Heat Treatment Processes

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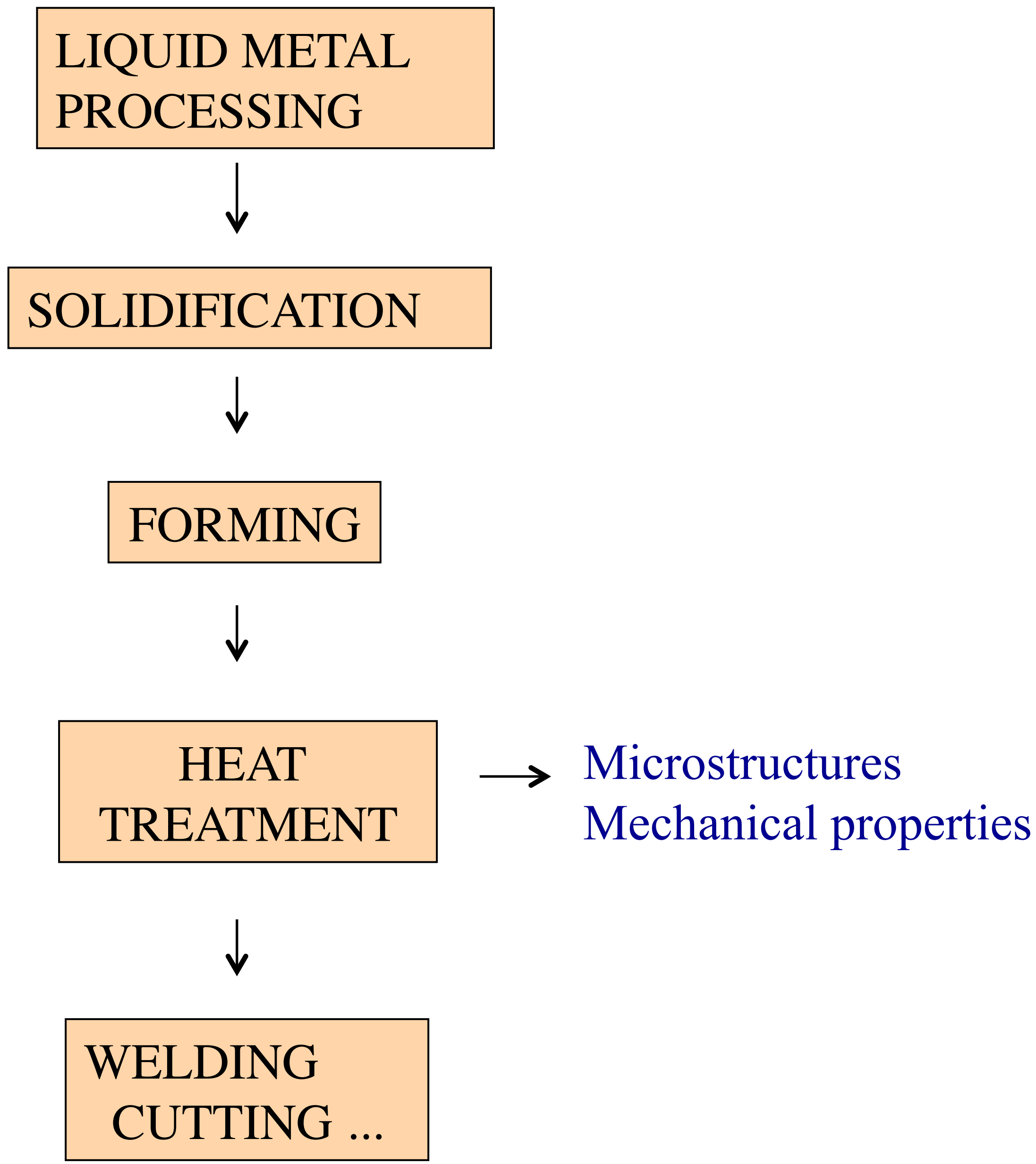
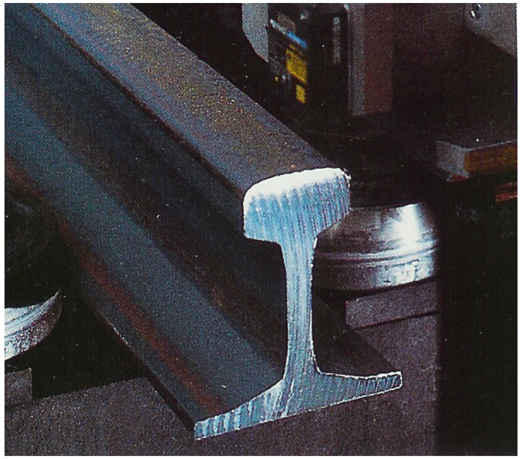
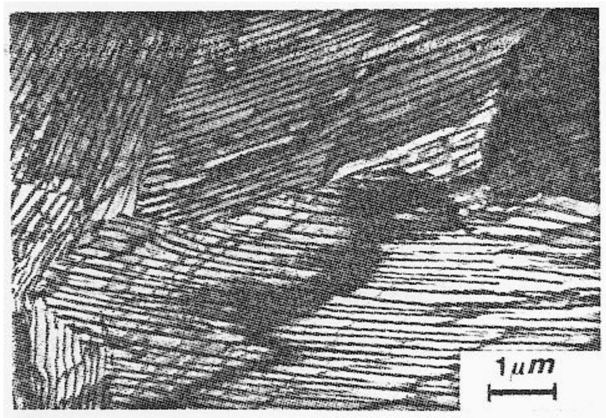
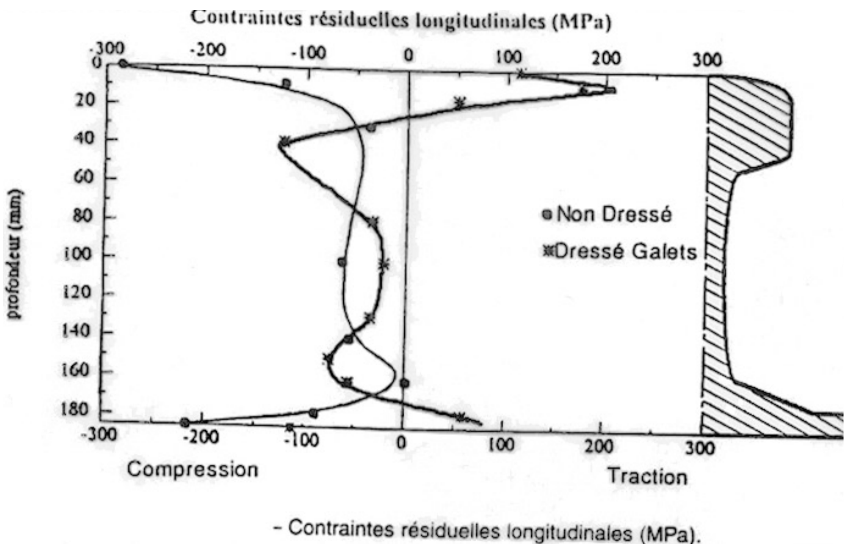
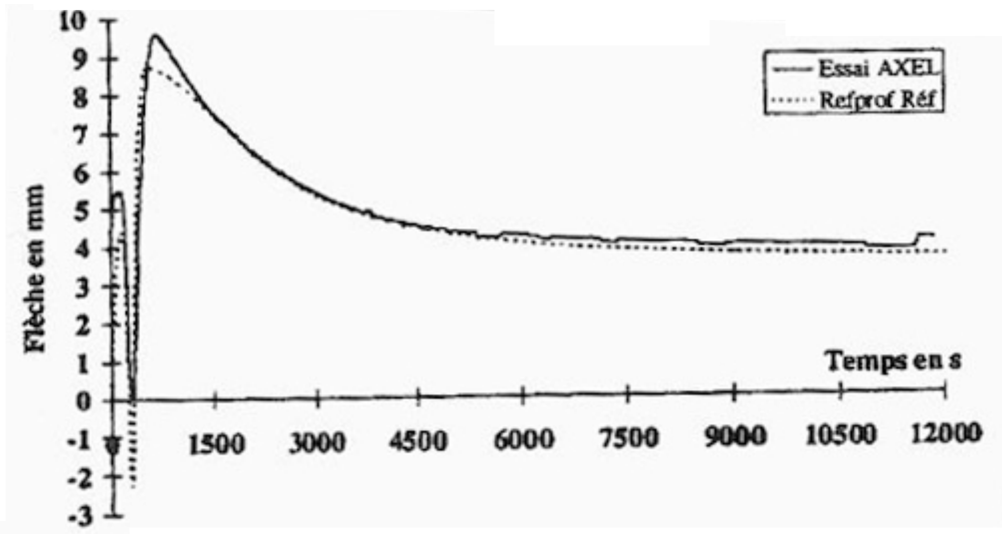

LIQUID METAL PROCESSING
SOLIDIFICATION
FORMING
HEAT TREATMENT
Microstructures
Mechanical properties
WELDING
CUTTING ...

Problem of heat treatment of metallic alloys









Study Sogerail, Irsid, LSG2M, Cemef

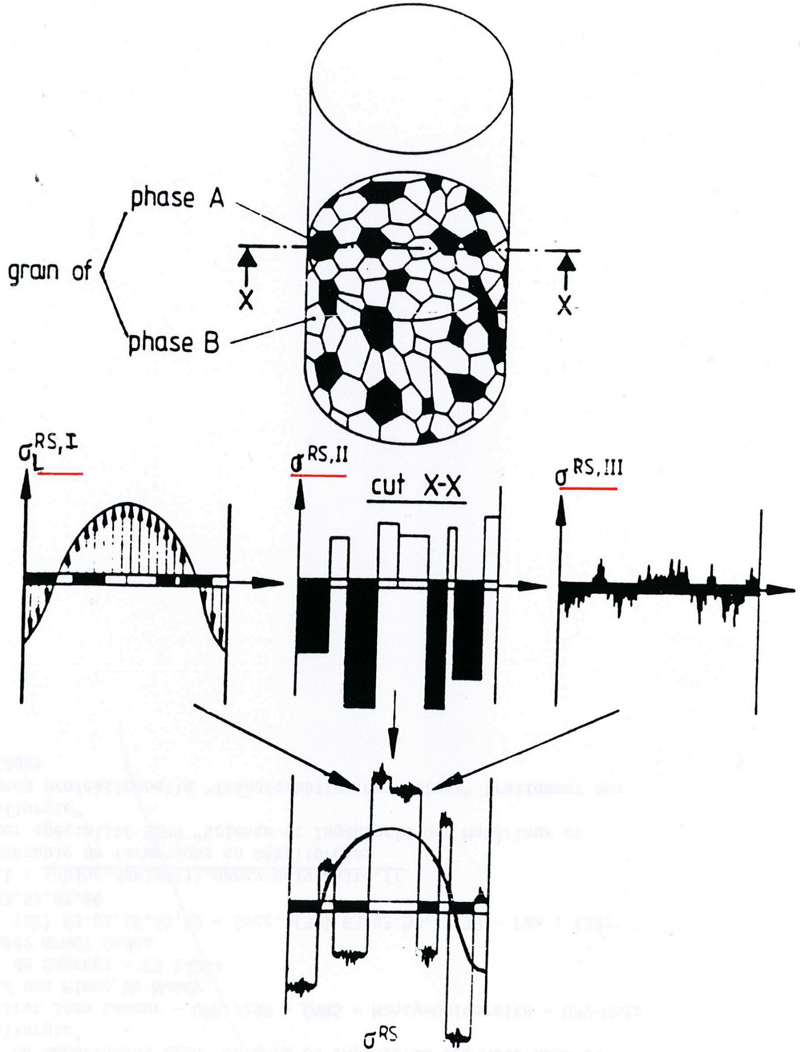


Illustration of the different stress orders

(E. Macherauch, K.H. Kloos 1986)

Heat treatment of metallic alloys

Control of microstructures

→ desired mechanical properties

Control of thermal gradients

→ avoid/limit deformations

→ avoid/limit residual stresses (quenching)

or obtain desired residual stress distributions
(surface heat treatments, thermochemical treatments)

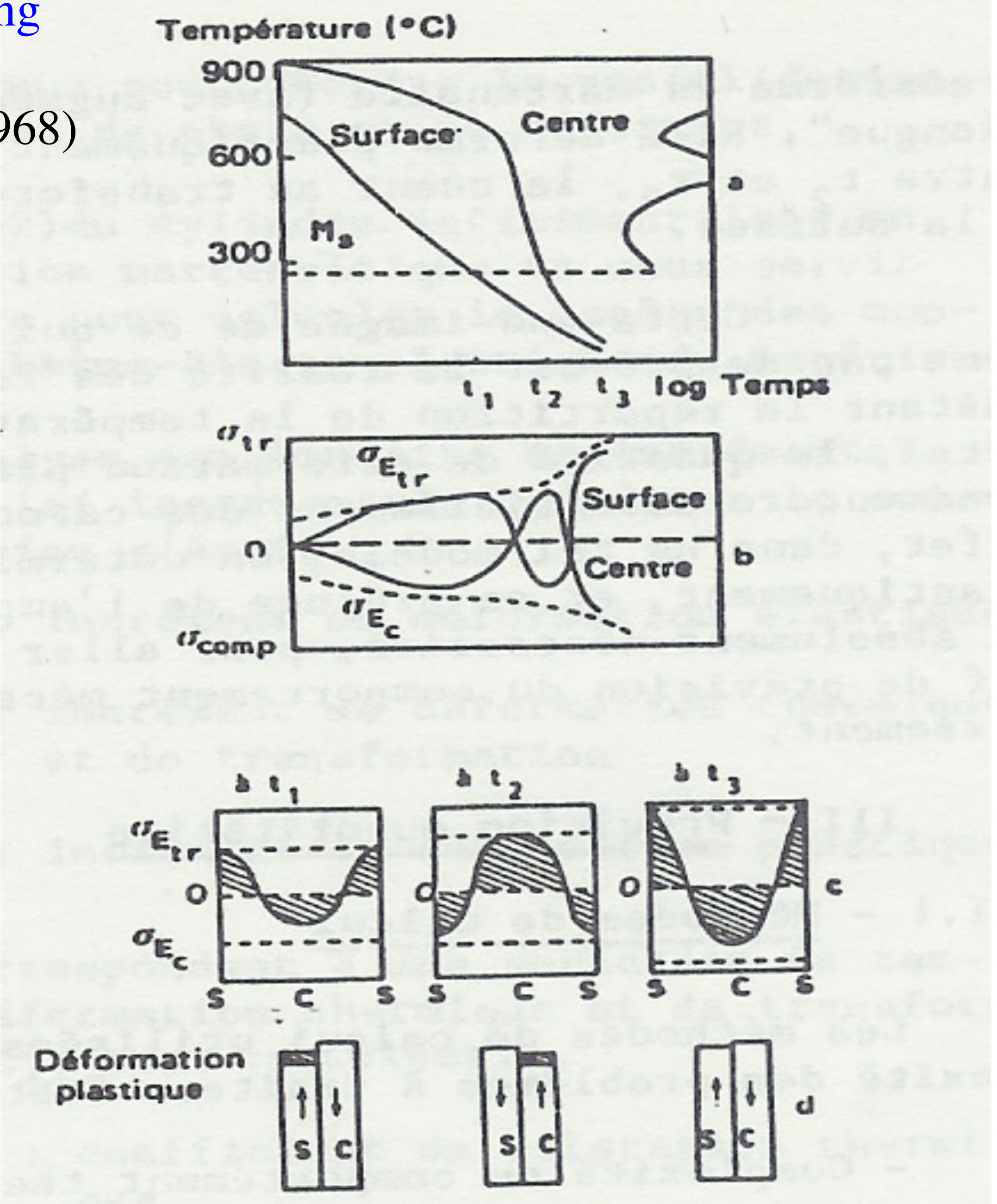
Better optimization = modelling and numerical simulation

Development of internal stresses during cooling

qualitative approach (Rose et Bühler 1968)

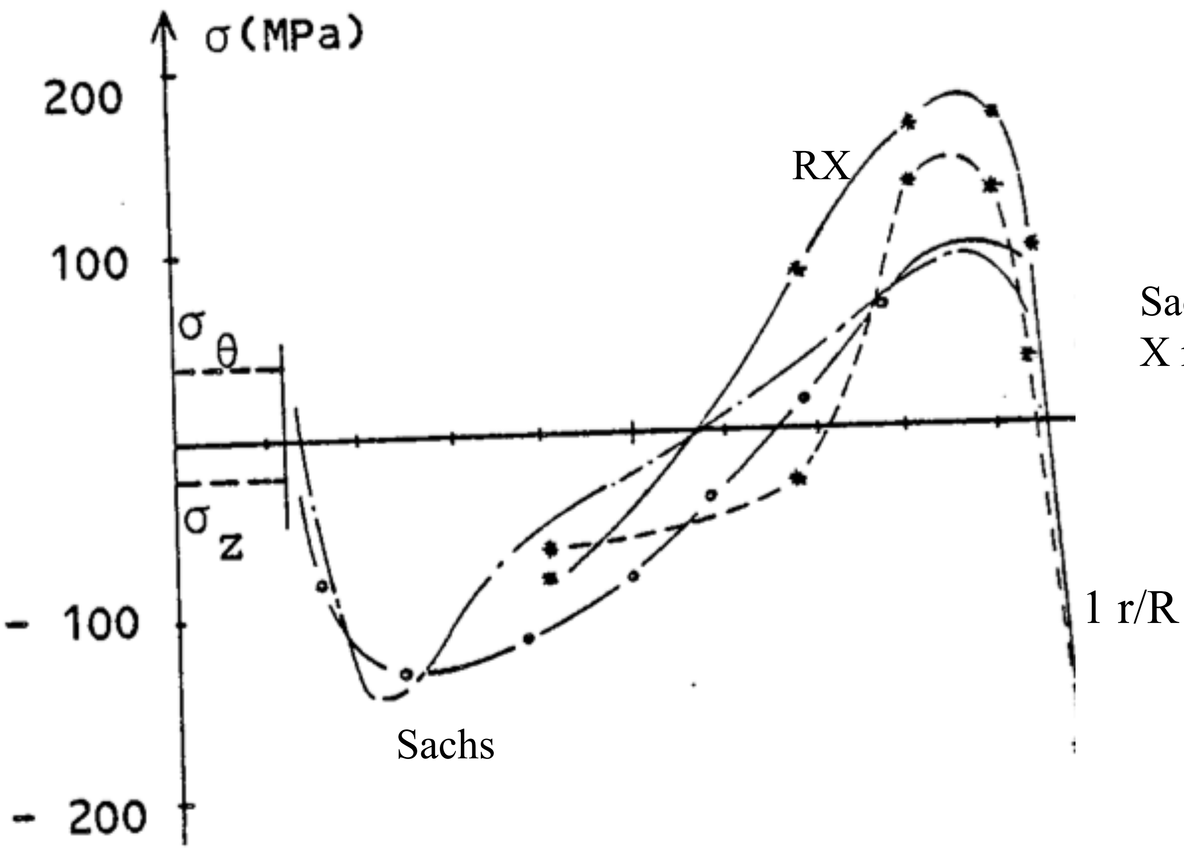
Origin of internal stresses :
Heterogeneous deformations
- thermal
- phase transformations

Origin of residual stresses and deformations :
Heterogeneous deformations
- plastic
- phase transformations



Example of experimental residual stress profiles

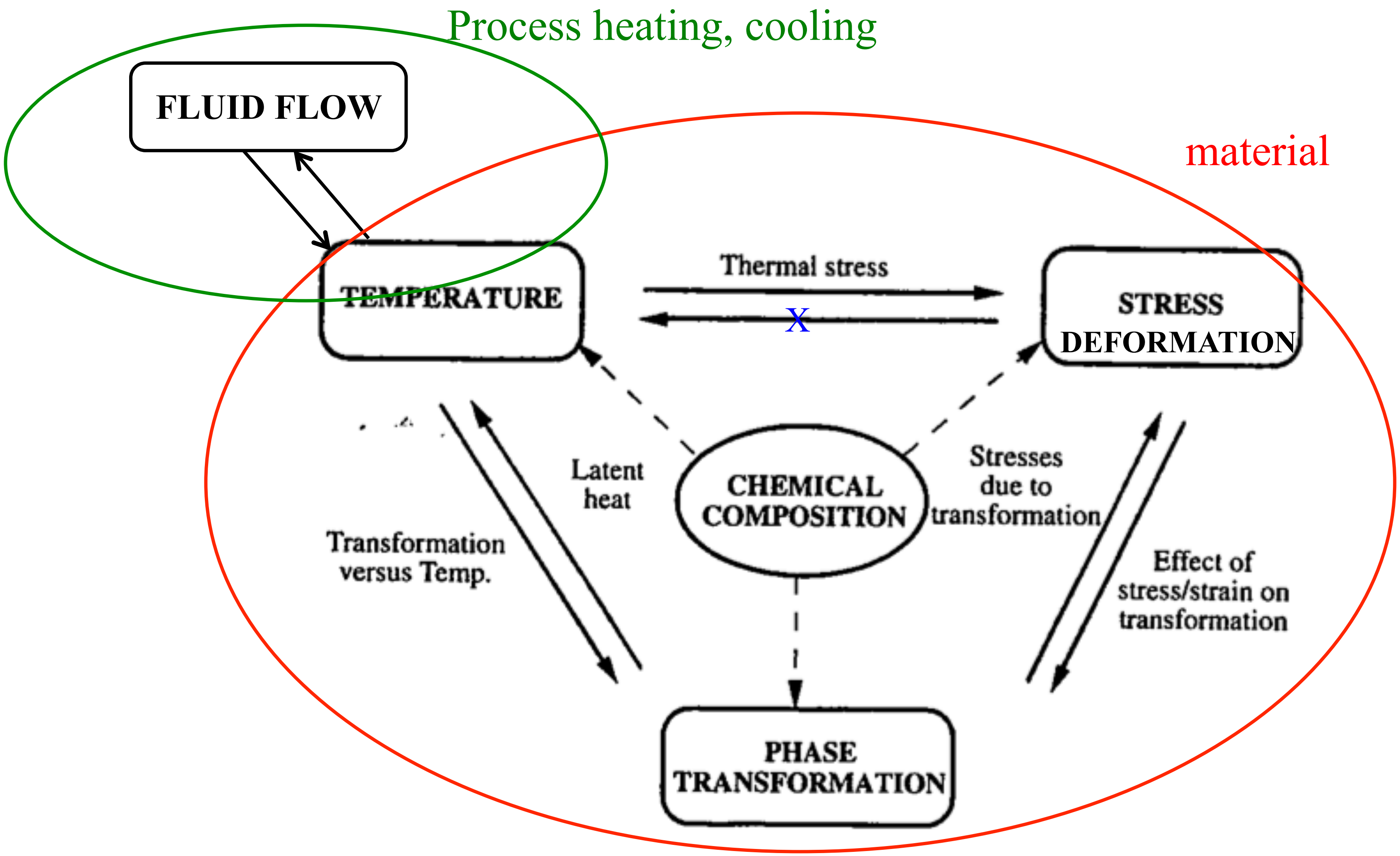
Water quenching of a 60NiCrMo11 steel cylinder
(diameter 40mm, length 120mm)



