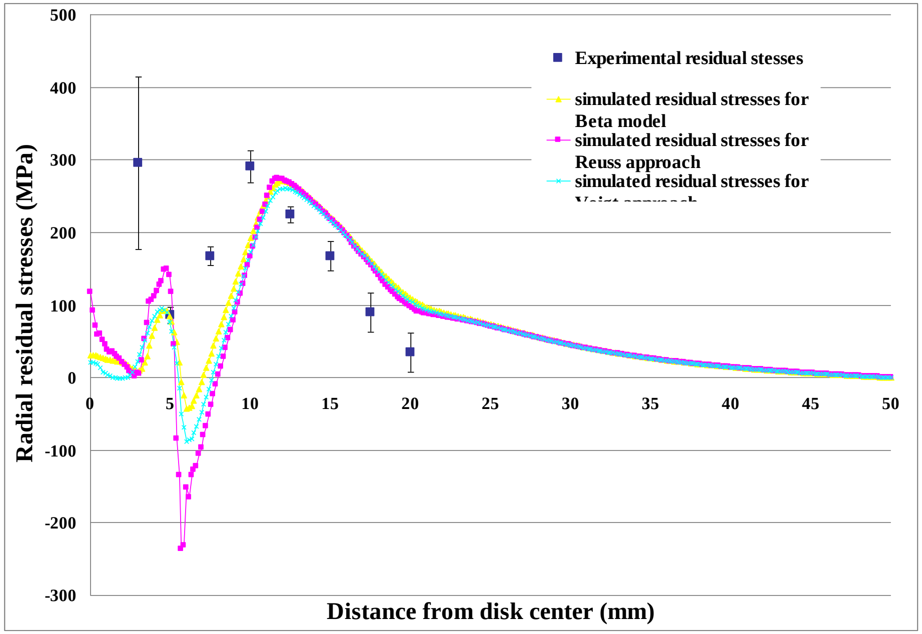


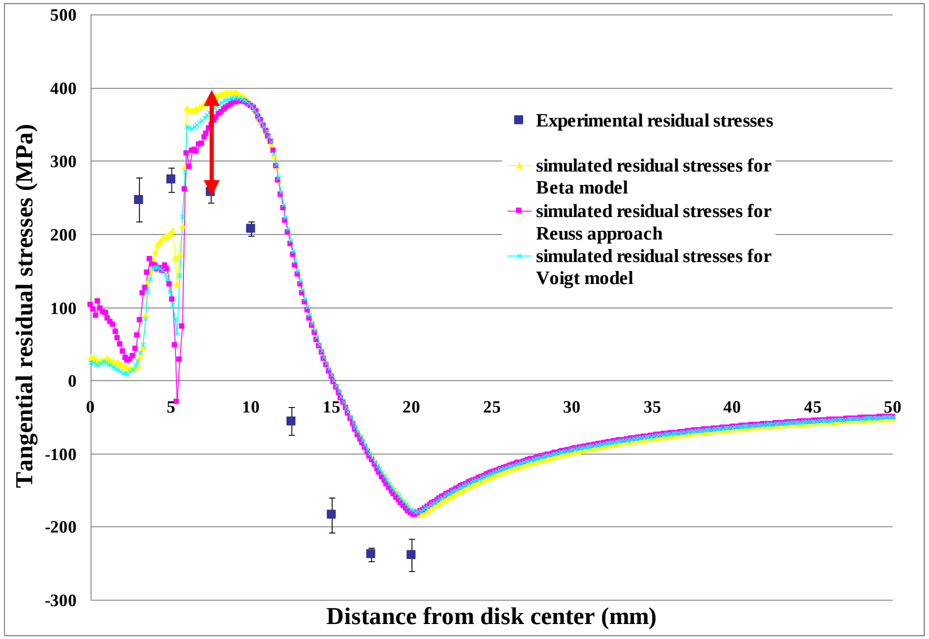


→ Radial shift (bad HAZ prediction?)