Sachs method
X ray diffraction

PhD Josserand 1980

Fluid – thermal – metallurgical – mechanical couplings in heat treatment

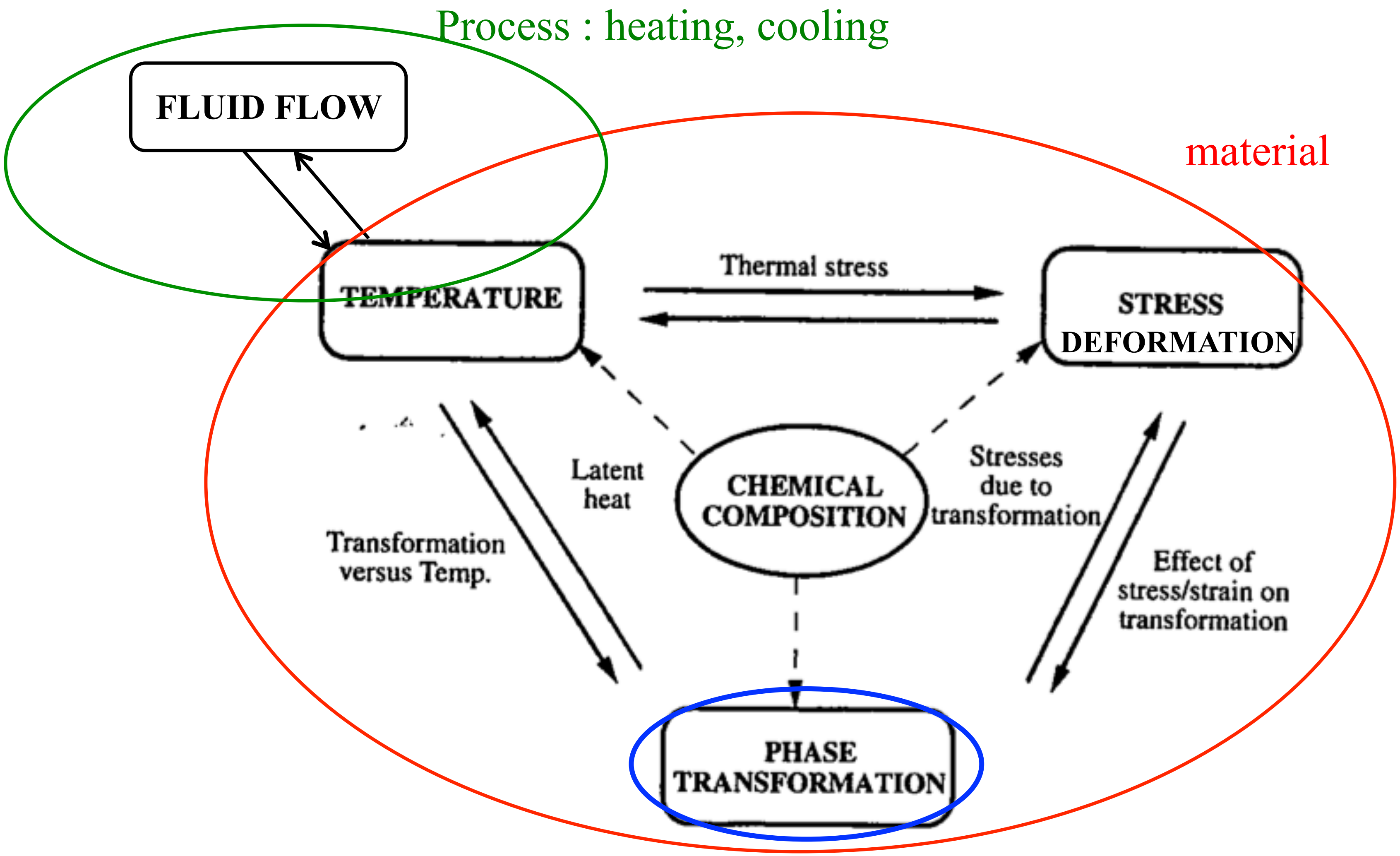


1972…prediction of thermal stresses (Al alloys, Ti alloys)

≈ 1980… main advances including phase transformations in steels

≈ 2000… precipitation Al alloys - consideration of fluid flow (gaz quenching)

Fluid – thermal – metallurgical – mechanical couplings in heat treatment



Overview of necessary experimental knowledge, present models, some open questions and example of results in steels

Modelling of phase transformation kinetics

(for the purpose of predicting internal stresses and deformations)

• **Global models (JMAK): (**1980 -1995)

- Modelling anisothermal kinetics from CCT diagrams
- Modelling kinetics from IT diagrams (additivity principle)

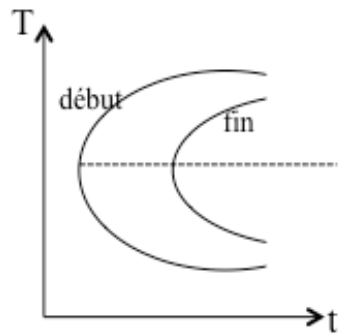
PHASE RC : prediction of kinetics during heating and cooling in steels from isothermal kinetics (additivity principle)

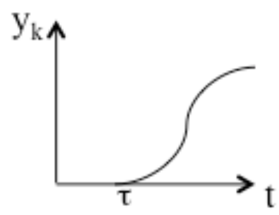
$$y_k = y_{maxk} \left(1 - \exp\left(- b_k t^{nk}\right)\right)$$

HEATING

IT diagram austenitization kinetics

carbon content of austenite and grain size





COOLING : IT diagram

austenite → proeutectoïd constituent

pearlite, bainite

. incubation period : Scheil's method $S = f_{inc} \Sigma \Delta t_i / \tau_i$

τ_i = f(T, grain size, comp., stress)

. progress

n, b = f (T, grain size, comp., stress)

austénite → martensite : $y_m = y_\gamma [1 - \exp(-\alpha (M_s - T))]$

Ms = f (grain size, comp., stress)

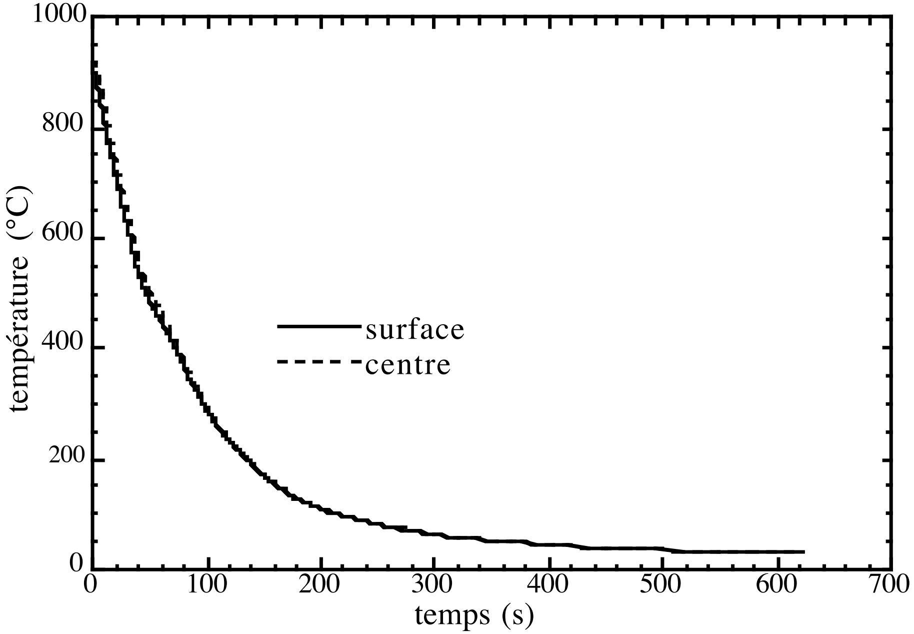
Hardness: $HV = \Sigma_{i,k} dy_k HV_k$ $HV_k = f(T_{formation}, comp.)$

PhD Fernandes, Farias, Mey…

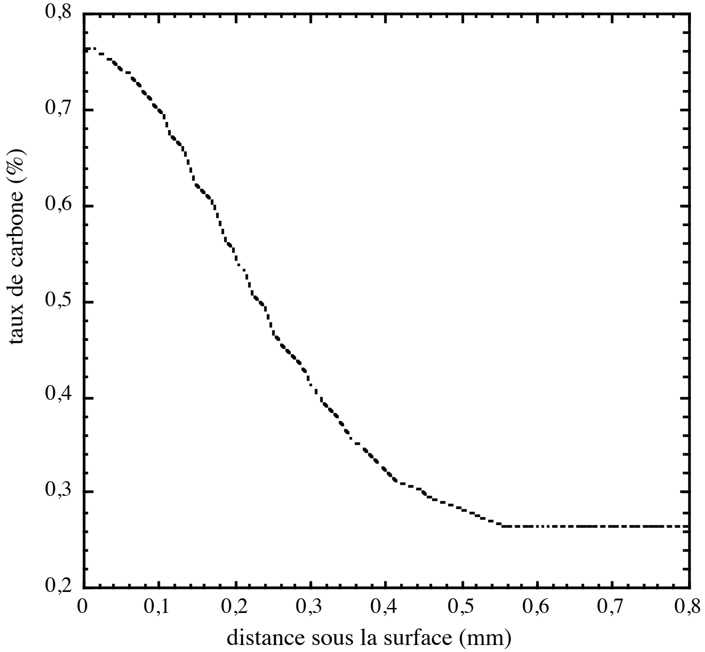
Example : Gaz quenching of carburized cylinders

Cylinders diameter 16mm length 48mm
steel 27MnCr5
Austenitization 930°C 40min
Gaz quenching (nitrogen 4 bars)

Temperature evolutions (median plane)

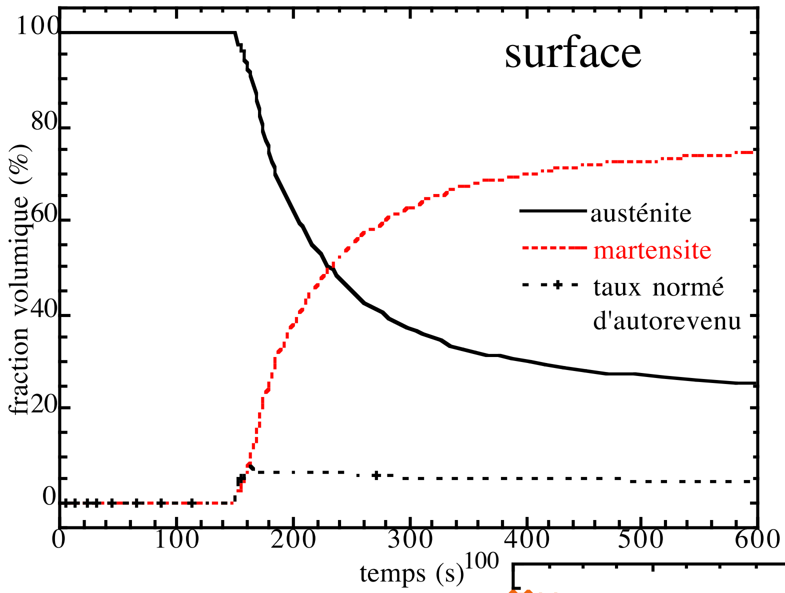


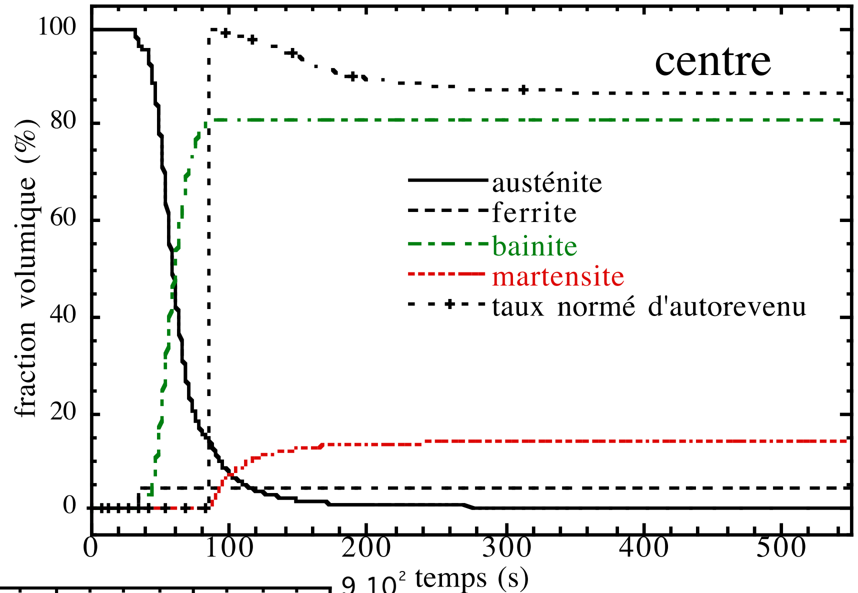
Radial carbon profile



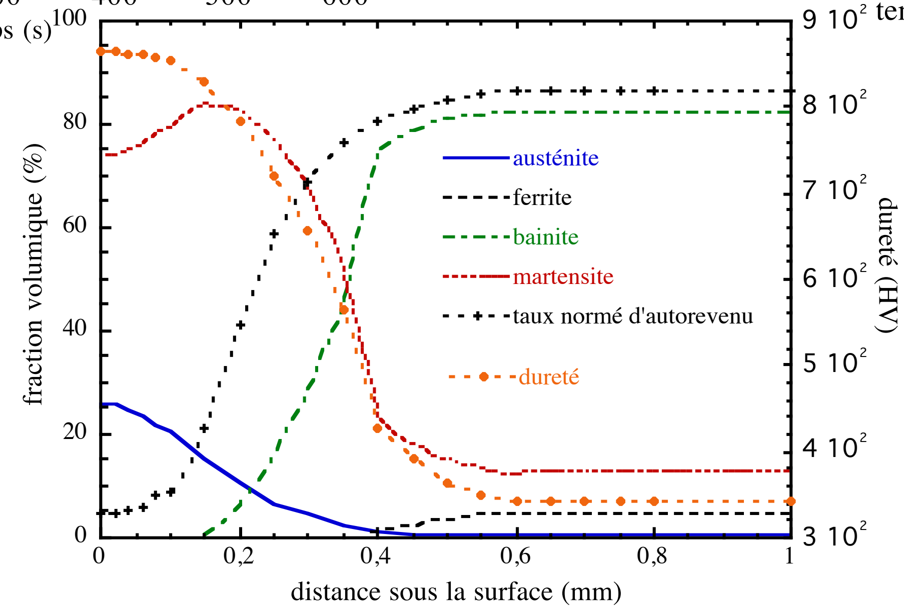
Dissertation C. Aubry 1998

Kinetics of transformation



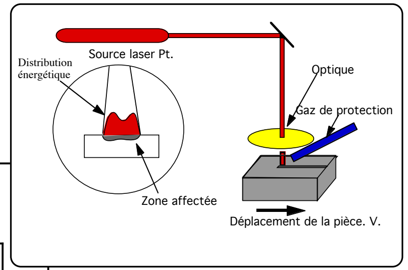


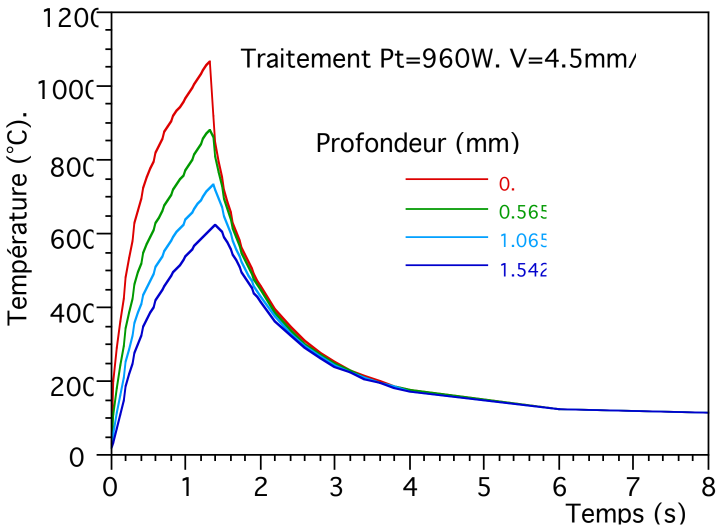
Final microstructure and hardness distributions

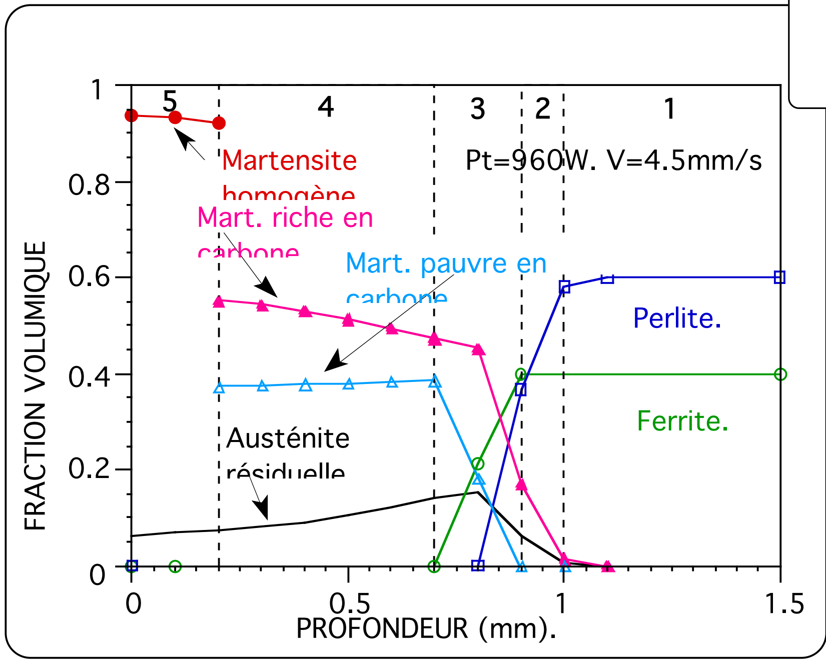


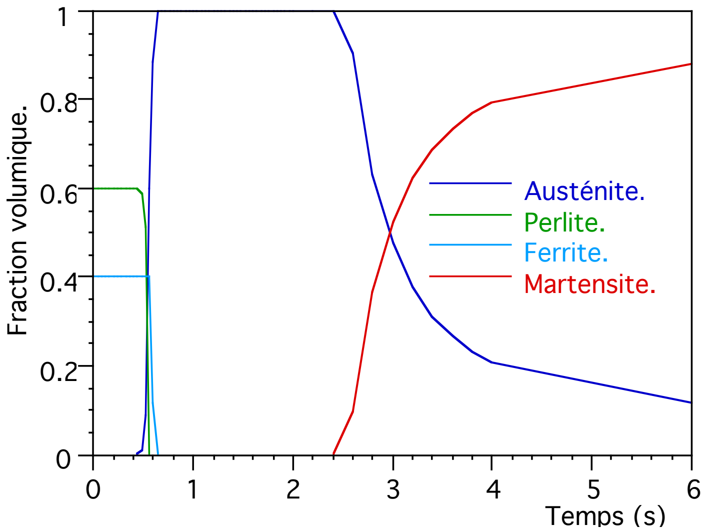
Ex. Prediction of microstructures during laser hardening of steels

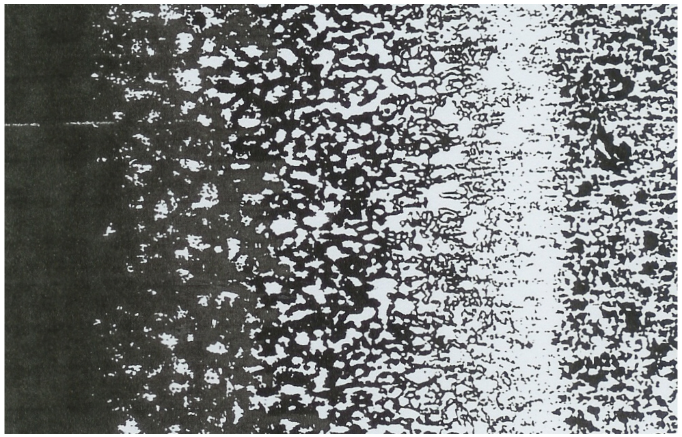
Plate moving under laser beam – steel C42





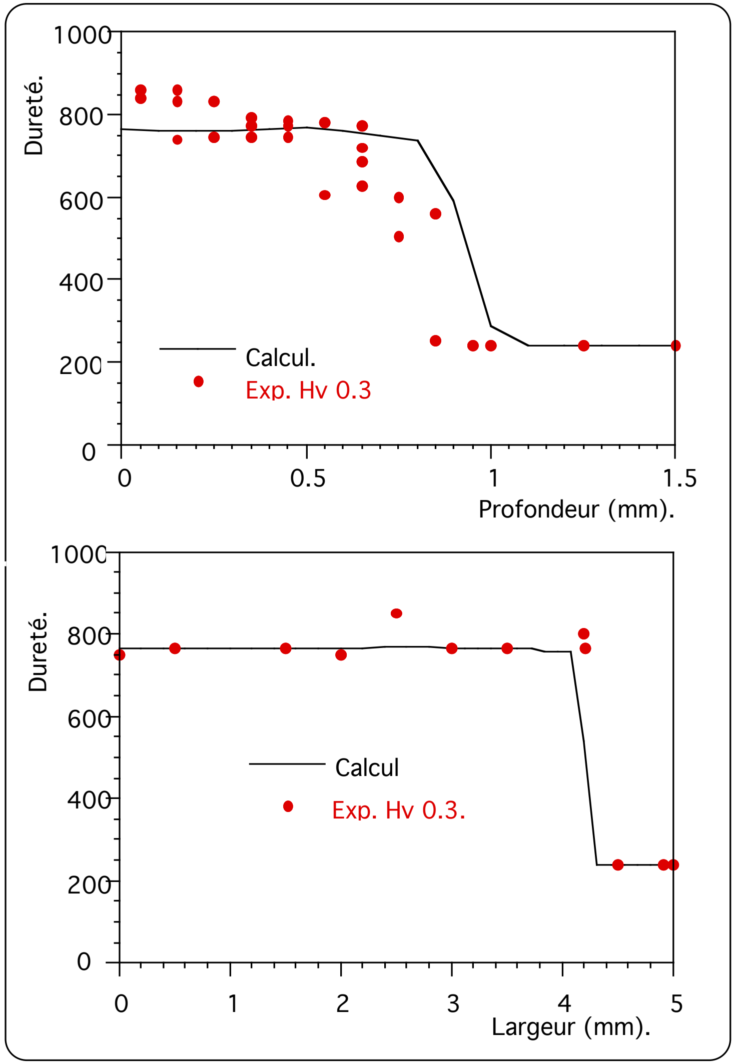


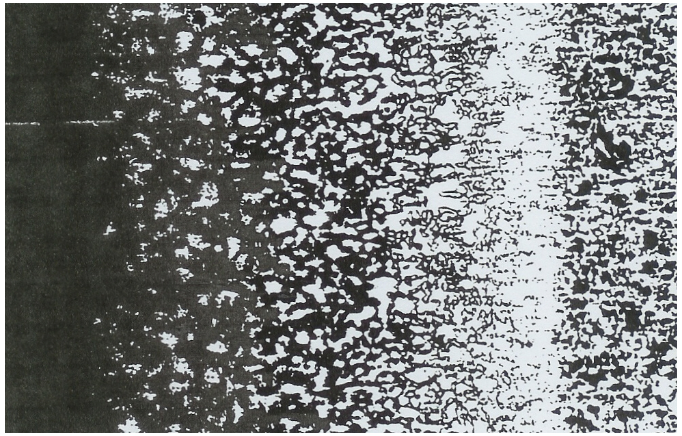




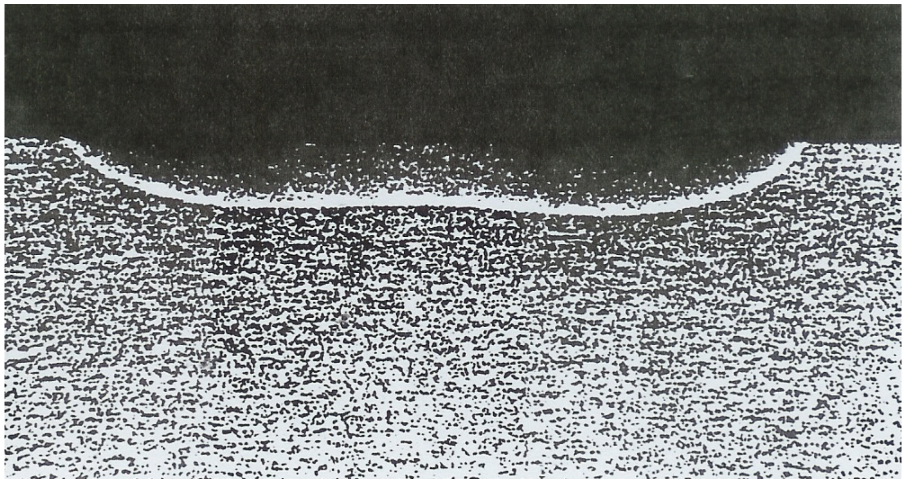
Dissertation Boufoussi 1993

Hardness and microstructure distributions comparison calculation-experiment





depth HAZ: exp. 0,85mm calculation 1,06mm



width HAZ : exp. 8,4mm calculation 8,5mm

Modelling of phase transformation kinetics
(for the purpose of predicting internal stresses and deformations)

• **Global models (JMAK):** most commonly used for steels
- Modelling anisothermal kinetics from CCT diagrams
- Modelling kinetics from IT diagrams (additivity principle)

can predict volume fractions of the phases for complex situations
→ *limitations : no morphological parameters of the microstructures*

difficult to take into account prior plastic deformation effects

• **Nucleation, growth, coarsening models**
- precipitation in Al alloys *D. Godard 1999*
- tempering of martensite in steels *Y. Wang 2006*

volume fractions of the precipitates, size distributions
matrix chemical composition

Modelling of phase transformation kinetics : nucleation, growth, coarsening

Multicomponent alloys - concommittant precipitations

- thermodynamic equilibrium :

. solubility product (stochiometric compositions)
or coupling with THERMOCALC

- nucleation rate

homogeneous/heterogeneous nucleation, take account of elastic strain energy

- growth (dissolution) coarsening rates

diffusion controlled
local equilibrium at interfaces
Gibbs Thomson effect and effect of elastic strain energy

⇨ **Results**

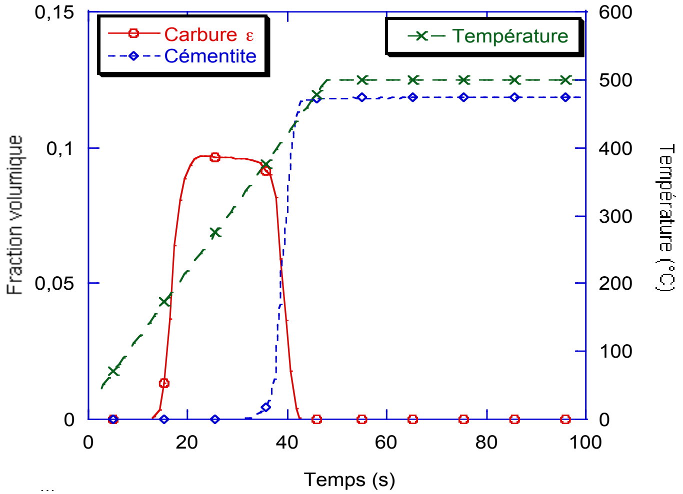
volume fractions of the precipitates
size distributions
matrix chemical composition

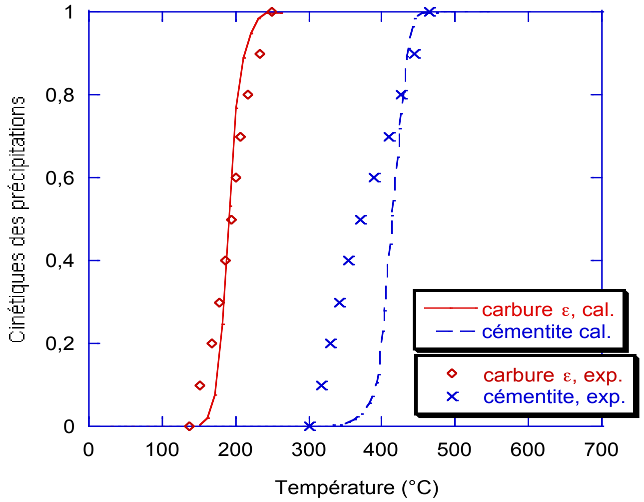
} during the treatments isothermal and anisothermal

Modelling of precipitation during tempering of martensite in steels

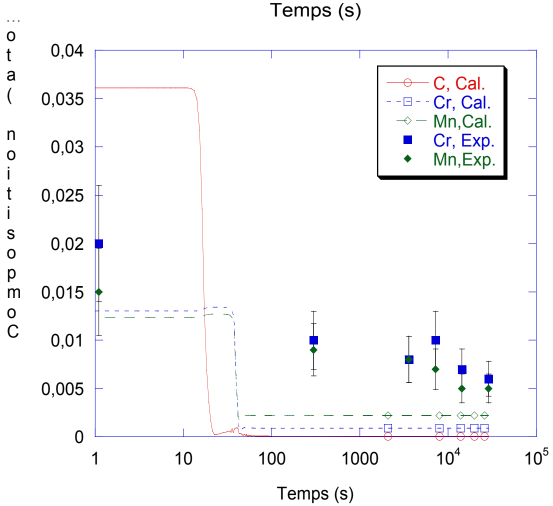
ε carbides ($Fe_{2,4}C$) coherent, homogeneous nucleation,
cementite ($(Fe,M)_3C$) incoherent, heterogeneous nucleation (disloc.)

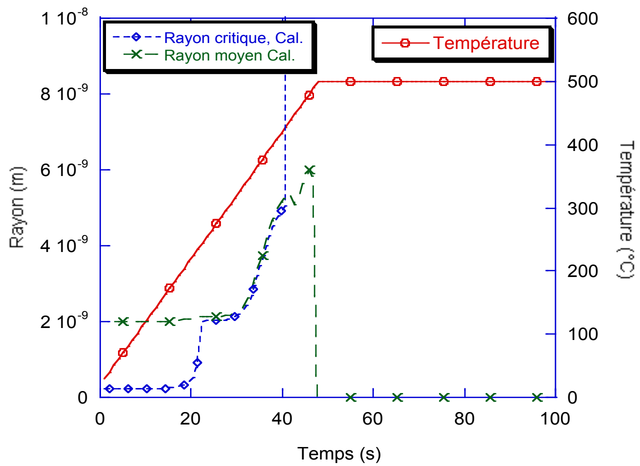
steel 80MnCr5
heating : 10°C/s
holding at 500°C

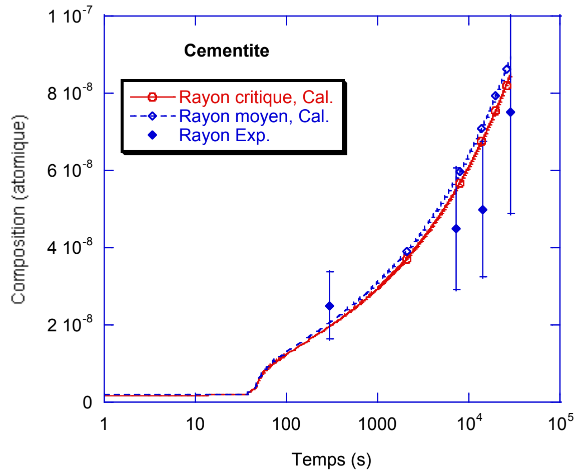




600°C 2h

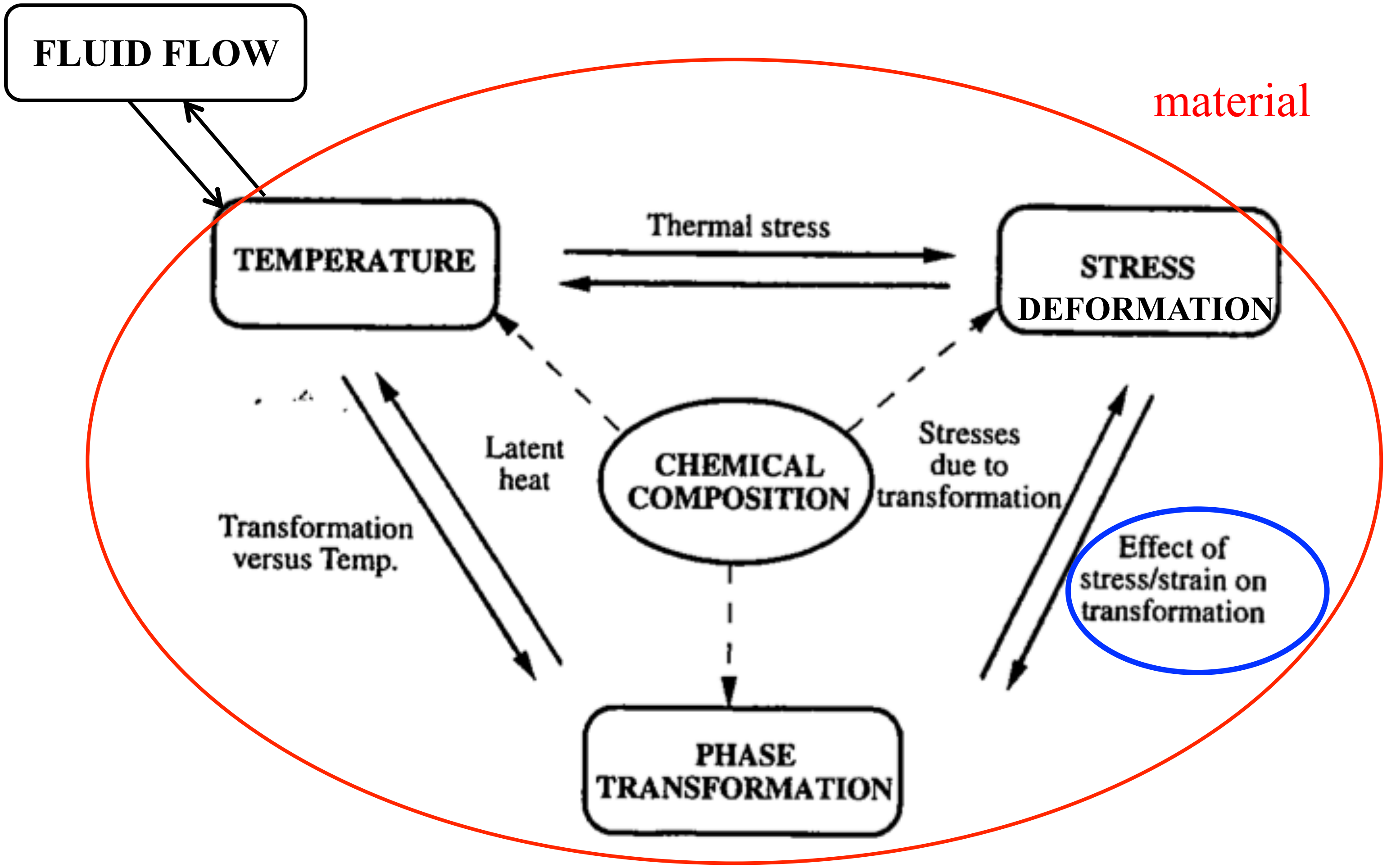




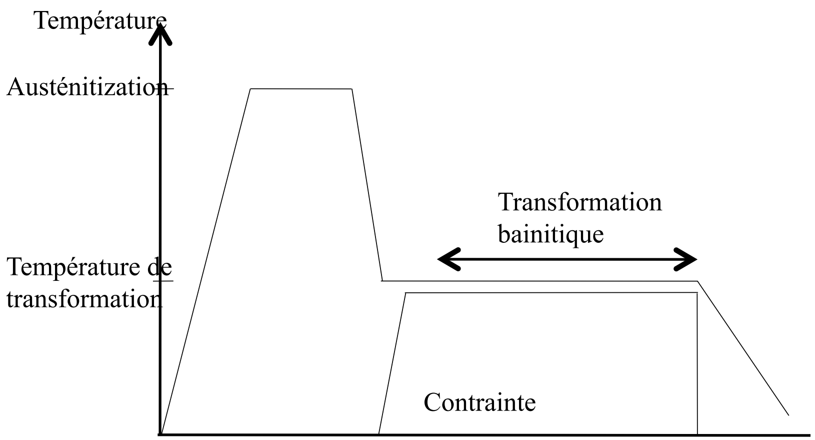


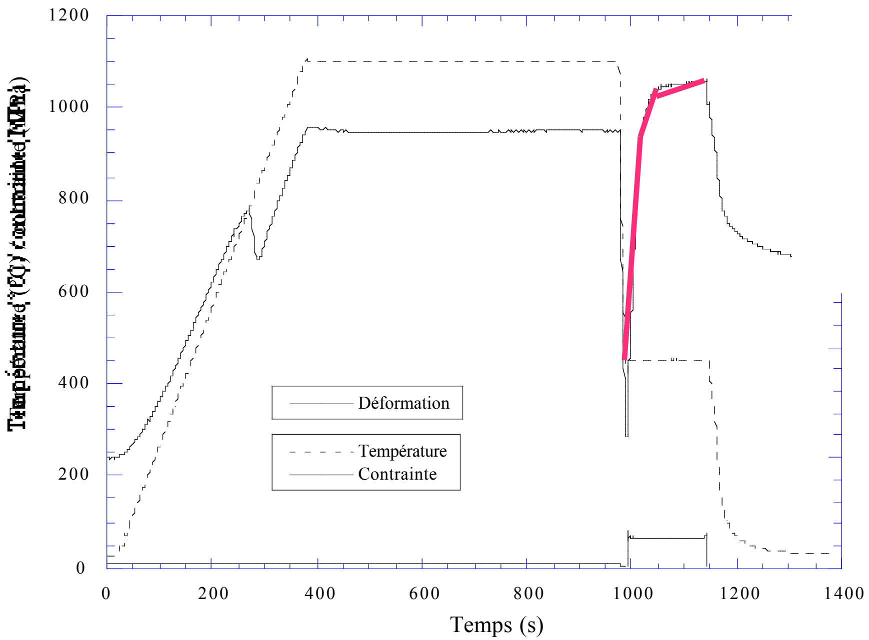
PhD Y. Wang 2006

Fluid – thermal – metallurgical – mechanical couplings in heat treatment

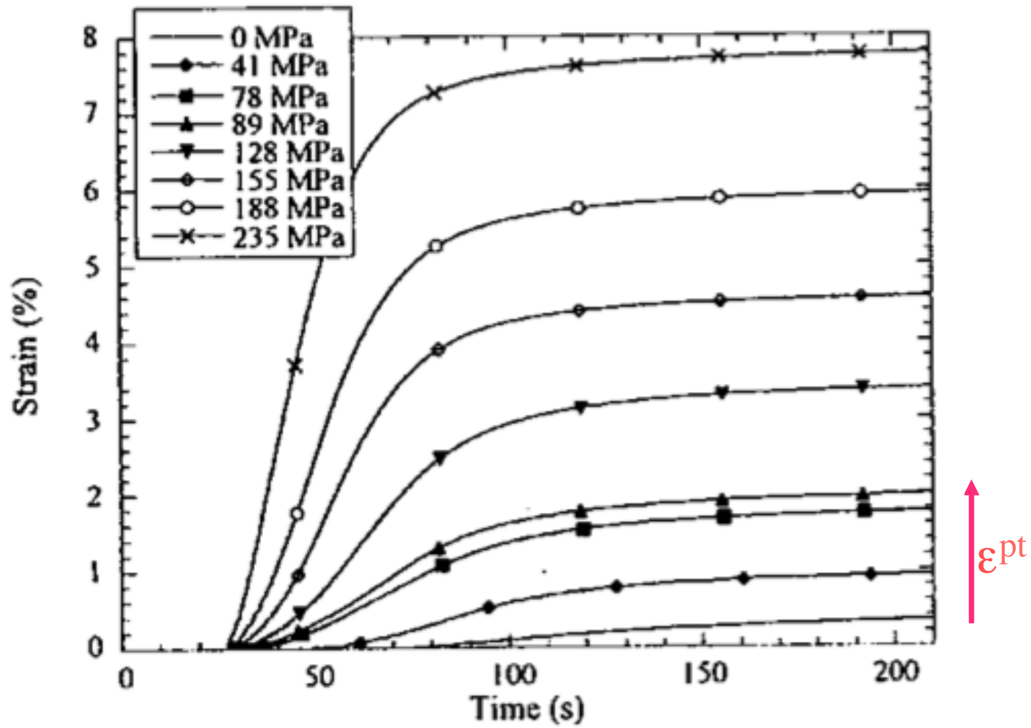


Bainitic transformation under stress
(thermomechanical simulator DITHEM)





Steel 35MnV7
Transformation at 350°C

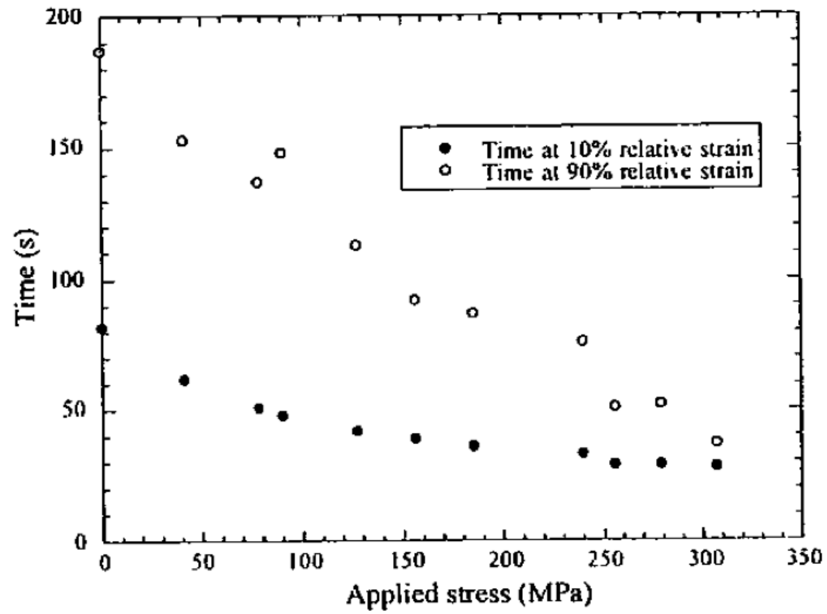


Transformation plasticity

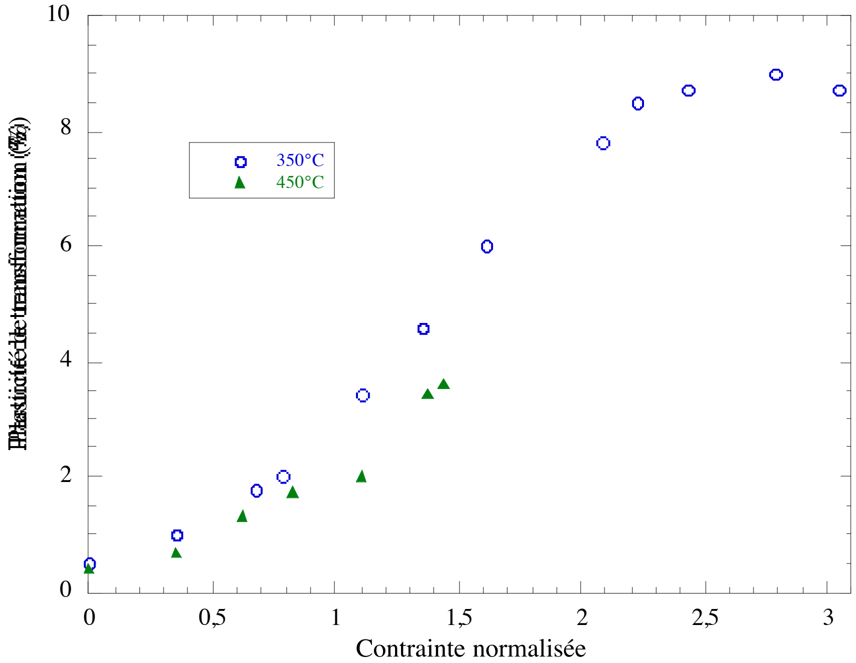
Acceleration of the transformation

PhD M Veaux 2003

Variations of times corresponding to 10% and 90% of length variation

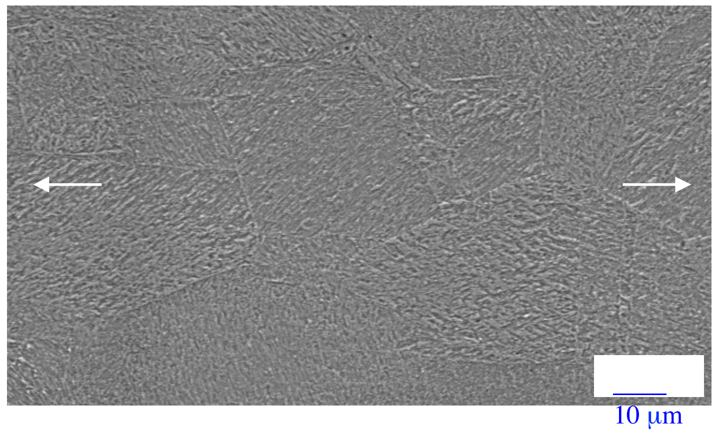


Transformation deformation versus applied stress



Acceleration of the transformation :
increase of nucleation rate and modification of growth rate

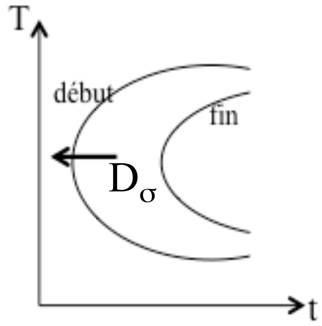
Mechanisms of transformation plasticity
- plastic accommodation of tranformation strains
- orientation of transformation product



bainite formed at 350°C under 310MPa

Phenomenological modelling of the coupling between internal stress states and transformation kinetics

During heat treatment material is under triaxial stress states, small plastic deformations



For diffusion dependent transformations

effect of plastic strain and pressure can be assumed negligible

acceleration of the transformation due to stress

$D_\sigma = \Delta t/t_0 = h(\sigma_e)$ σ_e Von Mises stress

h experimental function

Incubation period : $\tau_\sigma = \tau\,(1+D_\sigma)$

(Scheil's method)

Progress of transformation : $n_{k\sigma} = n_k$ $b_{k\sigma} = b_k/(1+D_\sigma)n_k$

(JMKA law)

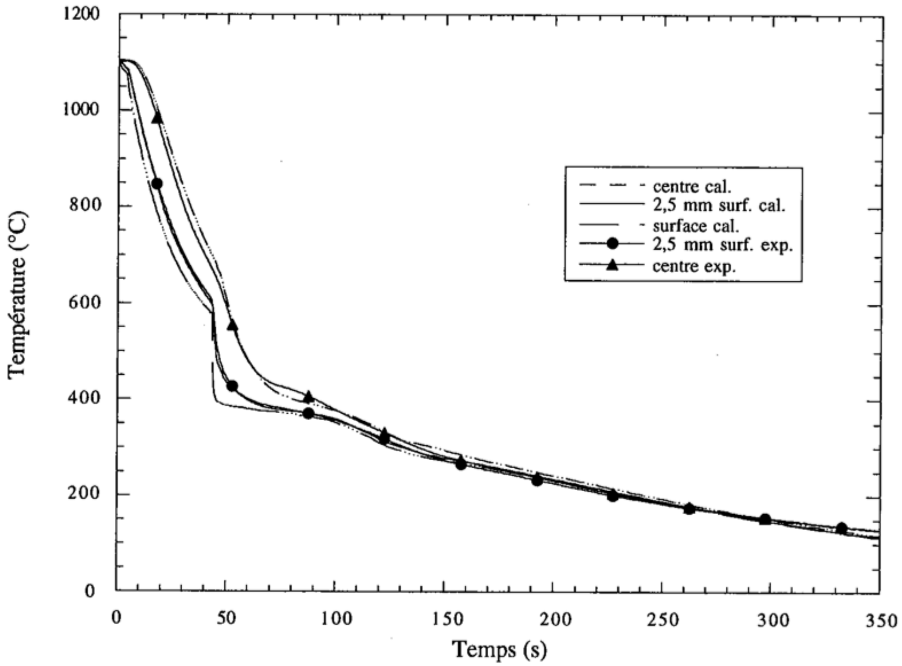
For martensitic transformation

Effect of plastic strain assumed negligible in comparison with stress effect

Variation of Ms with stress state

$\Delta M_s = A\sigma_m + B\,\sigma_e$ A and B constants (Inoue)

Ex effect of internal stress – kinetics interaction

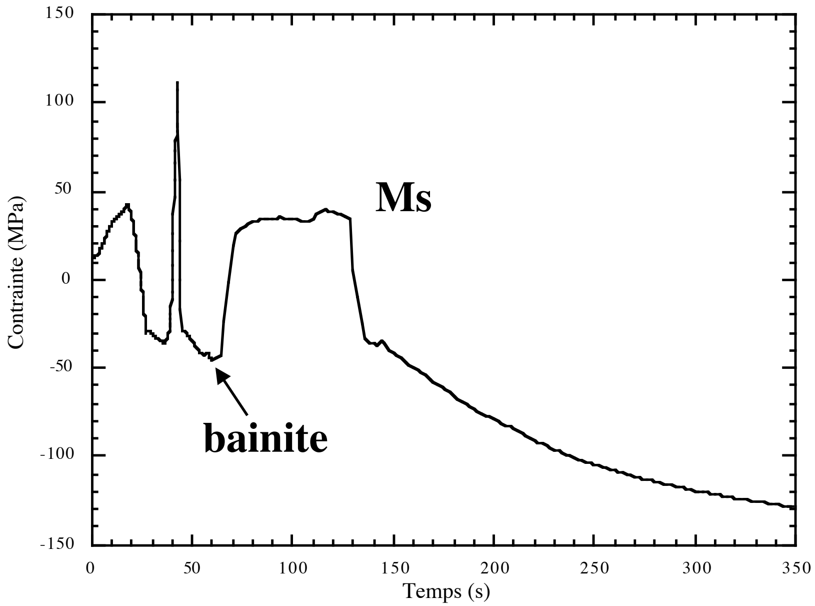


Oil quenching of cylinders
diameter 35mm length 105mm
steel 35MnV7 (*PhD M Veaux 2003)*