Simulation of Disk Spot experiment

Residual stresses on upper surface (X ray diffraction measurements):



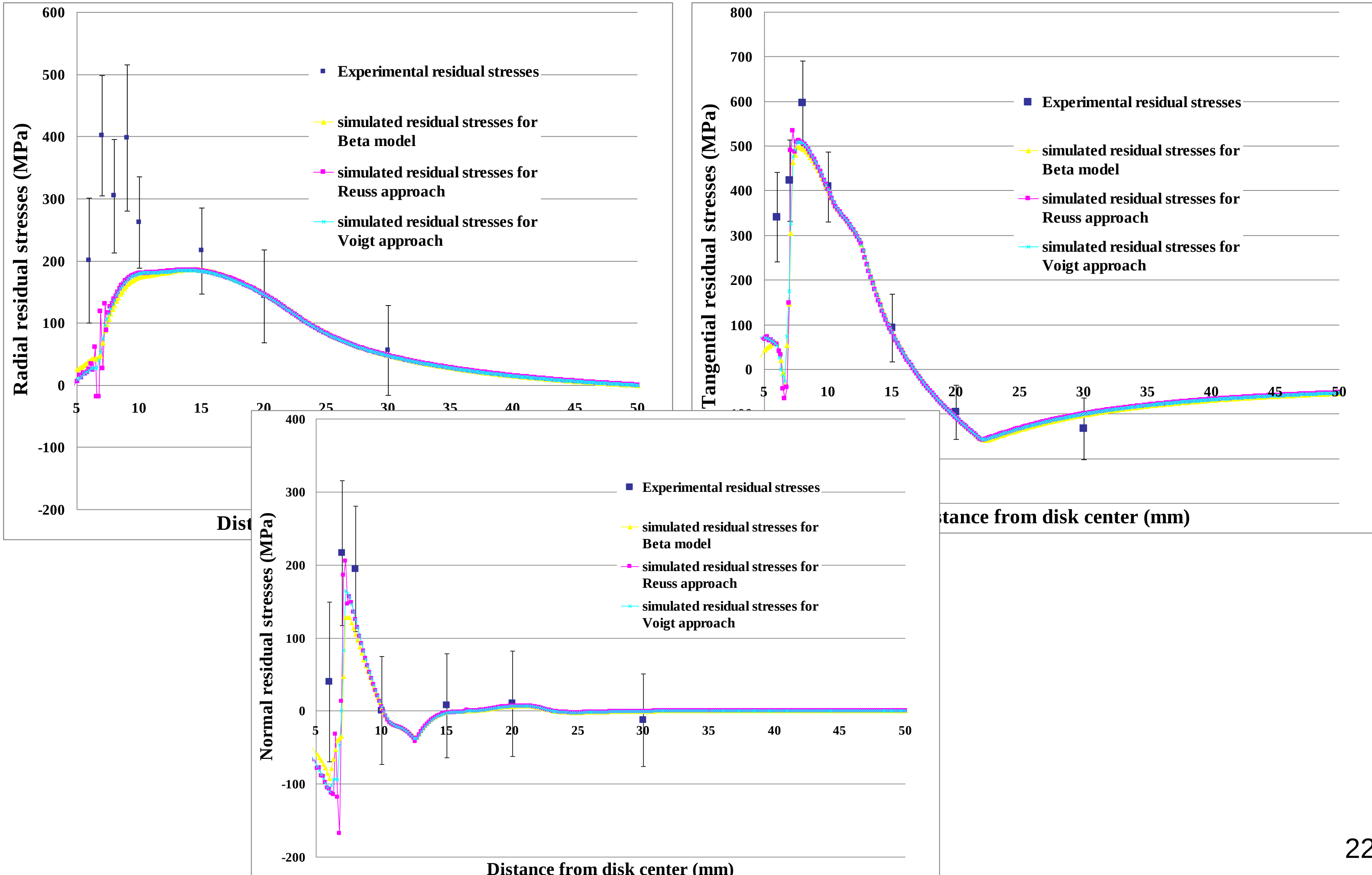


→ Again overestimation of TRIP effect

→ Similar stress distribution with Beta model and Voigt Approach