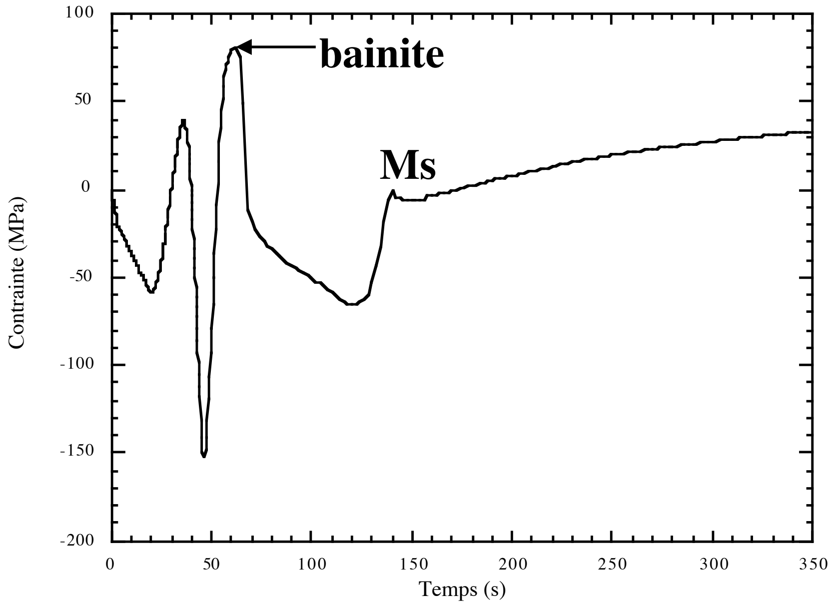
Temperature evolutions
(center and surface)

Complex stress evolutions due
to temperature gradients

Calculated axial stress versus time at the surface

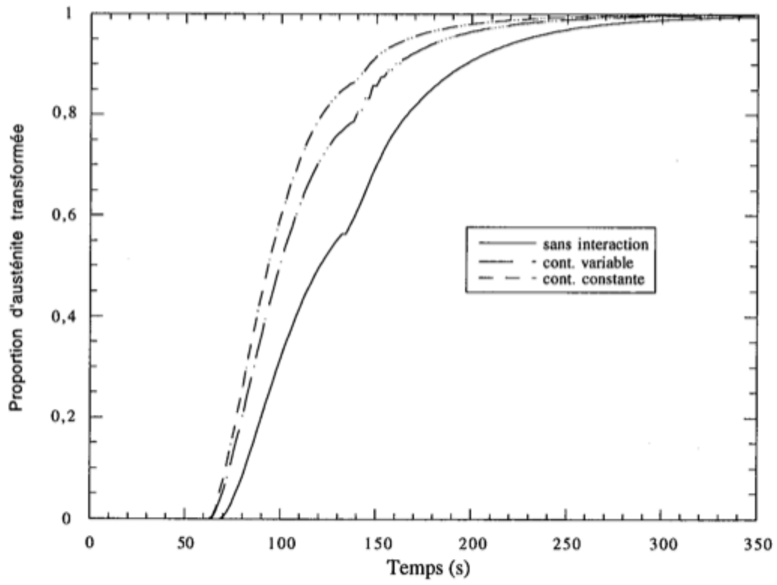


Axial stress versus time in the center

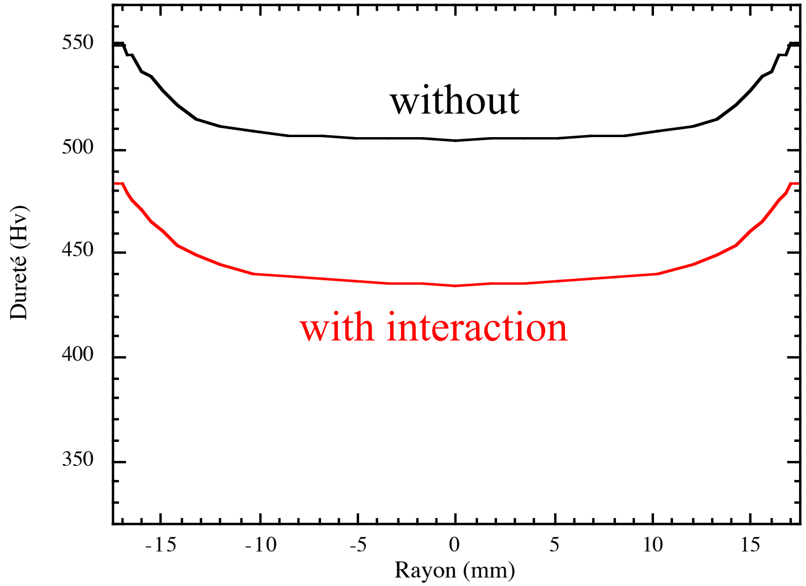


Ex. effect of the internal stress-kinetics interaction

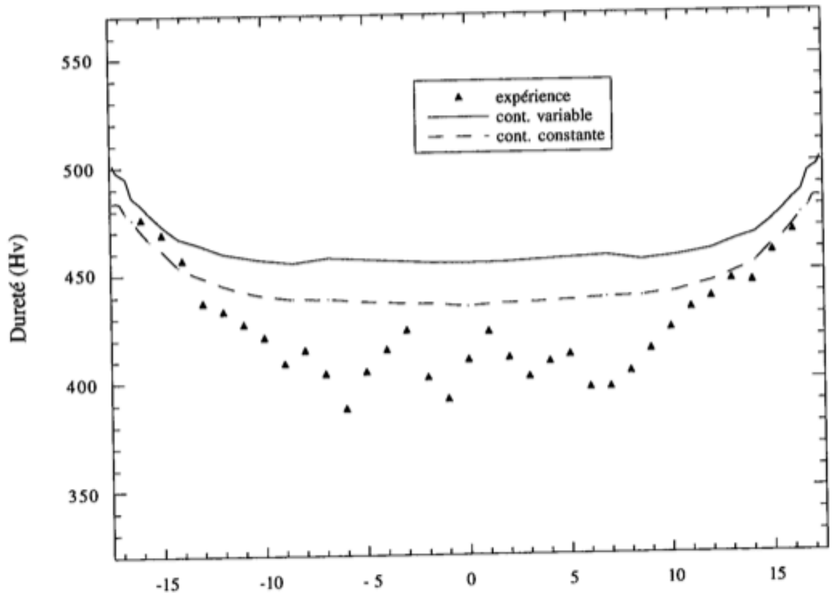
in the center



Hardness profiles



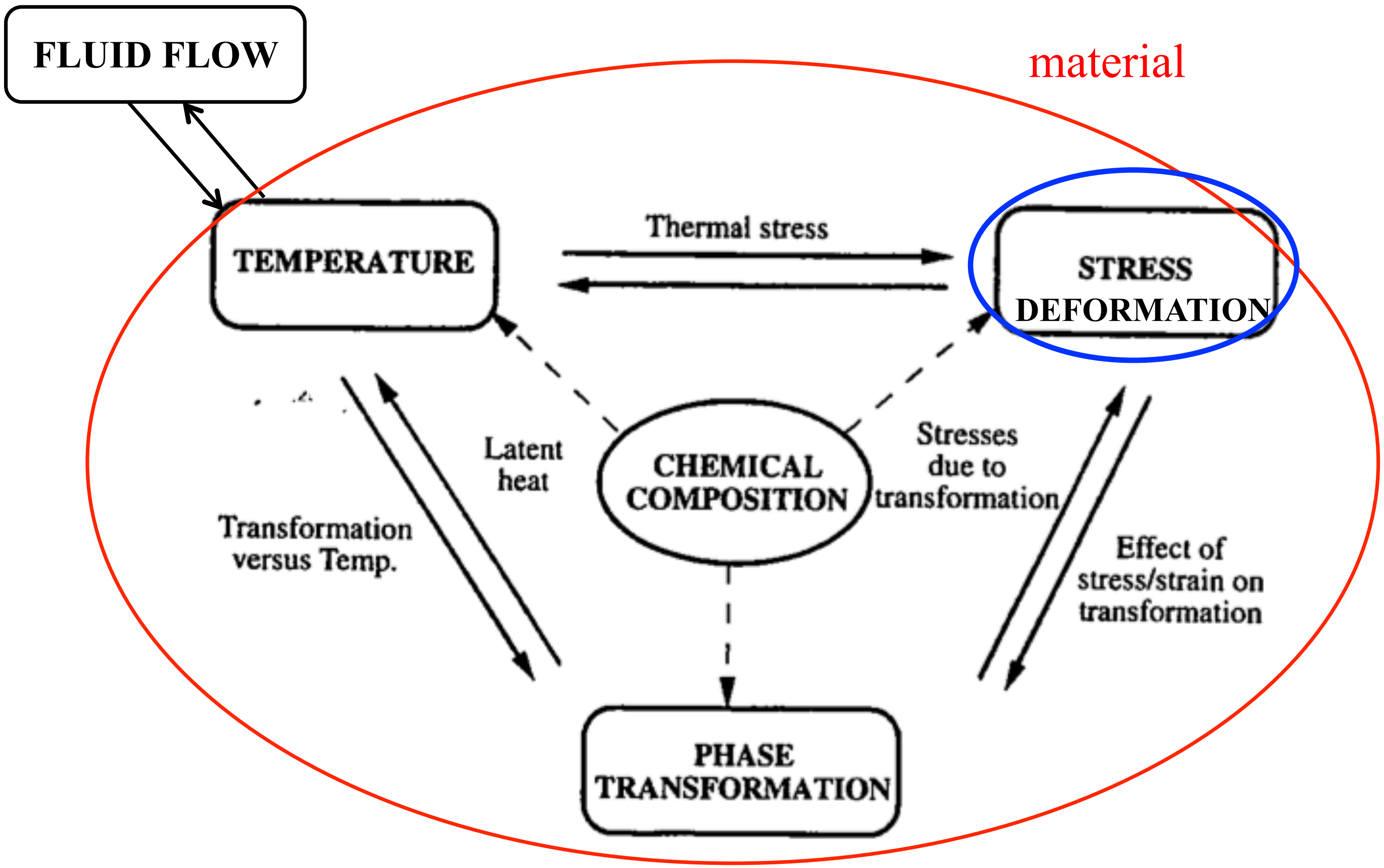
Comparison with experiment



- important effect in a massive specimen
- prediction not fully satisfactory

need of better knowledge of the effect of complex thermomechanical paths

Fluid – thermal – metallurgical – mechanical couplings in heat treatment



Calculation of stress and strain fields

Hyp. small deformations, material homogeneous isotropic
Stress equilibrium
Compatibility of deformations

Behavior law of the material

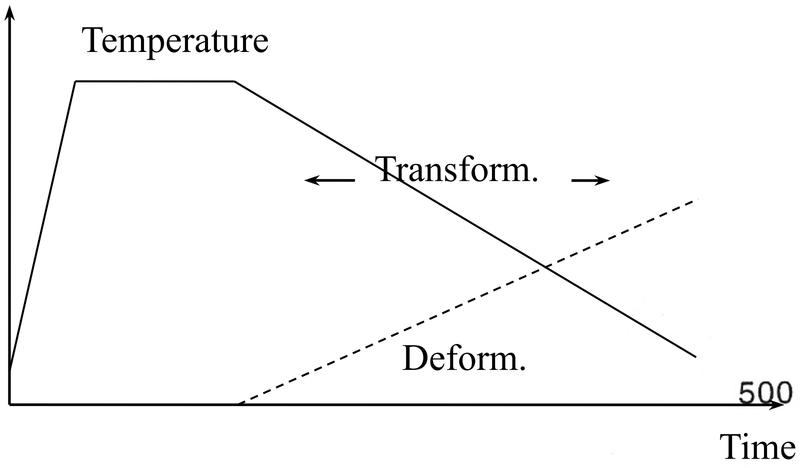
↓

Effect of phase transformations

- change of mechanical properties
- additionnal deformations : volumic variations and transformation plasticity

Thermomechanical behaviour during phase transformation

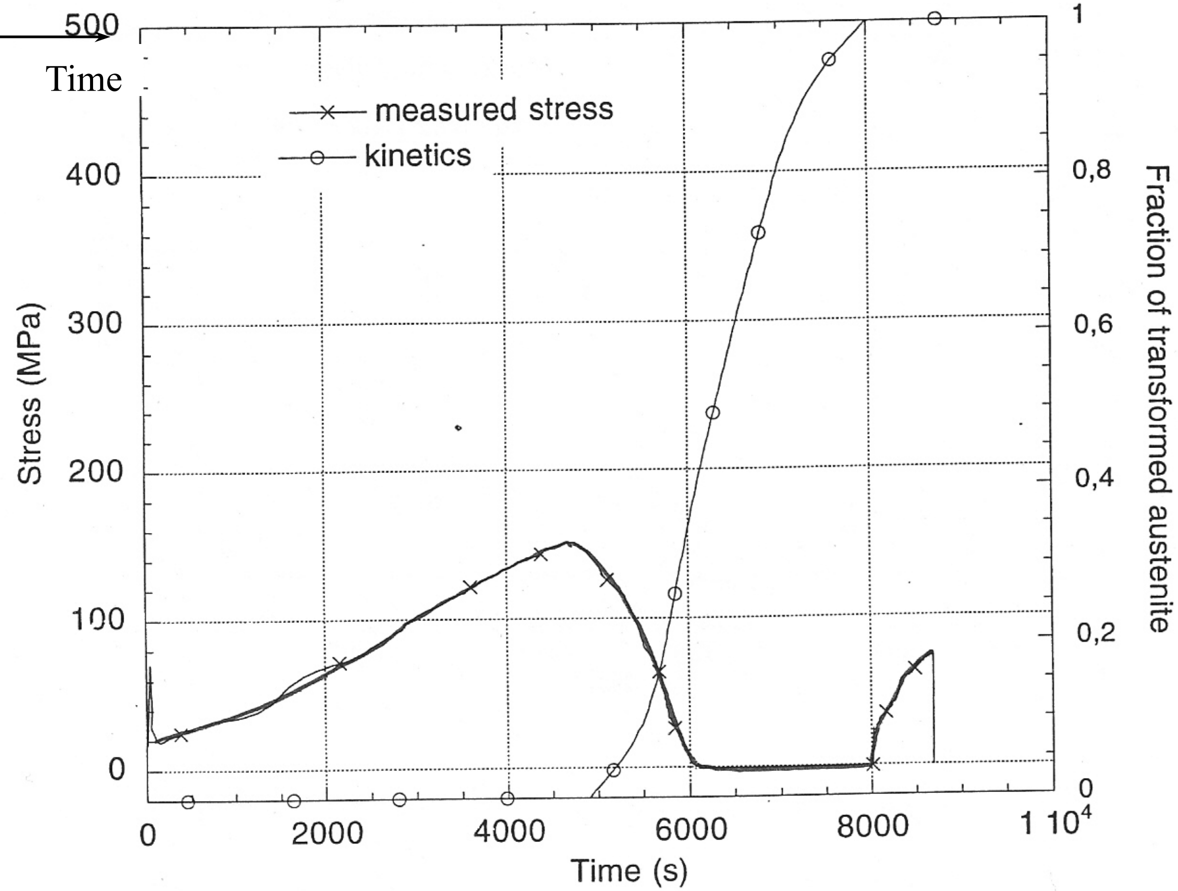
Tensile test during continuous cooling



DITHEM experiment

bainitic transformation
Steel 40CrMnMo8
Constant cooling rate

Deformation rate : 10^{-4} s^{-1}



PhD J. Ch. Louin 1998

Macroscopical phenomenological approach

Take into account the different sources of deformations

$$d\varepsilon_{ij}^{t}=d\varepsilon_{ij}^{e}+d\varepsilon_{ij}^{p}+d\varepsilon_{ij}^{th}+d\varepsilon_{ij}^{tr}+d\varepsilon_{ij}^{pt}$$

Thermal strain

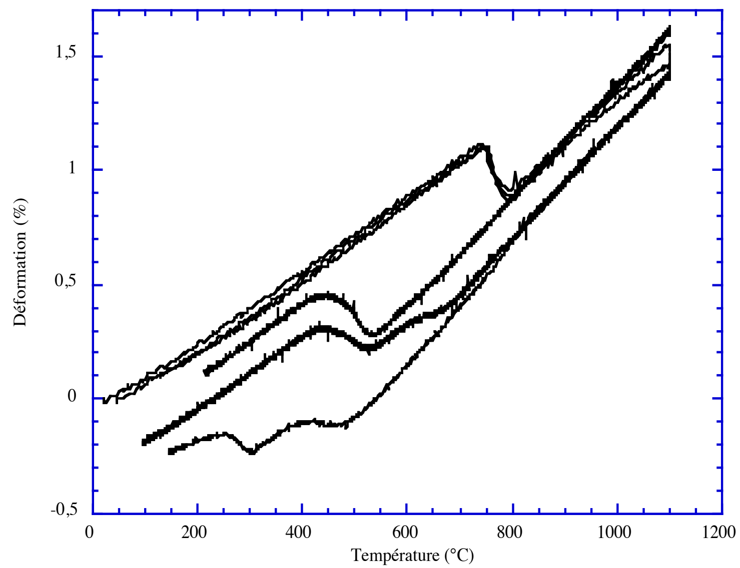
$\varepsilon_{ij}^{th} = \delta_{ij} \Sigma y_k \alpha(T) dT$

$\alpha(T)$ thermal expansion coefficients of the phases

Transformation strain (volumic variation)

$\varepsilon_{ij}^{tr} = y_k \Sigma \varepsilon_k^{tr}{}_{0°C}$

Continuous cooling dilatometry
35MnV7 steel (PhD M. Veaux)



Macroscopical phenomenological approach

$$d\varepsilon_{ij}^{t} = d\varepsilon_{ij}^{e} + d\varepsilon_{ij}^{p} + d\varepsilon_{ij}^{th} + d\varepsilon_{ij}^{tr} + d\varepsilon_{ij}^{pt}$$

Elastic strain

$d\varepsilon_{ij}^{e}$ Hooke's law E, $\nu = f$ (temperature, microstructure) Mixture law

plastic/viscoplastic strains :

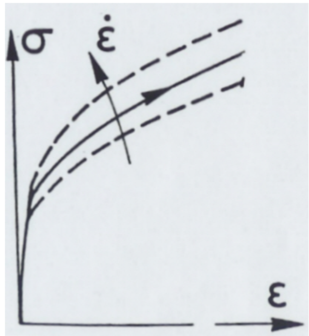
classical theory, Von Mises yield criterion and associated flow rule, isotropic-kinematic hardening rules

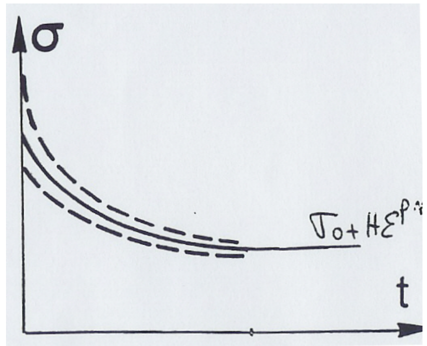
For each phase

$$\sigma_k = \sigma_{0k} + H_k\, \varepsilon_{vp}^{\,nk} + K_k\, \dot{\varepsilon}_{vp}^{\,mk}$$

$\sigma_0(T)$ threshold stress
hardening : H(T), n(T)
viscous stress : K(T), m(T)

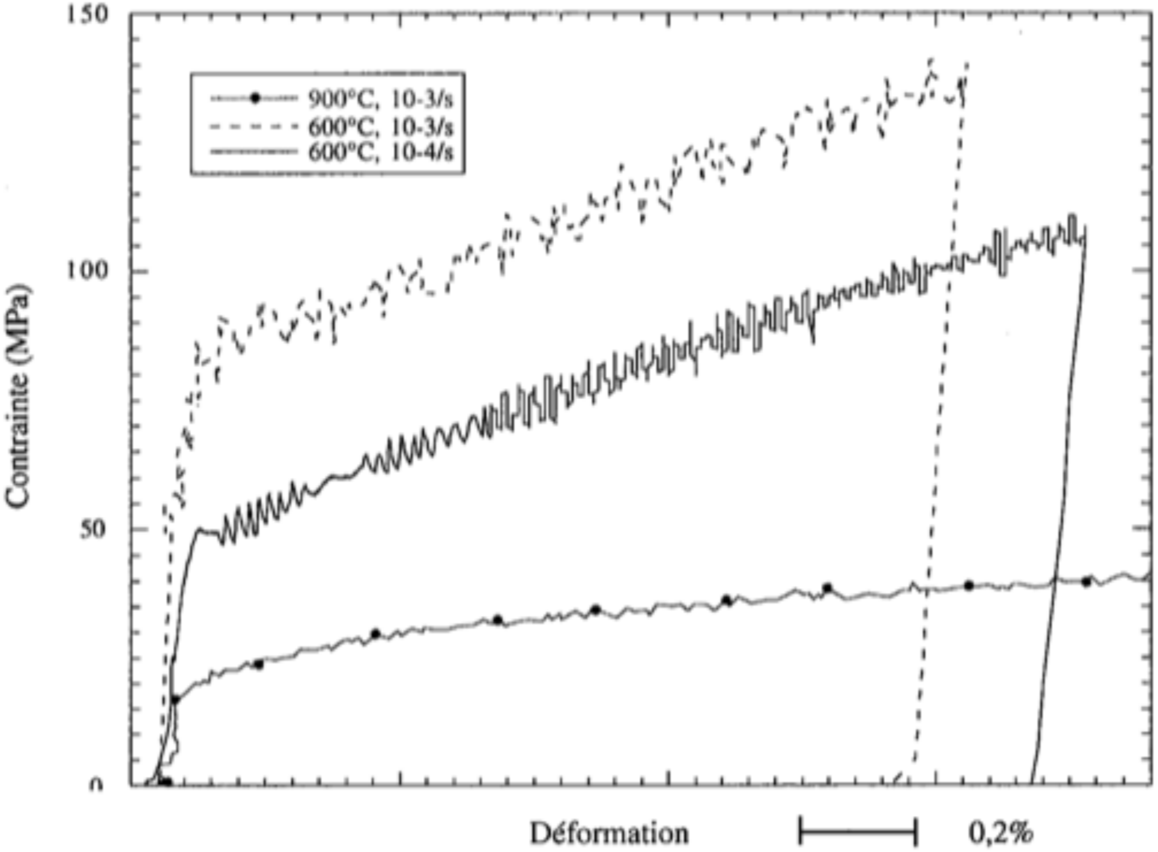
for multiphase material :
mixture law $\sigma = \Sigma y_k \sigma_k$





Thermomechanical behaviour of the different phases/constituents at different temperatures and strain rates

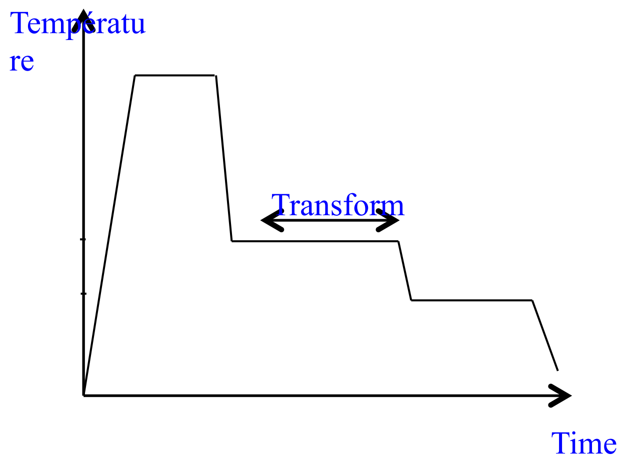
austenite 35MnV7 steel

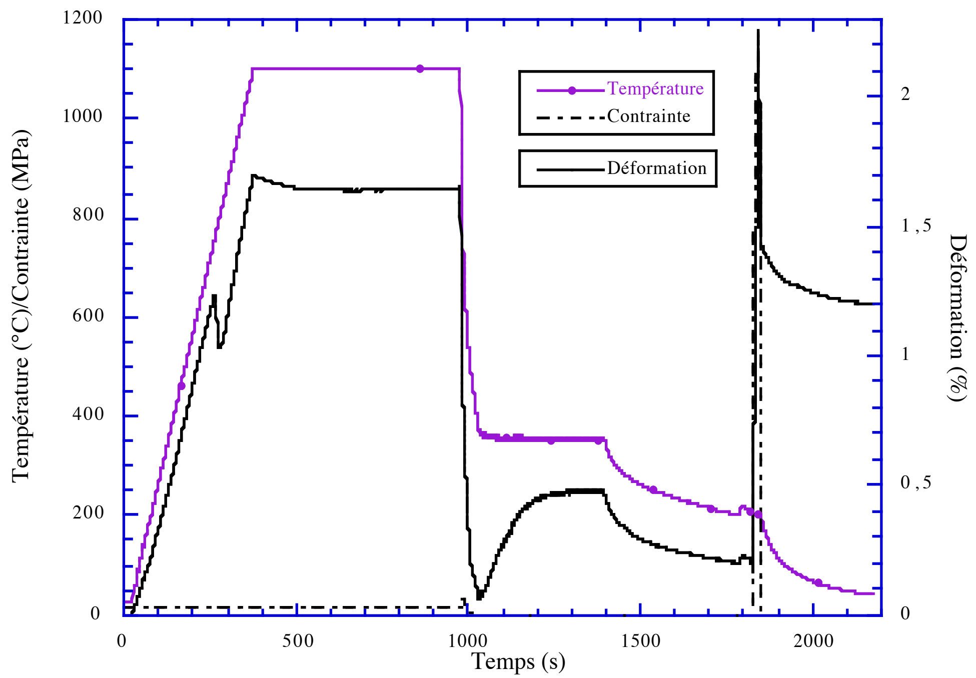


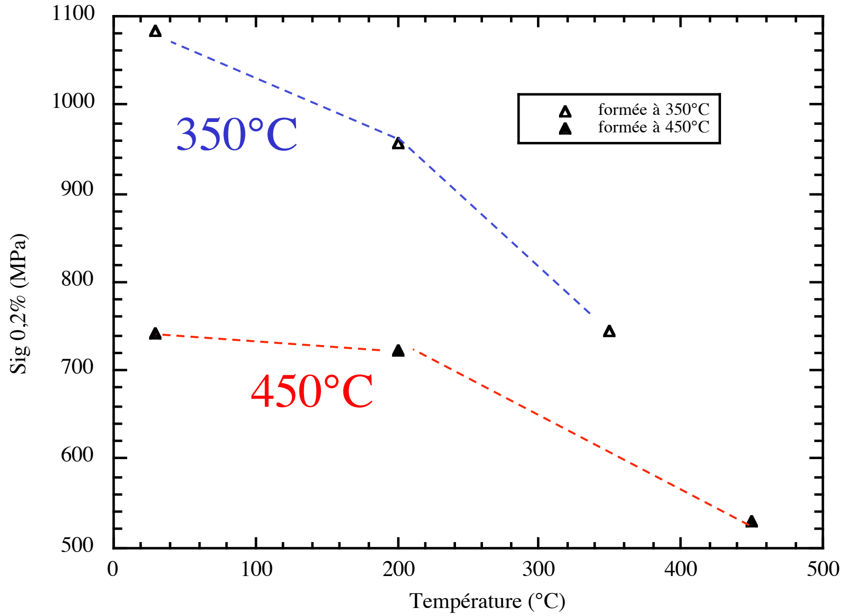
Example : thermomechanical behaviour of bainite

Steel 35MnV7 Austenitization 1100°C 10 min

Bainite formed at 350°C/450°C tensile test at 200°C, 20°C







thickness of bainite plates
0,057µm at 350°C
0,239 µm at 450°C

Yield stress (0.2%)
bainitic microstructures

Macroscopical phenomenological approach

$$d\varepsilon_{ij}^{t} = d\varepsilon_{ij}^{e} + d\varepsilon_{ij}^{p} + d\varepsilon_{ij}^{th} + d\varepsilon_{ij}^{tr} + d\varepsilon_{ij}^{pt}$$

Elastic strain

$d\varepsilon_{ij}^{e}$ Hooke's law E, ν = f (temperature, microstructure) Mixture law

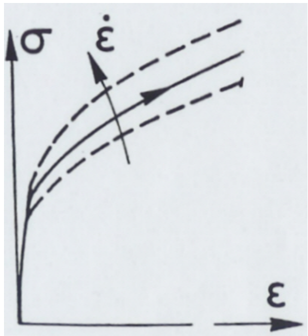
plastic/viscoplastic strains :

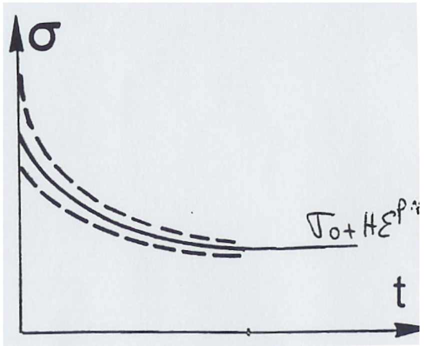
classical theory, Von Mises yield criterion and associated flow rule, isotropic-kinematic hardening rules

For each phase

$$\sigma_k = \sigma_{0k} + H_k\, \varepsilon_{vp}^{nk} + K_k\, \dot{\varepsilon}_{vp}^{mk}$$

$\sigma_0(T)$ threshold stress
hardening : H(T), n(T)
viscous stress : K(T), m(T)





for multiphase material :
mixture law $\sigma = \Sigma y_k \sigma_k$

question : strain hardening full or partial loss of memory during phase transformation?
(Sjöström, Leblond, Taleb…)

Modelling of transformation plasticity

- Phenomenological approach:

Experimental evolution law (uniaxial stress) : $\varepsilon^{pt} = K_k \sigma f(y_k)$

Generalization to triaxial stress states : **assumption $d\varepsilon^{pt}$ proportional to stress deviator** *Giusti*

$$d\varepsilon^{pt}_{ij} = 3/2 \; K_k f'(y_k) dy_k \, s_{ij}$$

holds when the mechanism only plastic accommodation

For diffusional transformation :

- no experimental results under mutiaxial stresses
- validation by micro - macro approaches *Leblond, Fischer, Sjöström, Ganghoffer, Barbe*

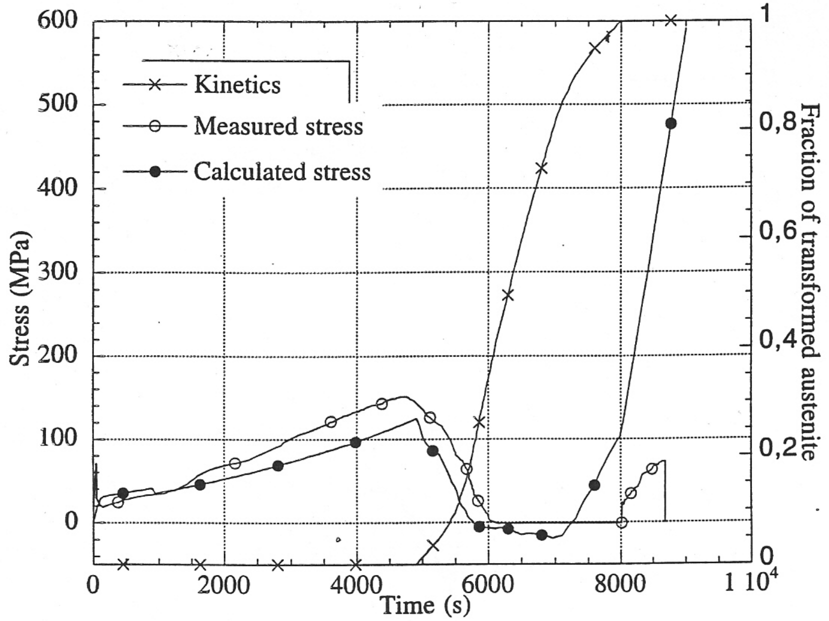
For martensitic transformation :

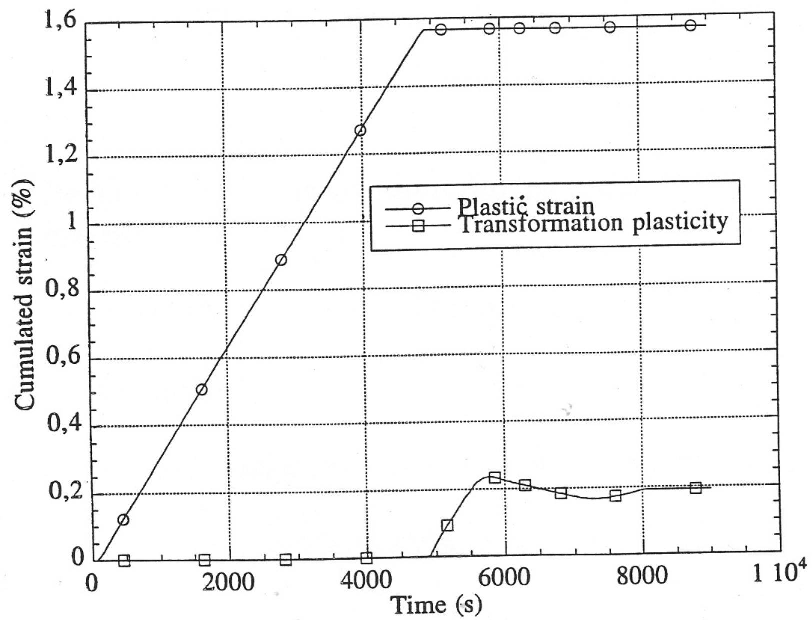
- experimental results : transform. plasticity larger under tensile stress than under compressive stress *Videau*
- micromechanical approach show clearly strong dependency on local stresses *Wen*

⟶ *formulation of a macroscopical law still an open question (N phase model, Cailletaud 2004)*

Experimental validation of the macroscopical behaviour law for steel

$$d\varepsilon_{ij}^{t} = d\varepsilon_{ij}^{e} + d\varepsilon_{ij}^{p} + d\varepsilon_{ij}^{th} + d\varepsilon_{ij}^{tr} + d\varepsilon_{ij}^{pt}$$





PhD J. Ch. Louin

Modelling of the thermomechanical behaviour during precipitation

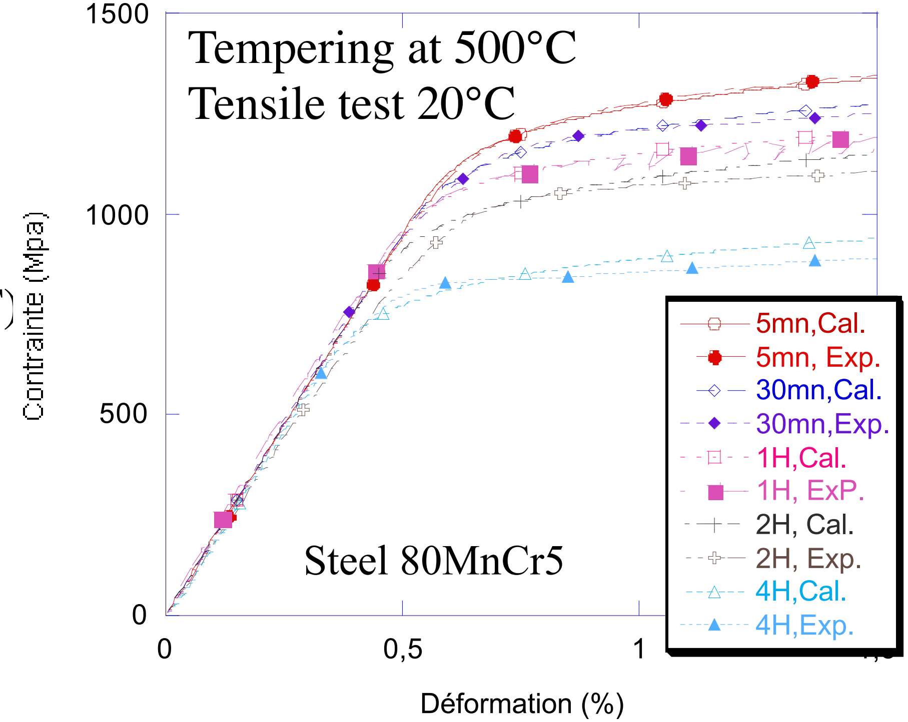
thermoelastoviscoplastic behaviour law

$$\sigma = \sigma_0 \quad + H\,\varepsilon_{vp}^{\,n} \quad + K\,\dot{\varepsilon}_{vp}^{\,m}$$

hardening = f(T)

viscous stress = f(T)

threshold stress



$$\sigma_0 = \sigma_{Fe} + \sigma_{ss} + \sigma_P + \sigma_{disl.}$$

σ_{Fe} friction stress f (T)

σ_{ss} solid solution hardening f (T, composition ss)

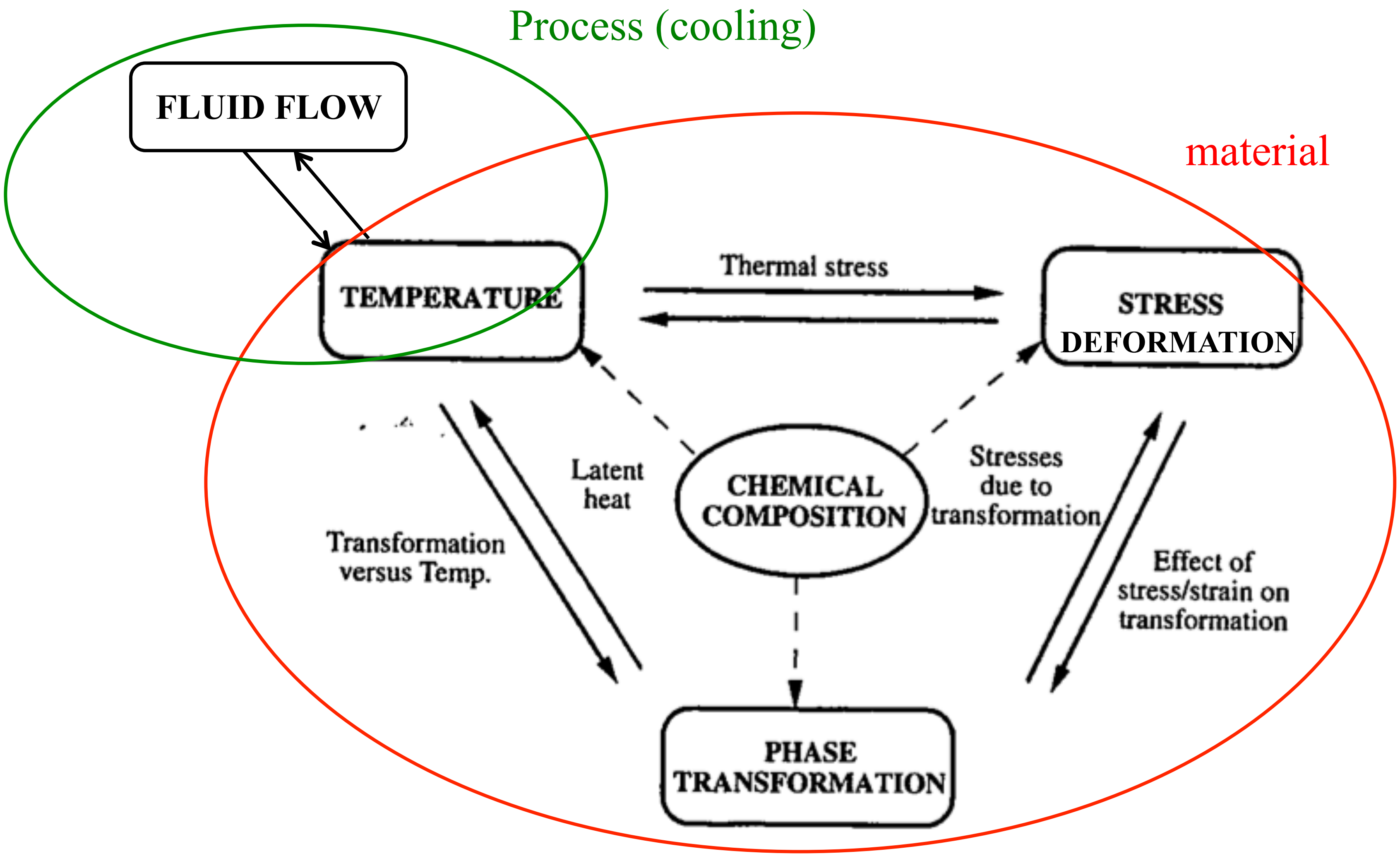
Precipitation model

σ_P precipitation hardening f (T, volume fractions and sizes of precipitates)

$\sigma_{disl.}$ hardening due to dislocation densities f (T, t)

PhD Godard 1999 (Al) PhD Y. Wang 2006 (steel)

Fluid – thermal – metallurgical – mechanical couplings in heat treatment



Modelling of heat transfer in the solid

Heat conduction equation : $\mathrm{div}\,(\lambda \,\mathrm{grad}T) + q^{tr} = \rho c_p\, \delta T/\delta t$

- q^{tr} power density associated with phase transformations

$$q^{tr} = \sum \Delta H_k\, dy_k/dt$$

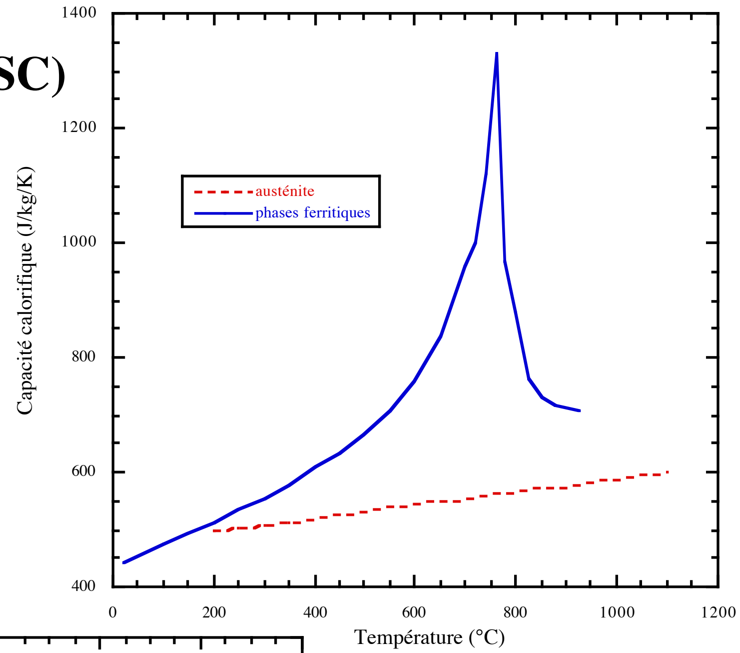
- mixture laws for thermophysical properties

$\lambda = \sum \lambda_k y_k$ $\quad c_p = \sum c_{pk} y_k$ $\quad \rho = \sum \rho_k y_k$ $\quad y_k$ volume fraction of phase k

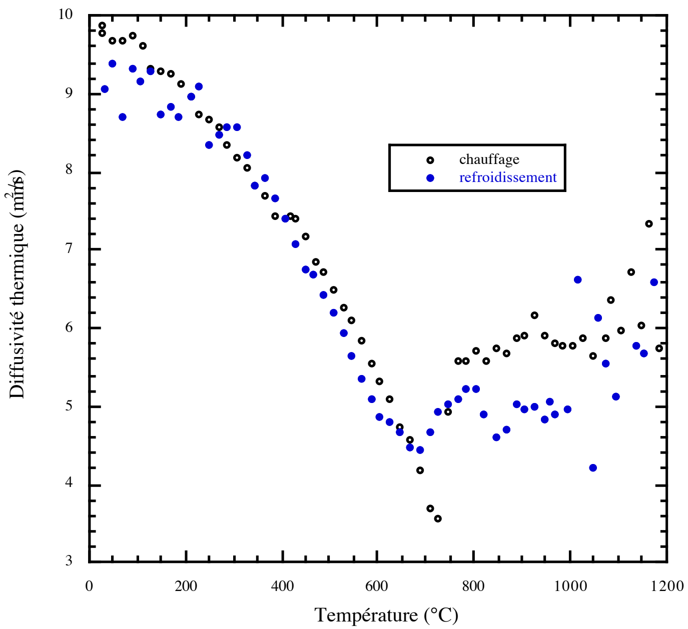
Thermophysical properties

Example : steel 35MnV7

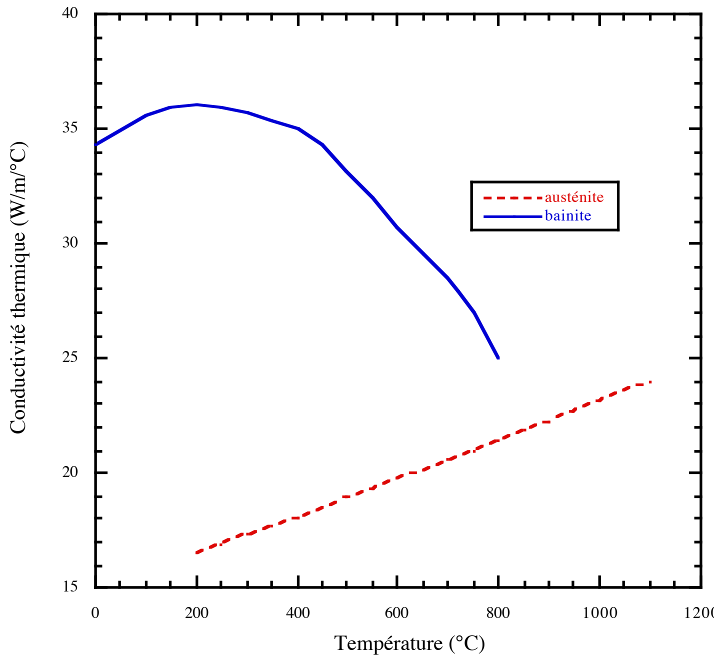
Specific heat (DSC)



Thermal diffusivity (« flash method »)



Thermal conductivity



Modelling of heat transfer in the solid

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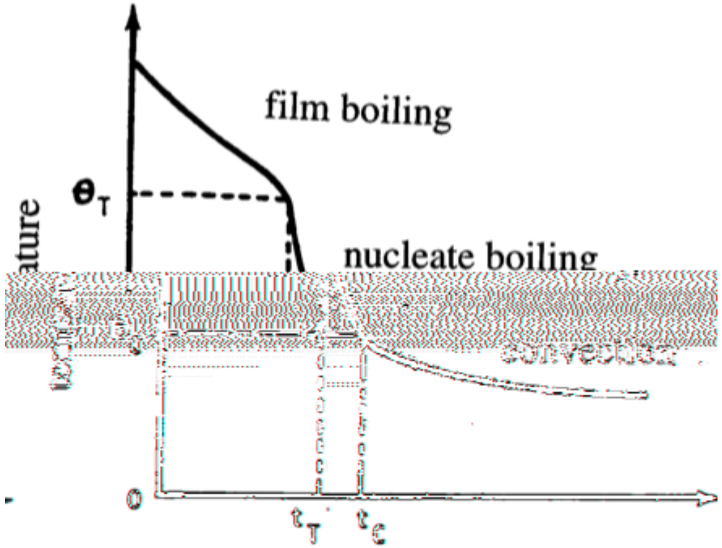
$\lambda = \sum \lambda_k y_k$ $\quad c_p = \sum c_{pk} y_k$ $\quad \rho = \sum \rho_k y_k$ $\quad y_k$ volume fraction of phase k