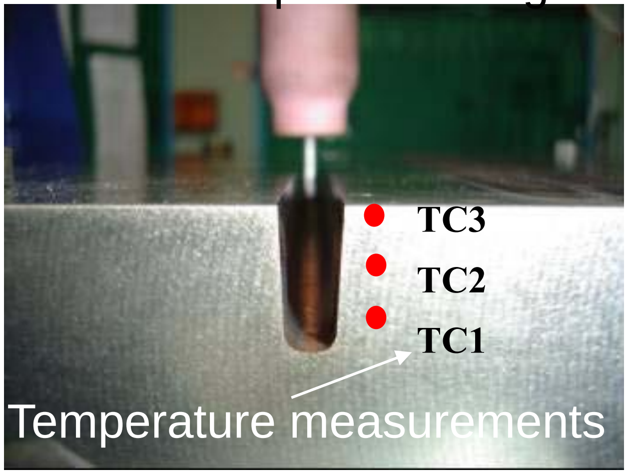
Simulation of Disk Spot experiment

Residual stresses on half thickness (Neutron diffraction measurements):

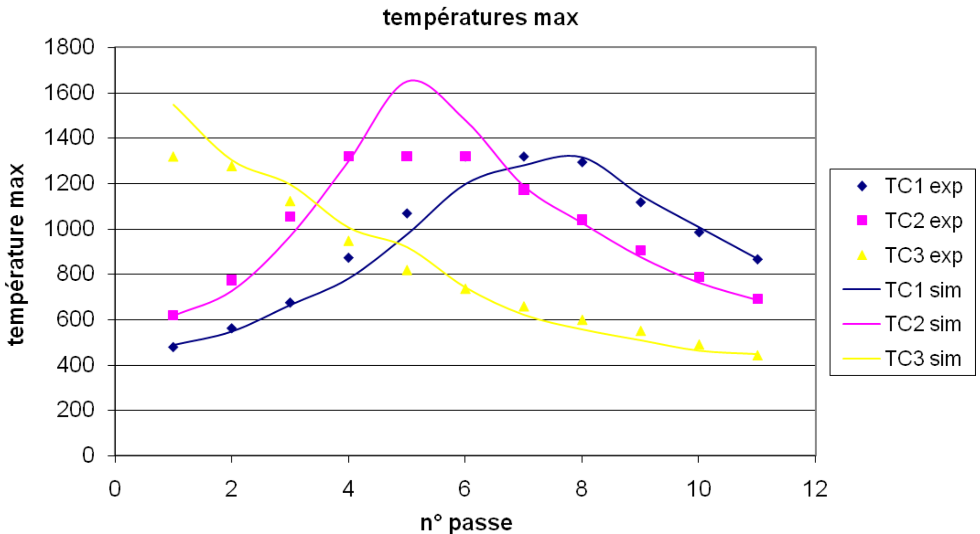


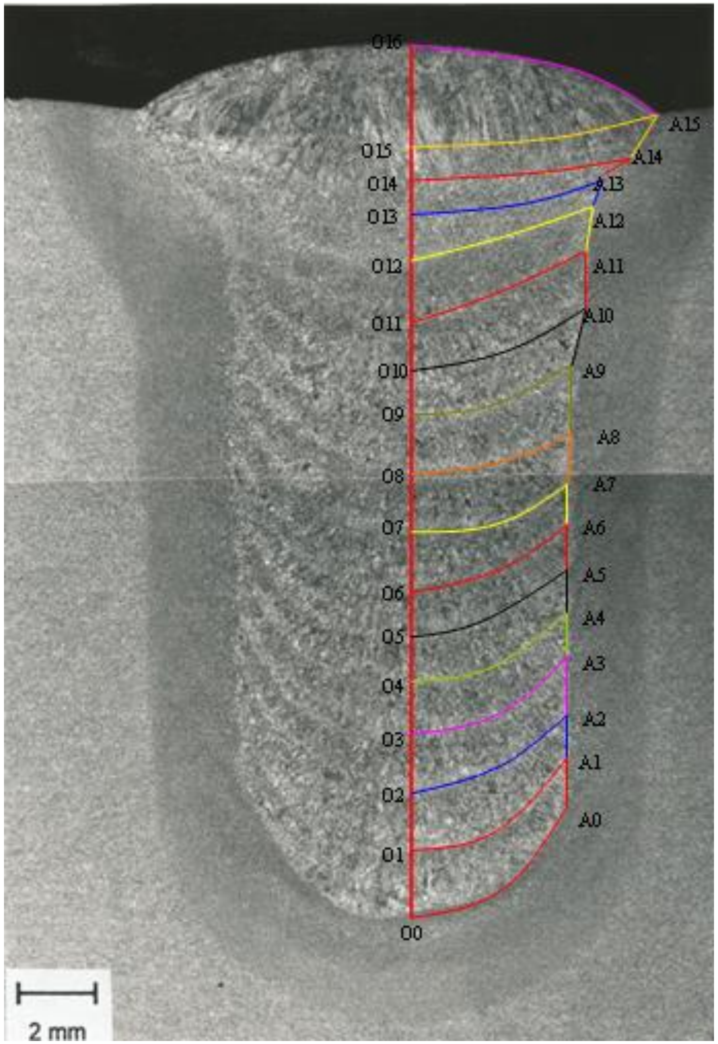
<u>Experimental set-up at DEN/DM2S/SEMT/LTA</u>

TIG multipass welding



Inverse identification of heat source for each pass [Hanna 2006]



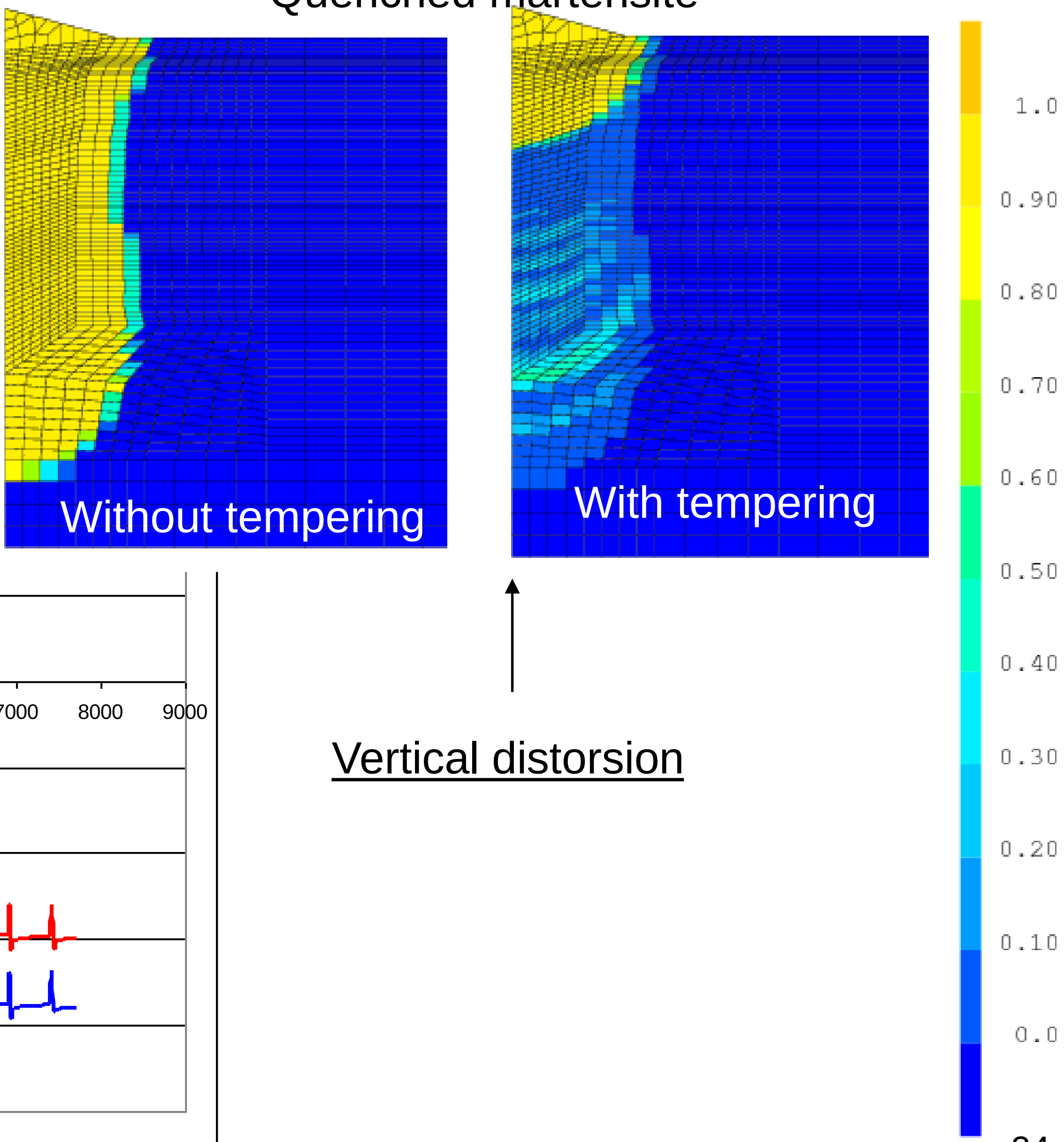