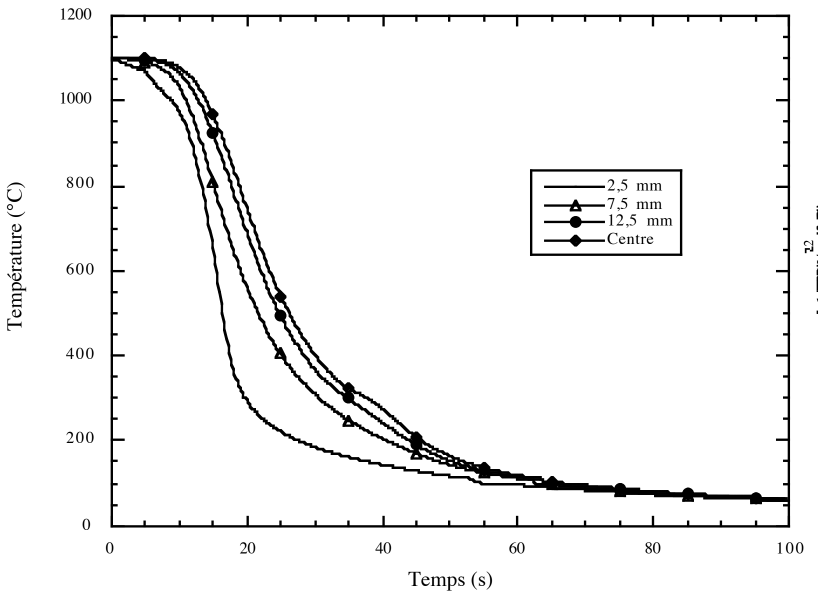
- surface boundary condition for quenching :
  $\Phi = -\lambda\,(\partial T/\partial n) = h\,(T_S - T_\infty)$

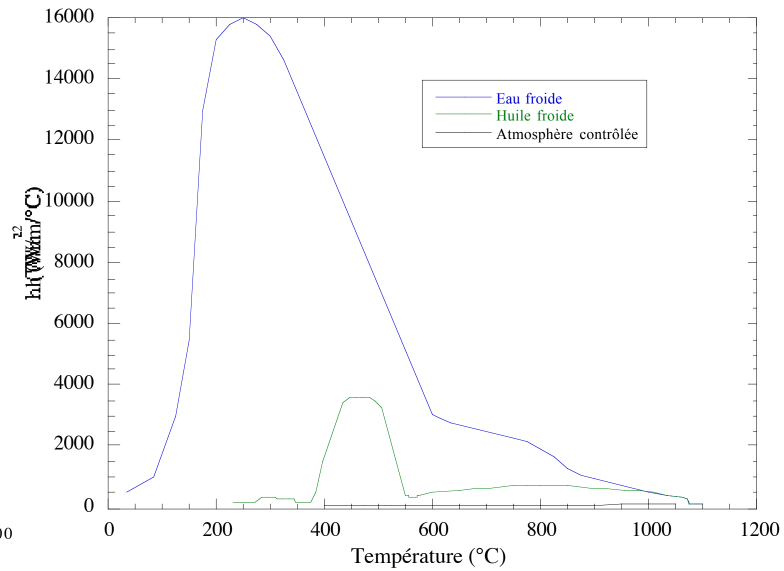
Heat transfer in vaporizable fluids (water, oil, …)



h (surface temperature, temperature and agitation of the bath, surface state, position of the piece …) difficult to determine ⟶ inverse methods

Ex : quenching in cold water (cylinder diameter 35mm length 105 mm steel 35MnV7





PhD Veaux

Modelling of heat transfer in the solid

Heat conduction equation : $\mathrm{div}\,(\lambda \mathrm{grad} T) + q^{tr} = \rho c_p\, \delta T/\delta t$

- q^{tr} power density associated with phase transformations $\quad q^{tr} = \sum \Delta H_k\, dy_k/dt$

- mixture laws for thermophysical properties

$\lambda = \sum \lambda_k y_k \qquad c_p = \sum c_{pk} y_k \qquad \rho = \sum \rho_k y_k \qquad$ y_k volume fraction of phase k

- surface boundary condition for quenching :

$\Phi = -\lambda\, (\partial T/\partial n) = h\, (T_S - T_\infty)$

most often : inverse methods to determine h(Ts)
(due to the complexity of heat transfer mechanisms
particularly in vaporizable fluids)

Promising approaches : coupling with fluid flow simulations

⟹ gaz quenching

⟹ heating in furnace

Modelling of flow and heat transfer in the gaz (code Fluent)

Solution of equations
- Navier-Stokes
- continuity
- heat transport
- turbulence transport : chosen model : k-ω

thermophysical properties of gaz: dynamic viscosity, thermal conductivity, density, specific heat

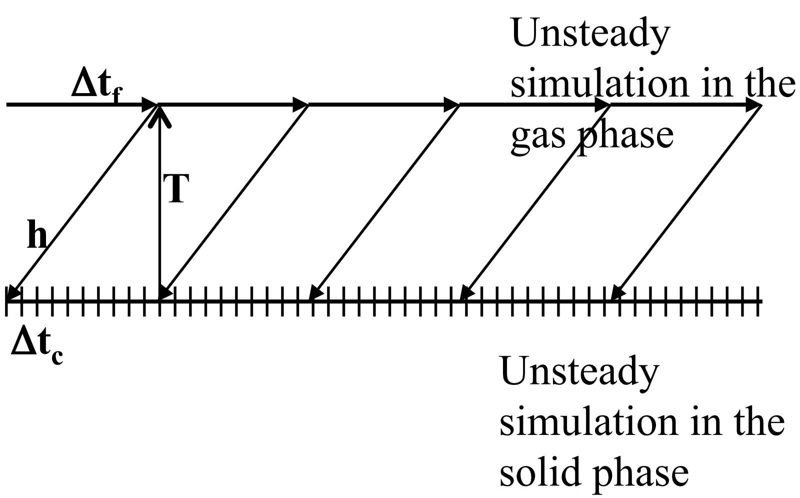
Prediction of the local wall heat transfer coefficient distributions

surface boundary condition for the solid :

$$\Phi_{loc} = -\lambda\,(\partial T/\partial n) = h_{loc}\,(T_p - T_\infty)$$

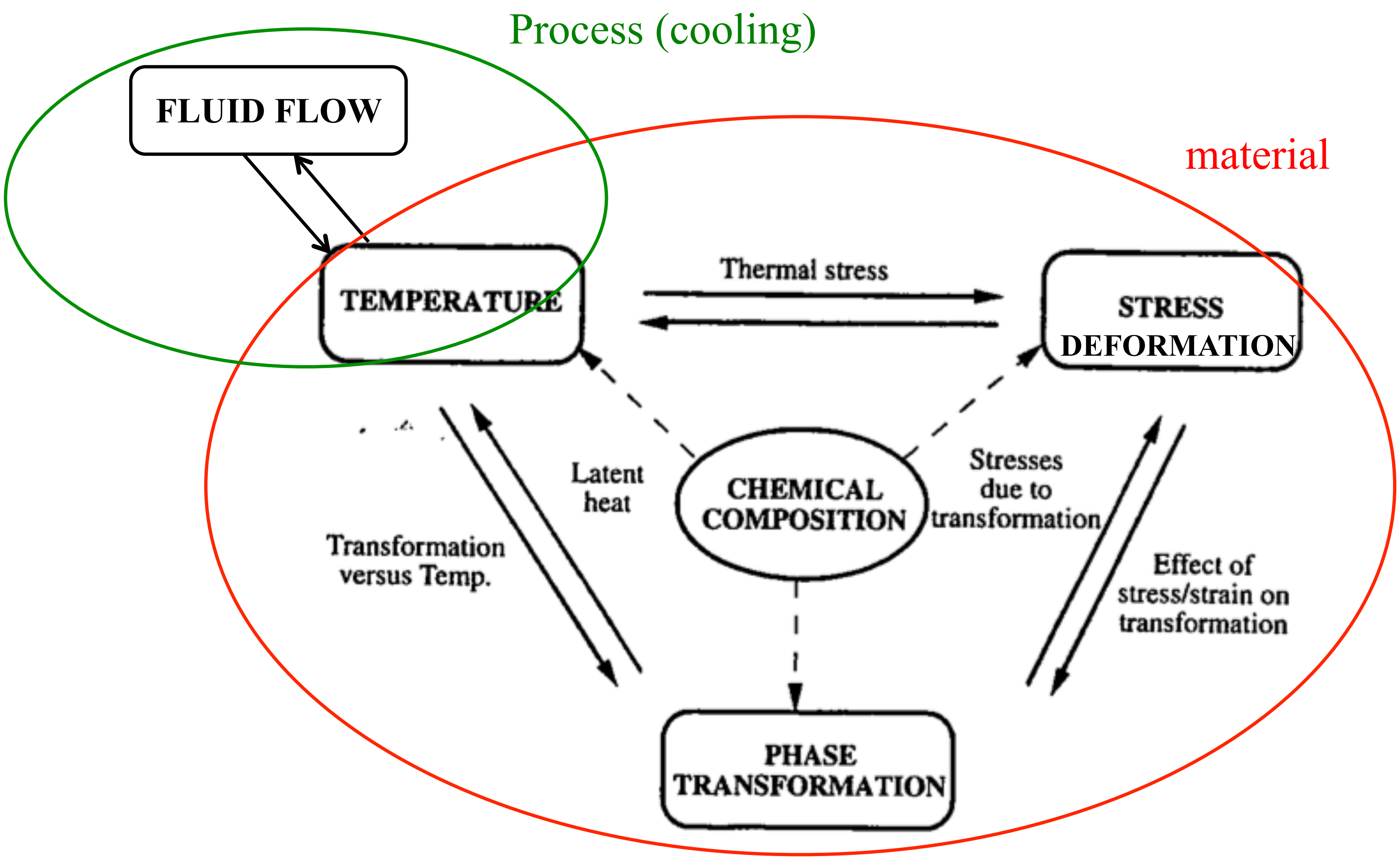
Coupling with simulations in the solid

Coupling between FLUENT and SYSWELD



J.F. Douce, J.P. Bellot, S. Denis, F. Chaffotte, G. Pellegrino HTM 61 (2006)

Fluid – thermal – metallurgical – mechanical couplings in heat treatment

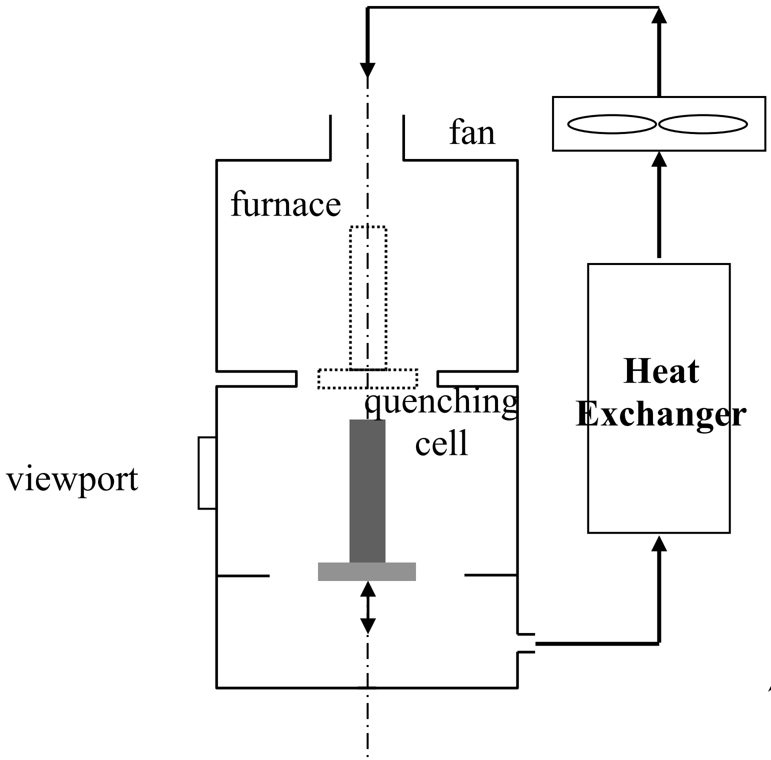


2 examples : gaz quenching

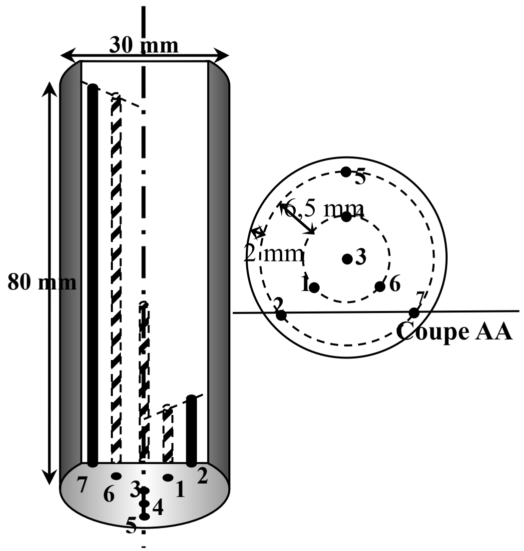
quenching and tempering

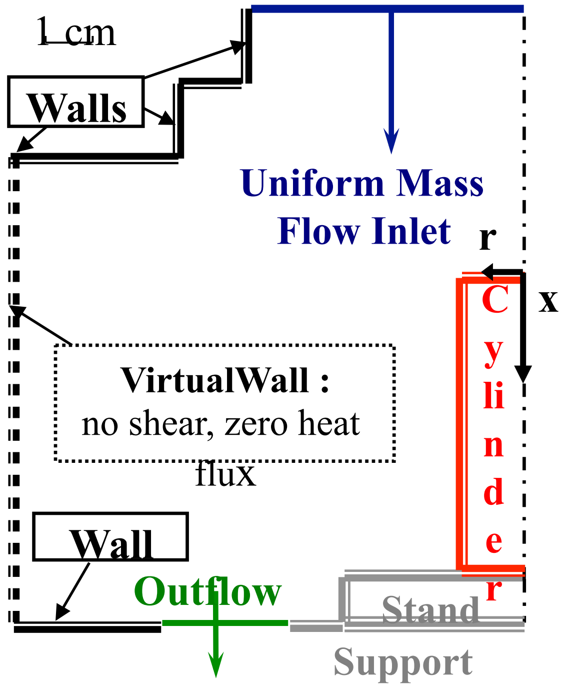
Application example : gaz quenching

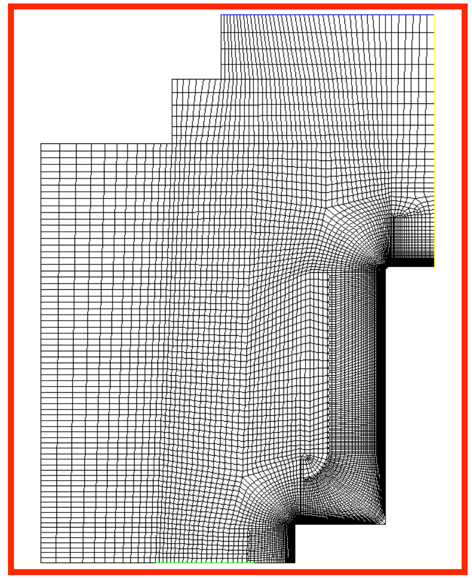
Experimental device from Ecole des Mines d'Albi



- nickel
- 27MnCr5 steel

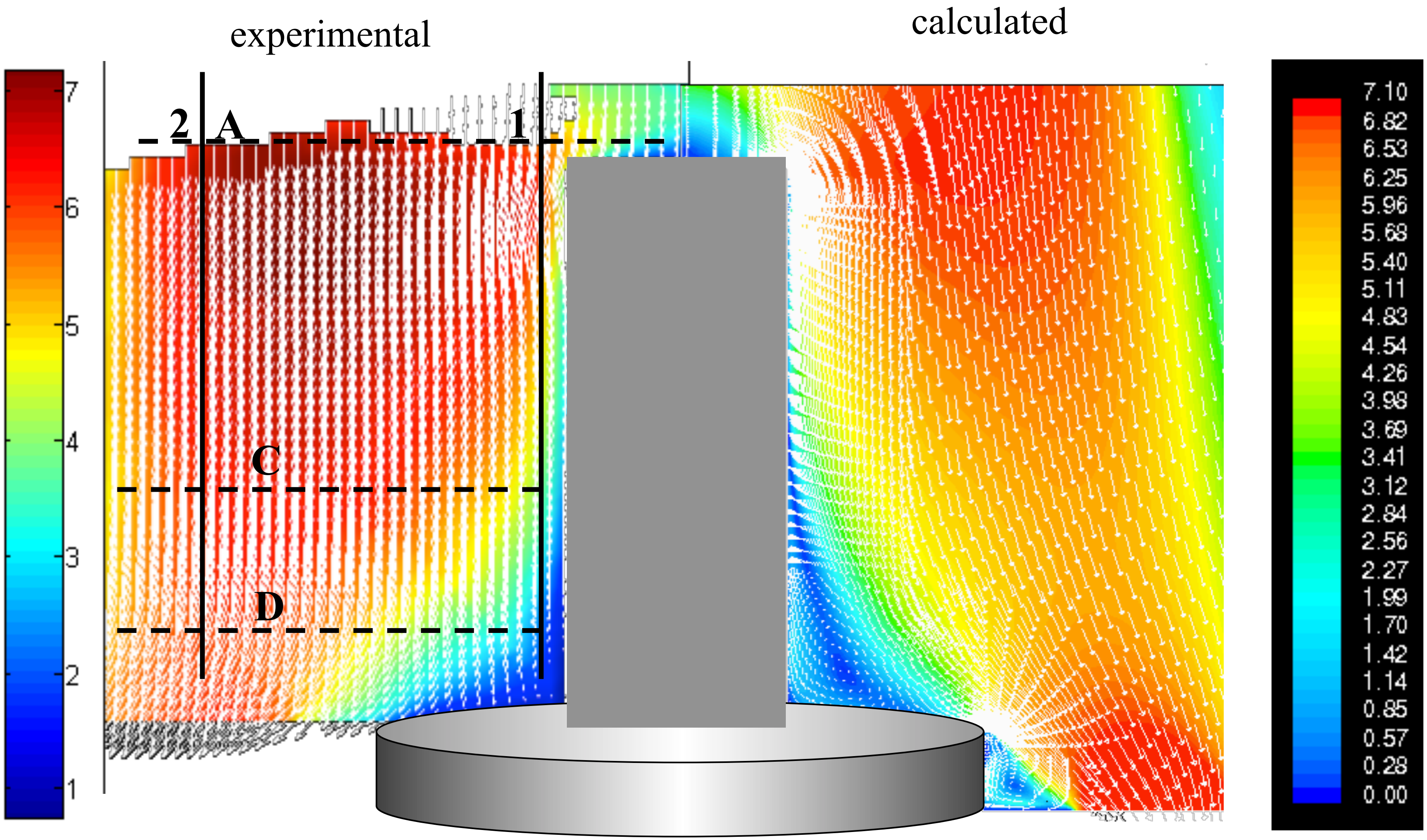






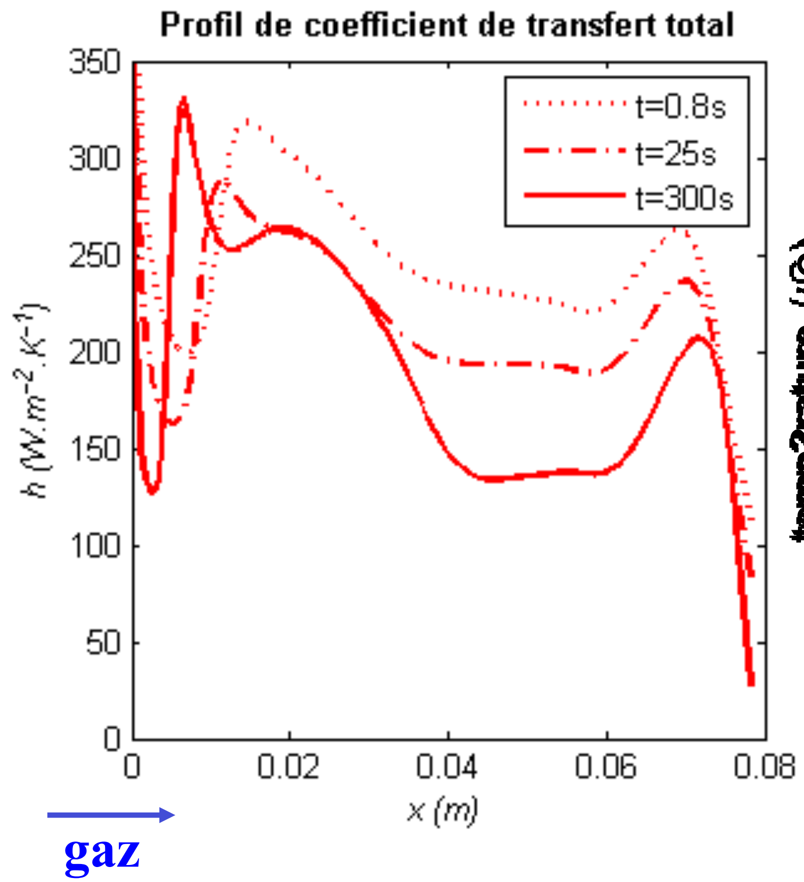
J.F. Douce, J.P. Bellot, S. Denis, P. Lamesle, F. Gouhinec, F. Chaffotte, G. Pellegrino, Int. J. Microstructures and Material Properties Vol.3, n°1, 2008

4.5 bar helium gaz quenching velocity vectors

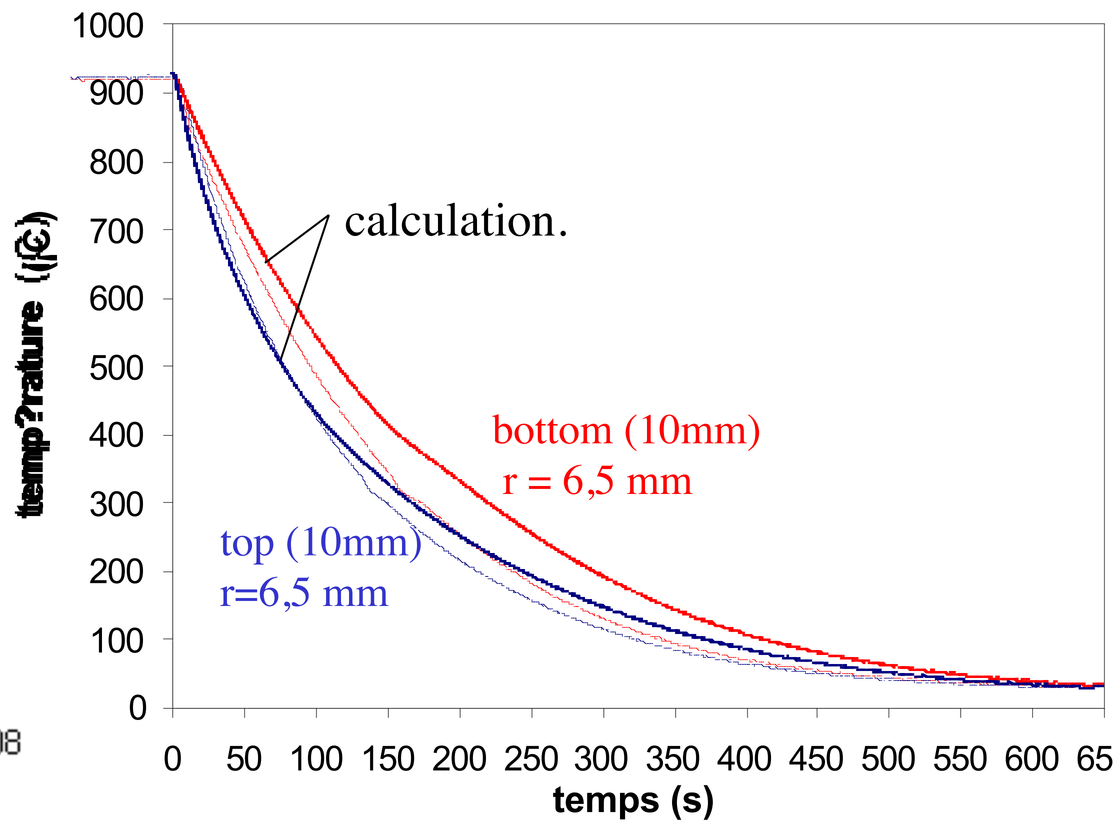


4.5 bar helium gaz quenching of a nickel cylinder

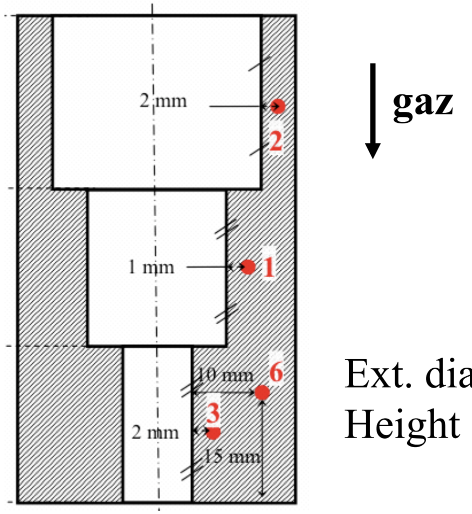
Heat transfer coefficient distribution along lateral surface



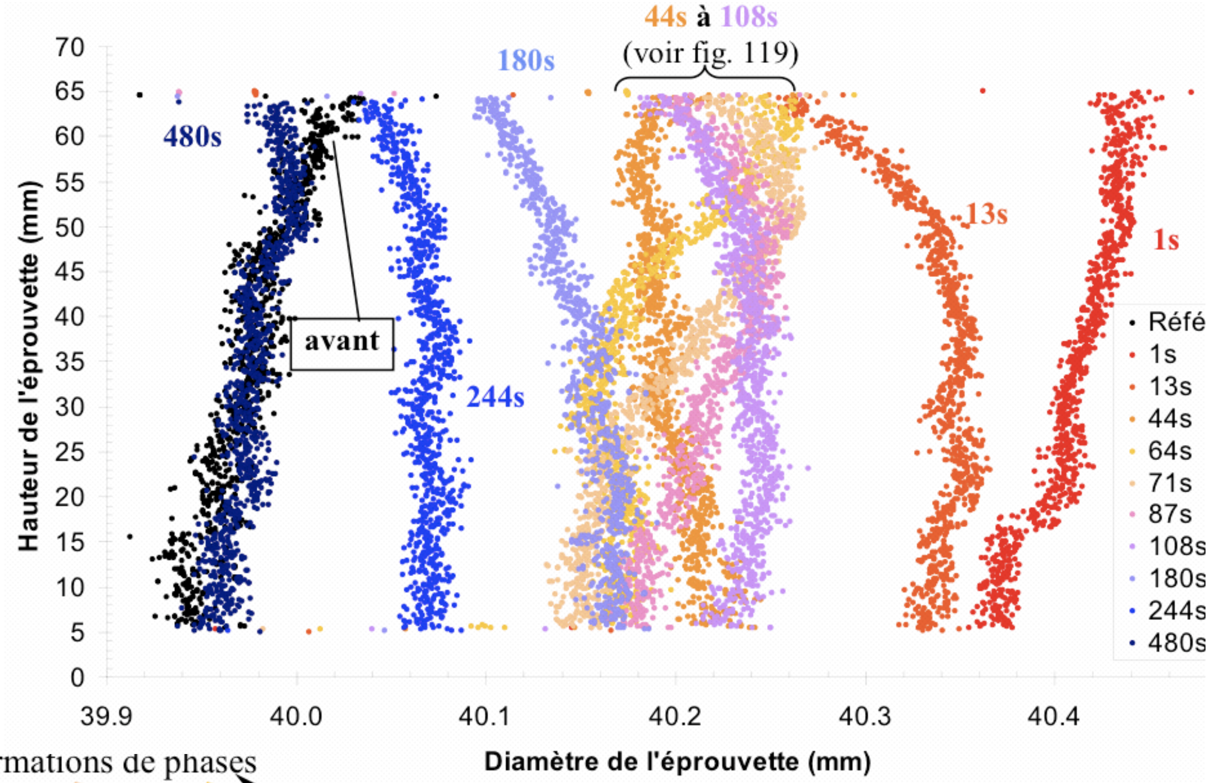
Temperature evolutions measured- calculated

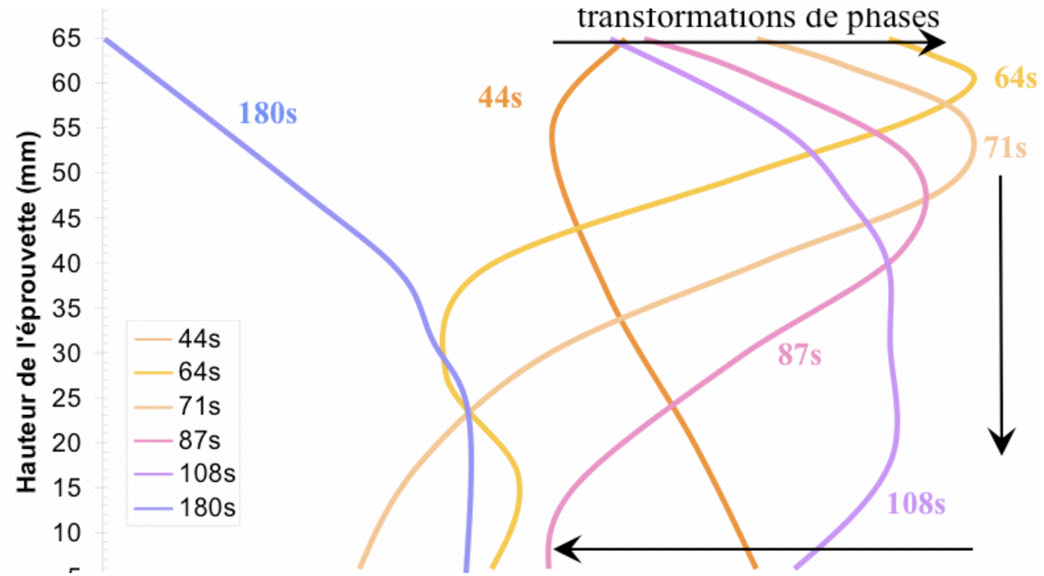


In-situ measurements of the deformation



Ext. diam. : 40mm
Height : 70mm

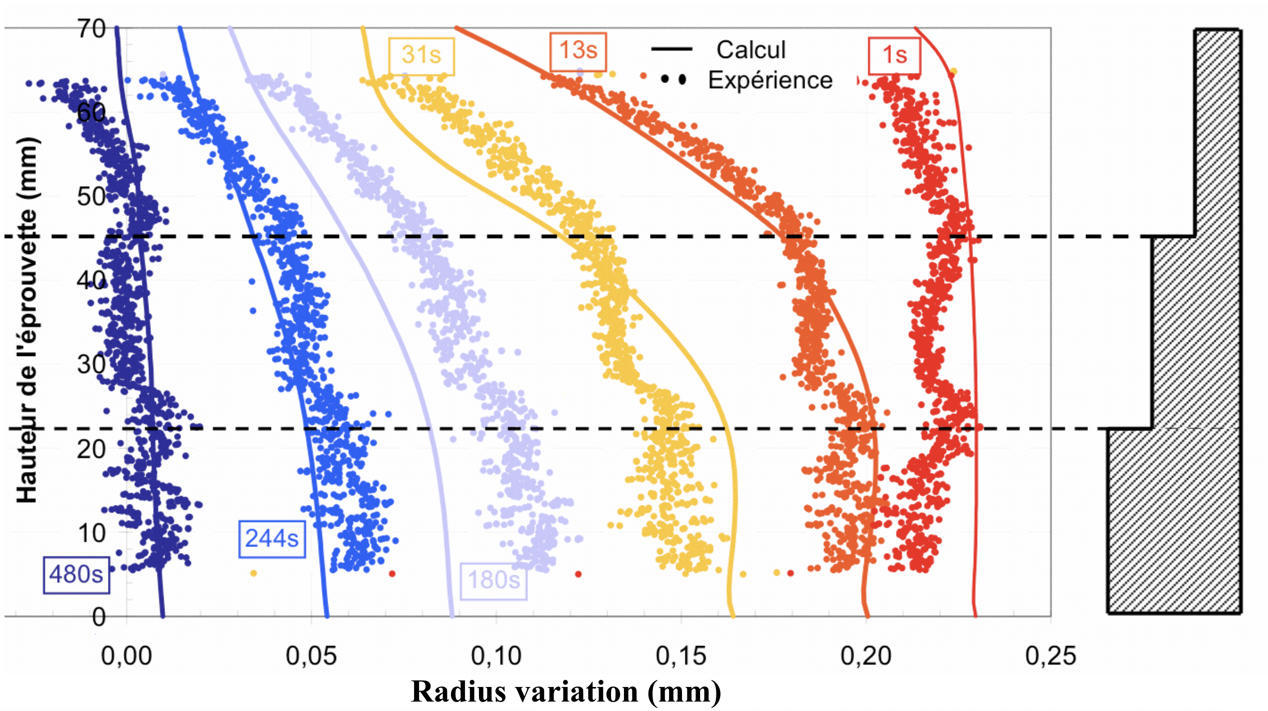


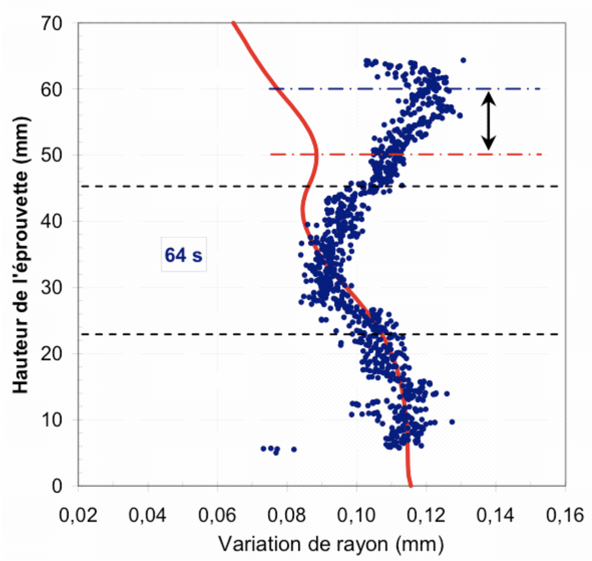


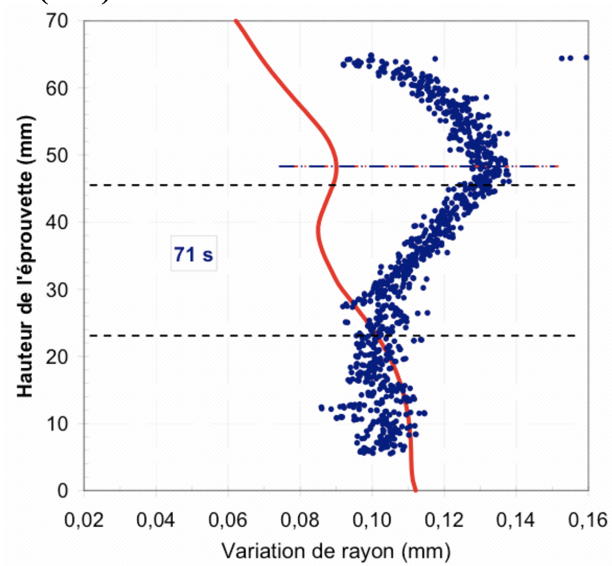
27MnCr5 steel

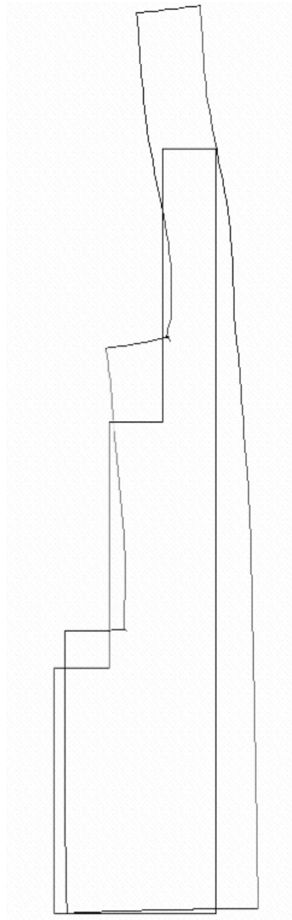
Dissertation J.F. Douce, 2008

Comparison measurements - calculation



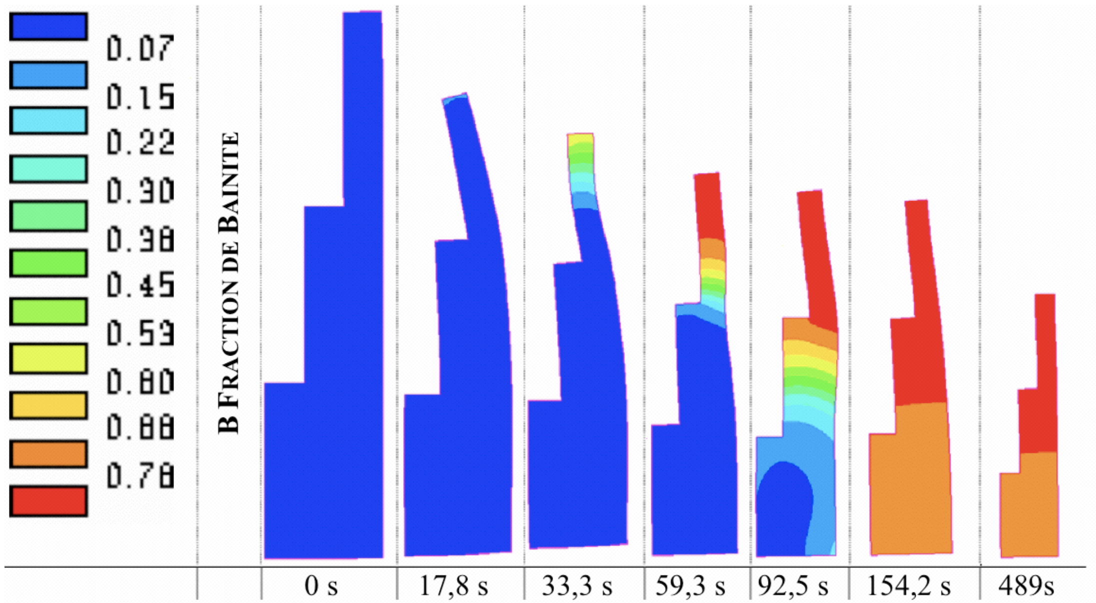




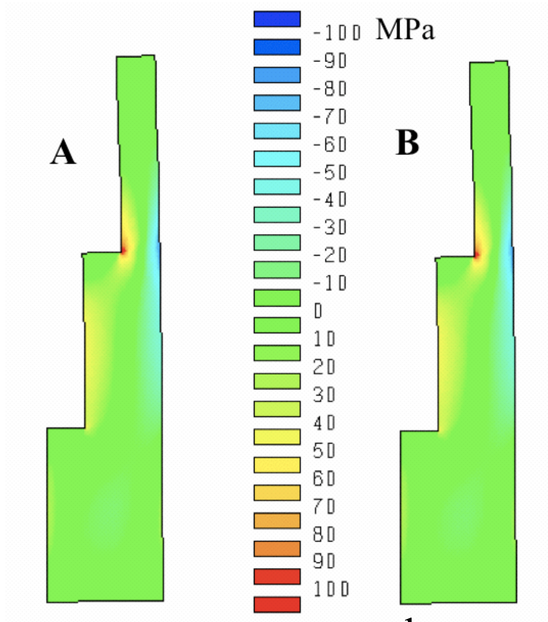


Final shape

Distributions of microstructures



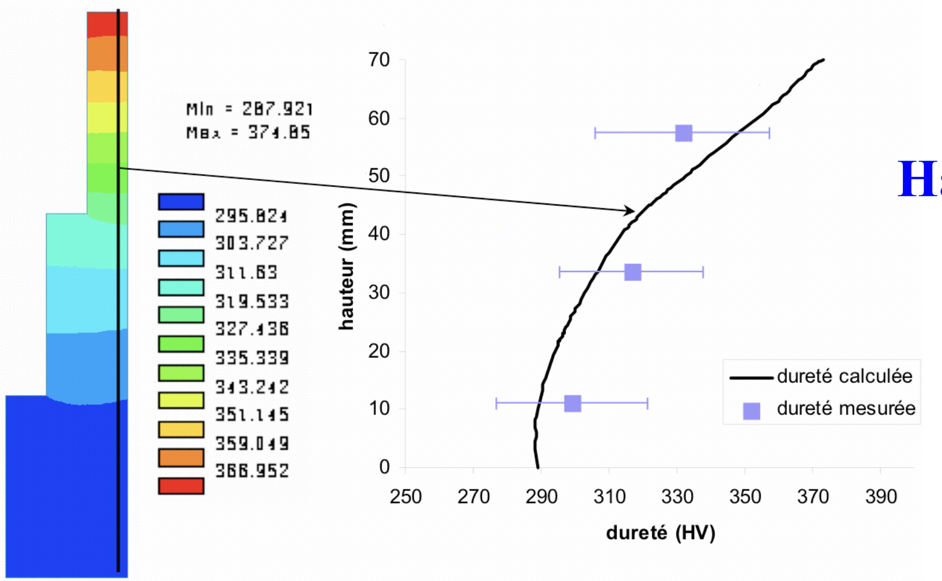
Residual stresses



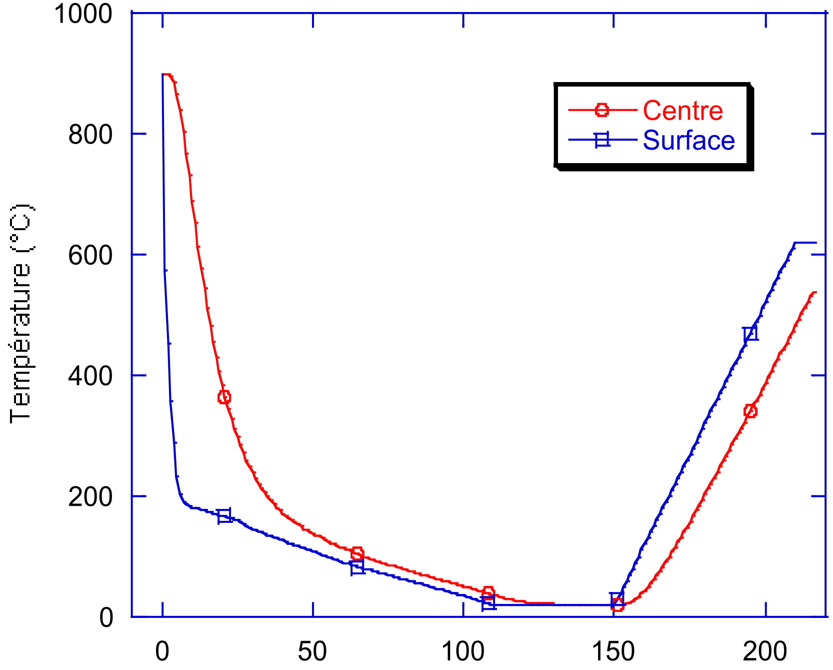
axial stress

hoop stress

Hardness

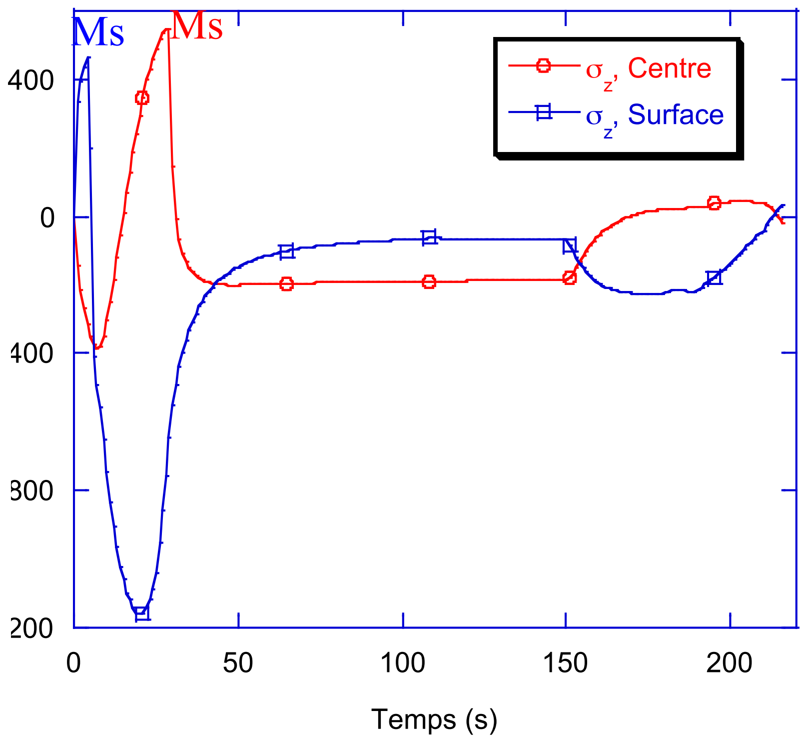


Chain different processes : quenching + tempering (FE code ZeBuLon)

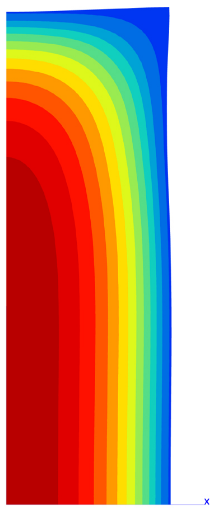


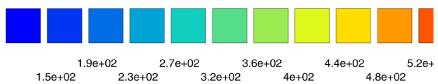
cylinder Φ 35mm L 105 mm
steel 60NiCrMo11
martensitic quenching from 900°C to 20°C
tempering 10°C/s 600°C