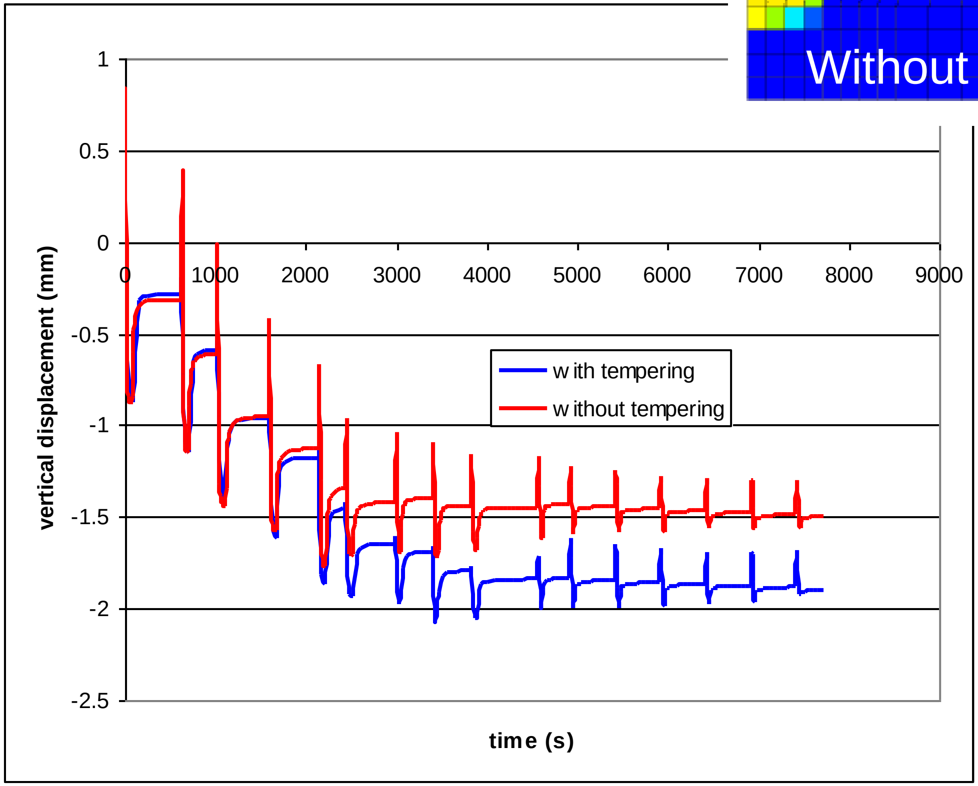
Multipass MUSICA experiment

Prediction of final metallurgical state:

→ Strong tempering effect of previous passes

Quenched martensite

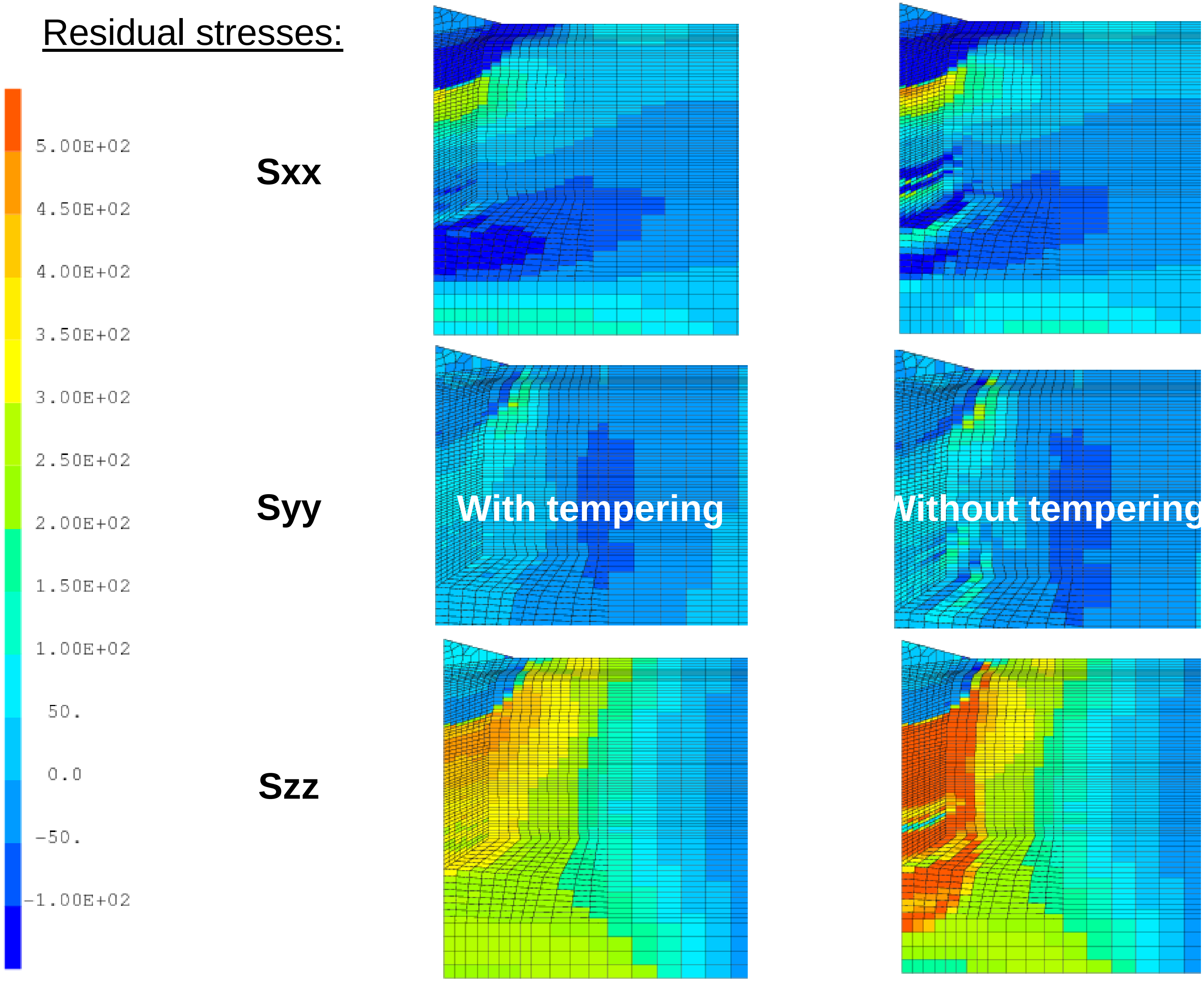




Vertical distorsion

Multipass MUSICA experiment

Residual stresses:



Conclusion & perspectives

•Differential model has been developed to model phase change

During cooling : - martensite transformation

During heating : - austenitization of quenched and tempered martensites

Not presented here - tempering of martensite

•This thermometallurgical model allows for the prediction of hardness profiles through welds by simple post-processing of heat transfer analyses

•This thermometallurgical model has been coupled to elasto-viscoplastic constitutive equations identified for each metallurgical phase

•A simple homogenization approach has been used associated to martensitic transformation

•This model could be applied for bainitic transformation (case of the 16MnD5 steel)

•This thermometallurgical mechanical model has been implemented in Cast3M and validated in terms of residual stresses prediction for welding experiments