Axial stress evolution

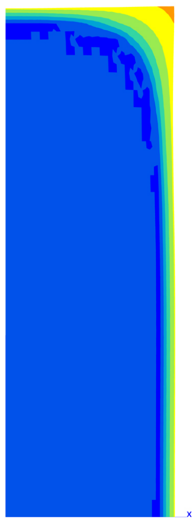


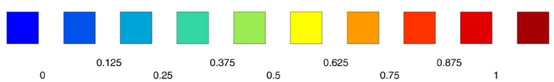
Temp
t=10s



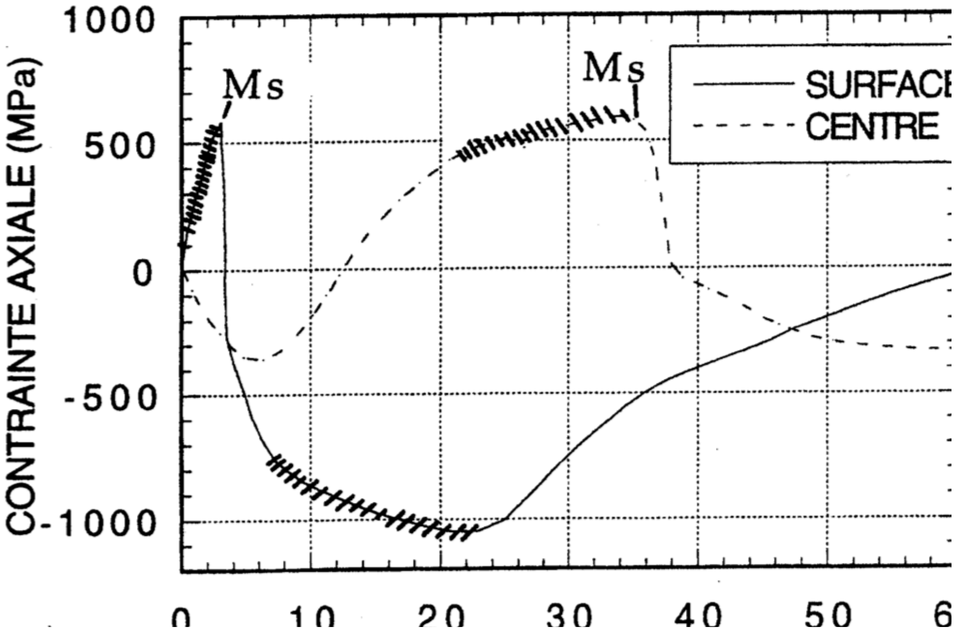


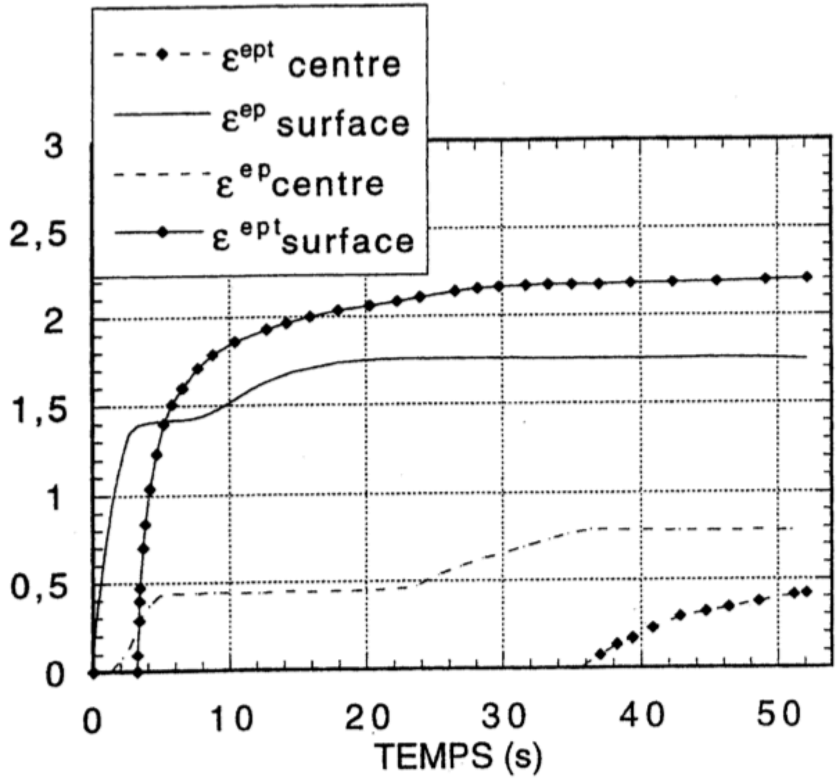
Martensite
t=10s



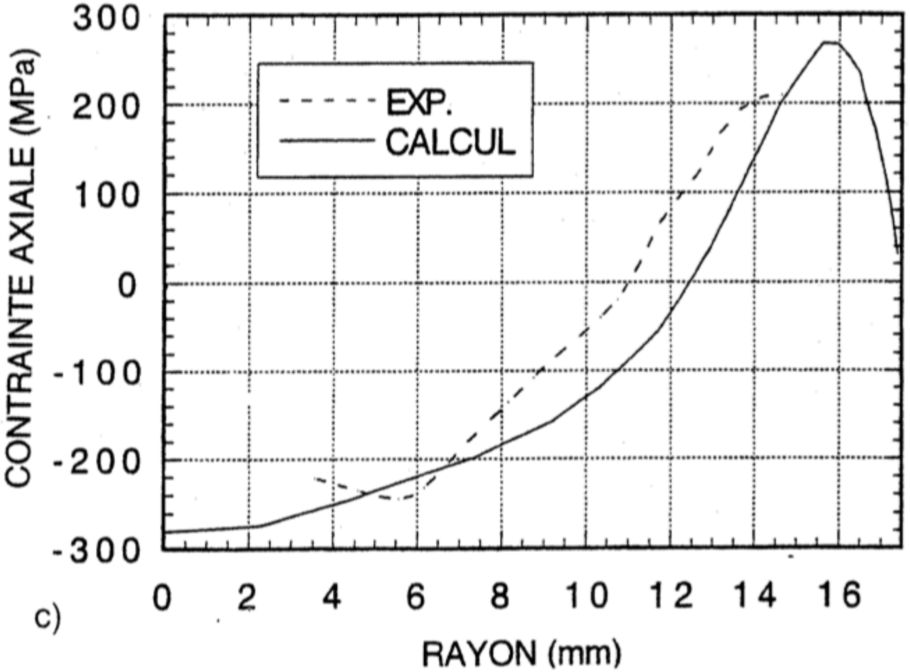


PhD Y. Wang , Nancy, 2006



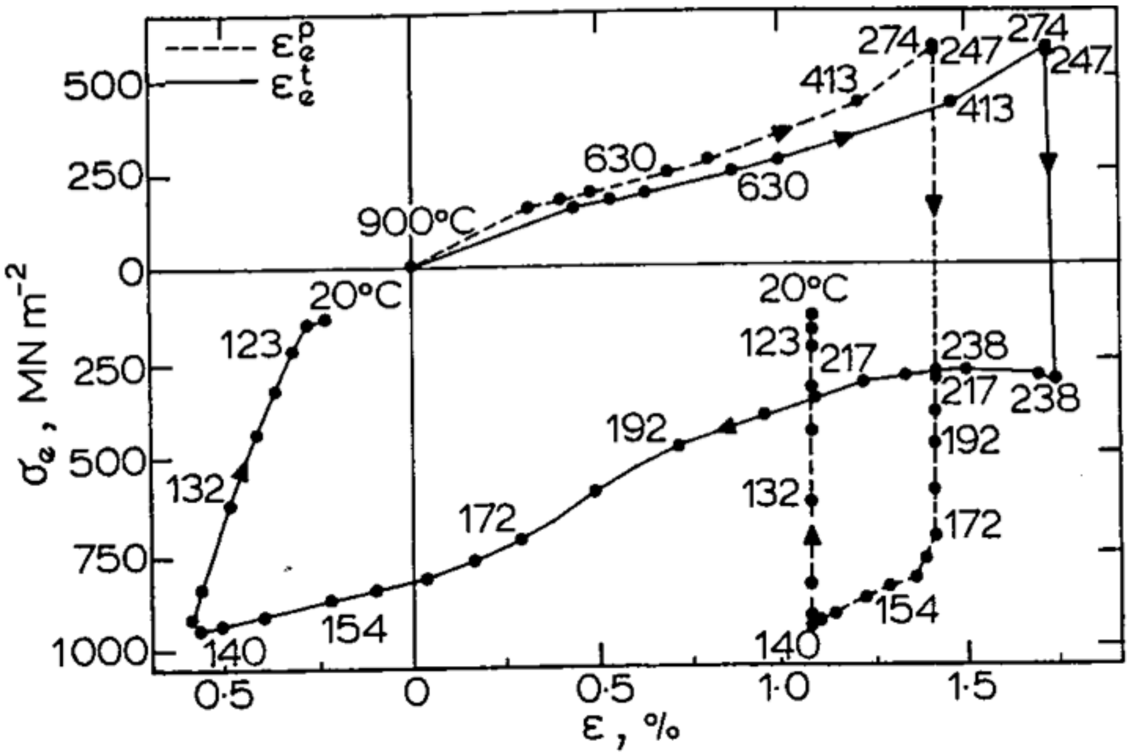


b)



c)

Quenching



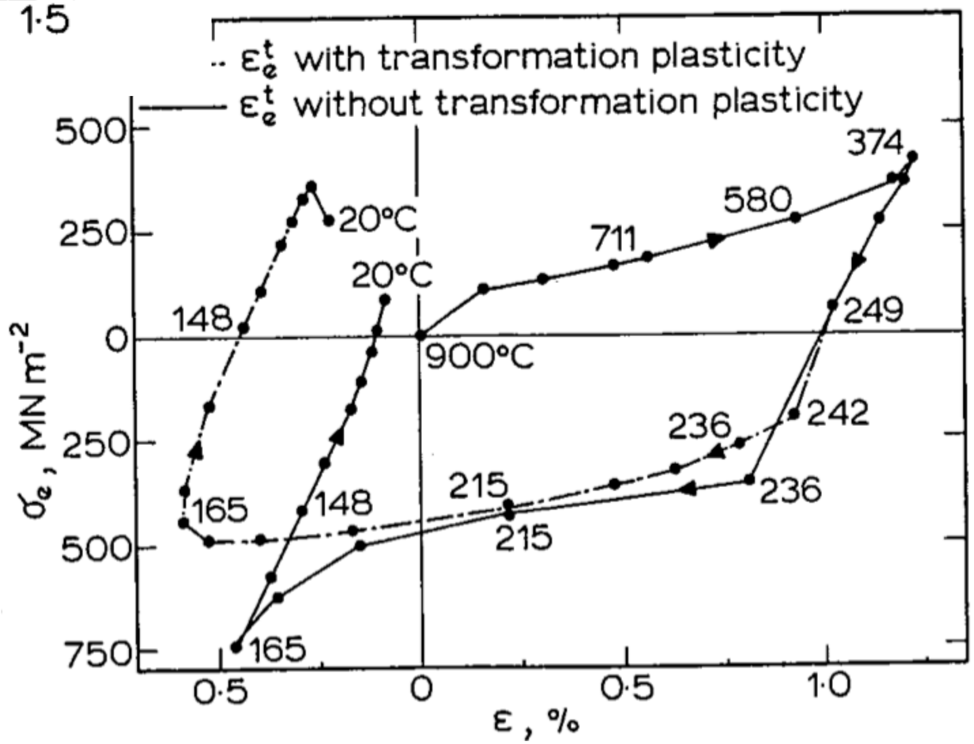
Calculated loading paths

Von Mises stress σ_e

equivalent plastic strain
$\varepsilon_e^p = \sqrt{2/3\ \varepsilon_{ij}^p \varepsilon_{ij}^p}$

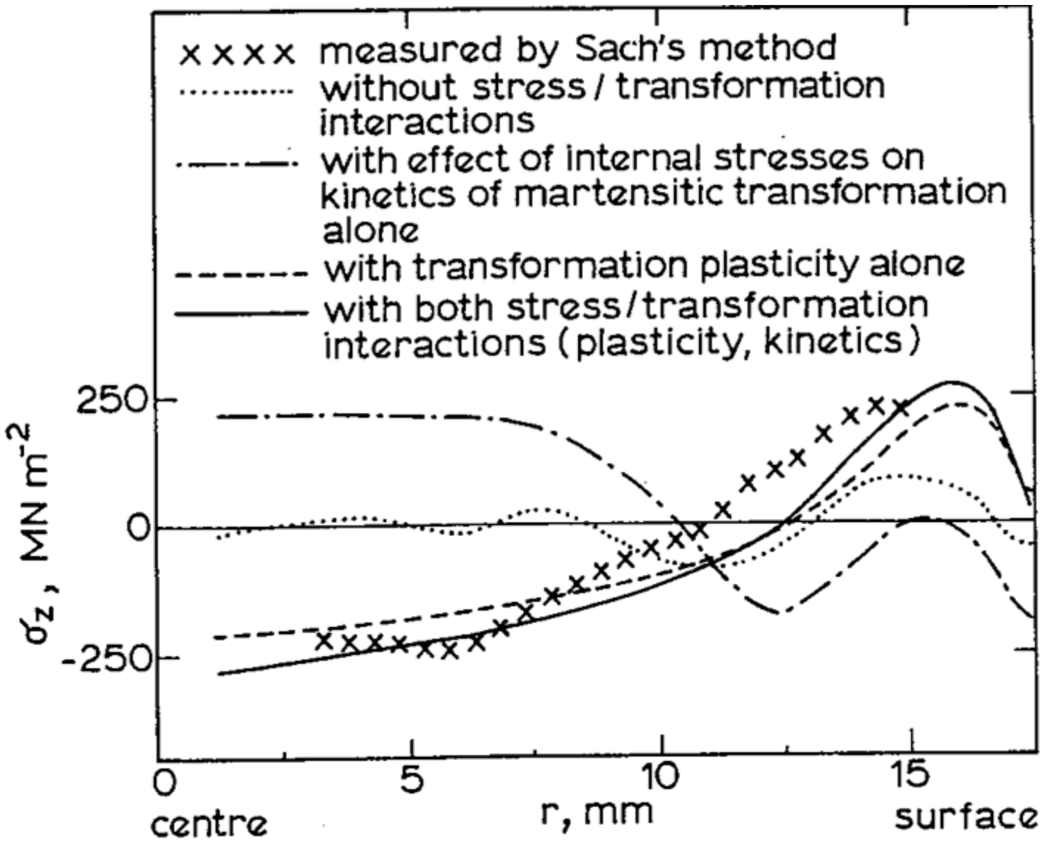
equivalent total strain
$\varepsilon_e^t = \sqrt{2/3}\ \varepsilon_{ij}^t \varepsilon_{ij}^t$

Role of transformation plasticity
during quenching



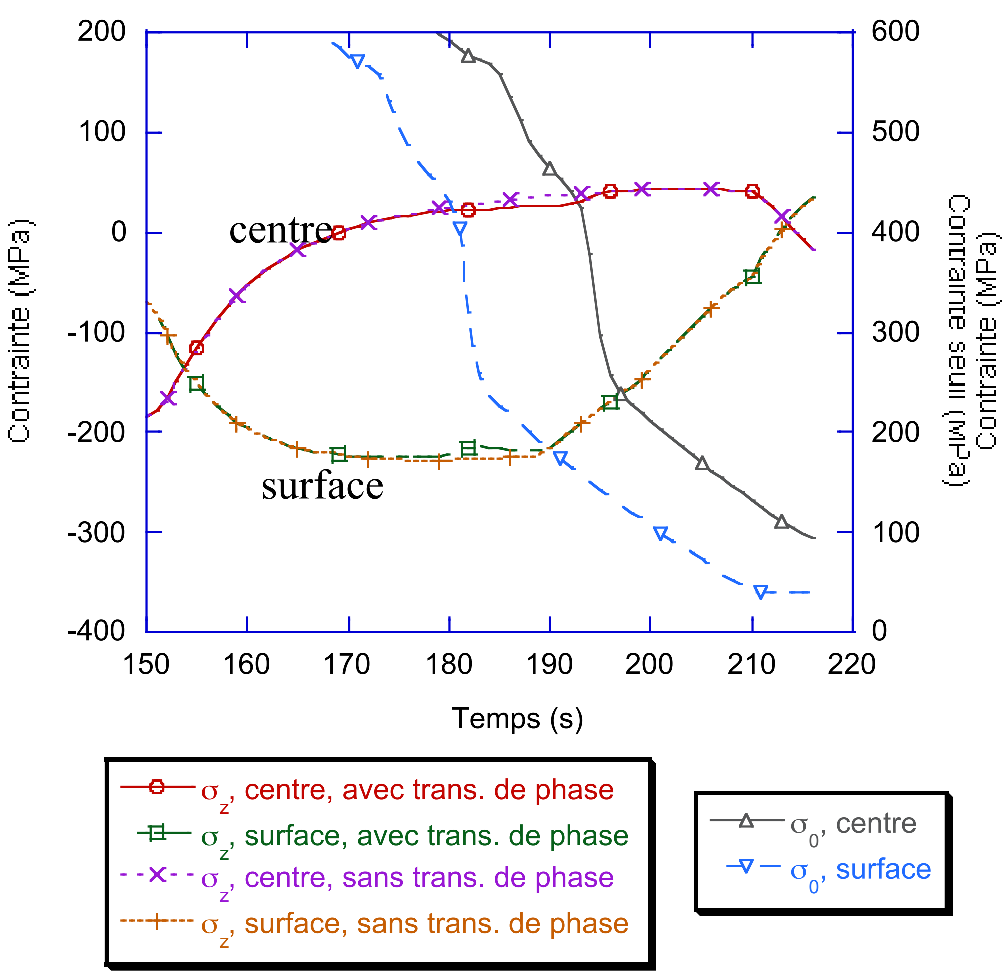
S. Denis et al, Mat Sci Technol 1985

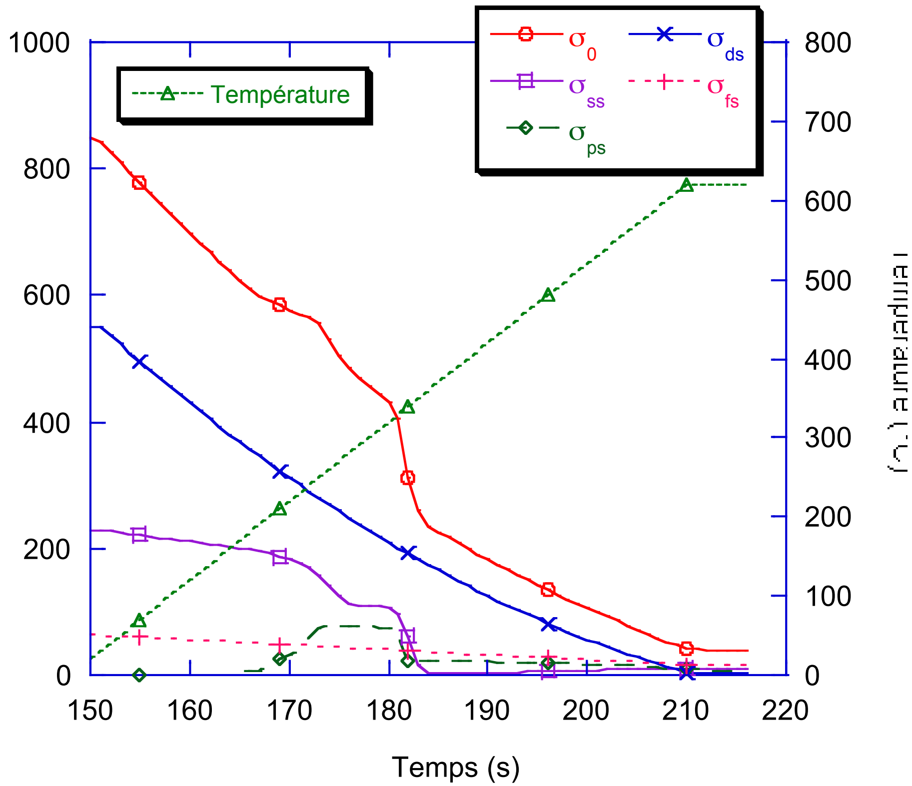
Residual stress profiles after water quenching
Role of stress – phase transformation interactions



S. Denis et al, Mat Sci Technol 1985

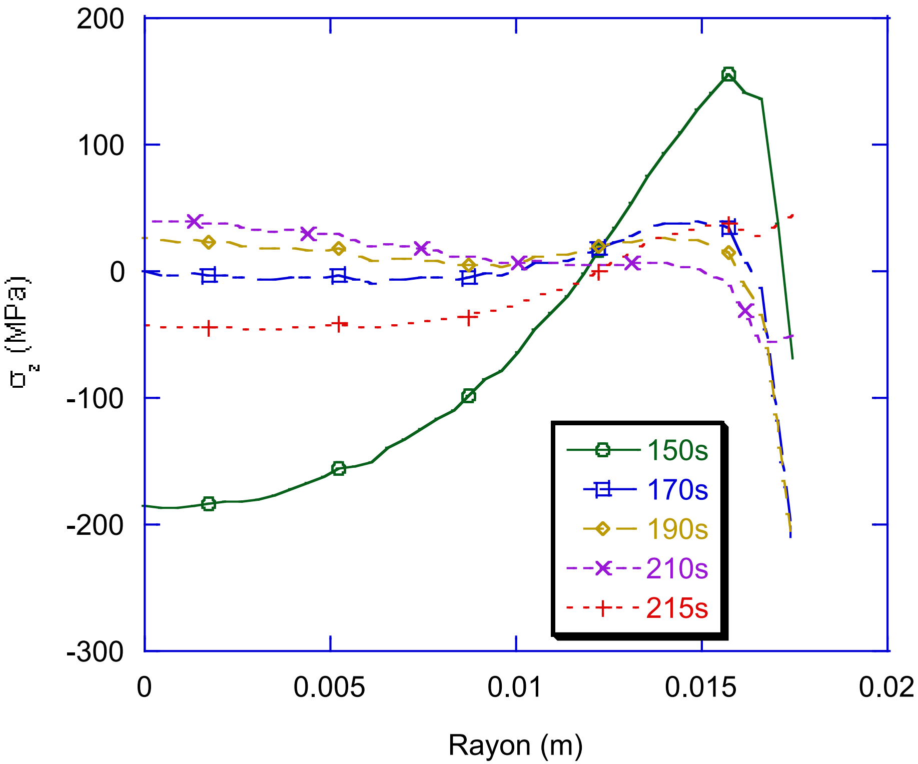
Relaxation of quenching residual stresses during tempering

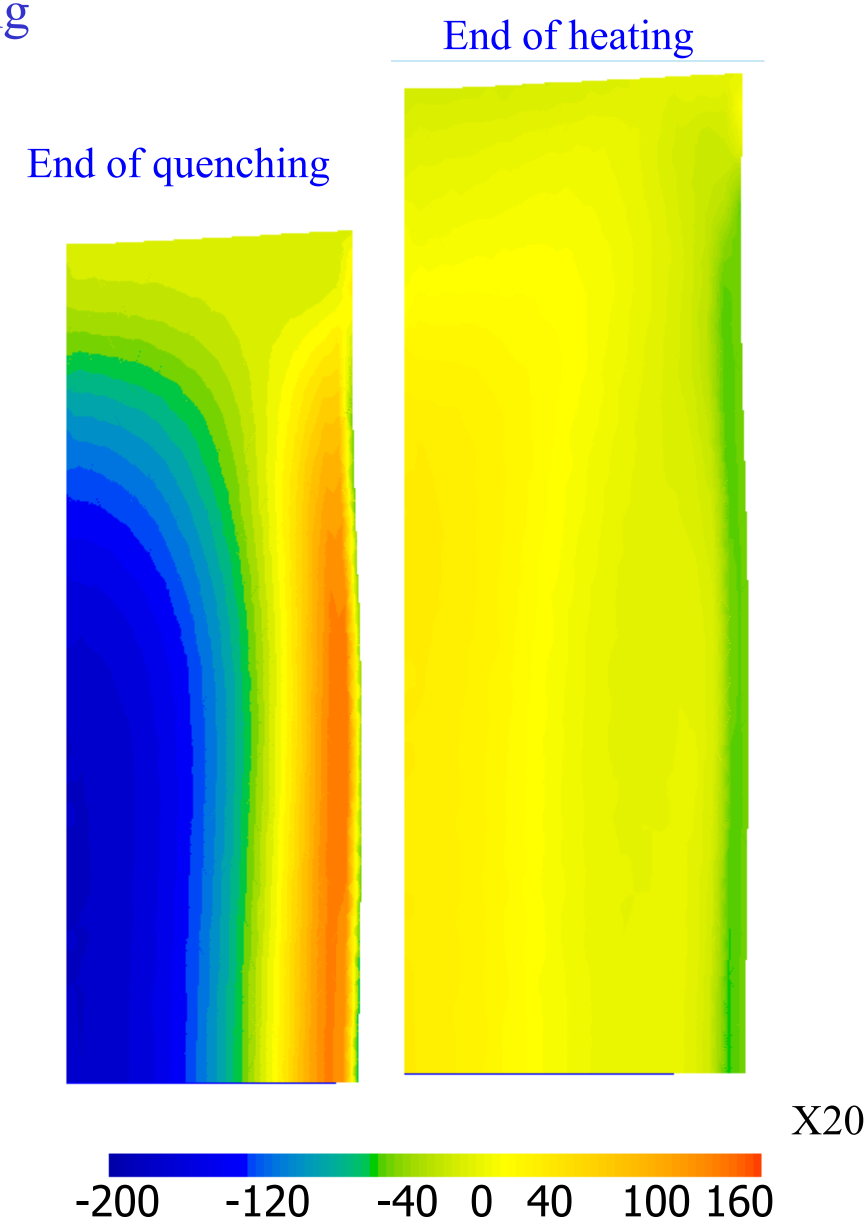




PhD Y. Wang , Nancy, 2006

Evolutions of stress profiles during tempering





PhD Y. Wang , Nancy, 2006

Conclusion - Future developments

• Material point of view

- metallurgical models

. global models work for industrial metallic alloys and complex situations → prediction of volume fractions

. models including nucleation and growth develop more and more for multicomponent alloys
→ volume fractions and morphological parameters allow prediction of mechanical properties
(Al alloys, Ti alloys…)

. *take into account chemical composition gradients (carburizing, carbonitriding, solidification segregations)*

. *effects of prior plastic deformations, effect of stresses*

Conclusion - Future developments

- thermomechanical behaviour with phase transformations

. phenomenological laws exist
extension to other metallic alloys (Ti alloys…)
better description of multiphase material (morphology)
micro-macro approaches must be further developped

• Heat treatment processes

- **coupling between fluid and solid :**
  developments for vaporizable fluids (experiments and modelling)
- include **heating processes** (furnace, induction…)
- ***in situ measurements*** *(solid + fluid) for rapid processes*
- ***chain different processes*** :
  liquid metal processing + solidification + forming + heat treatment…

• Numerical aspects

Two review papers
S. Denis, Revue de Métalurgie CIT/SGM, février 1997, pp. 157-176
S. Denis, P. Archambault, E. Gautier, A. Simon, G. Beck, JMEPG Vol 11 (1), 2002, pp. 92-102

Common work with

A. Simon, E. Aeby-Gautier, P. Archambault, J.P. Bellot, B. Appolaire

PhD students :

FMB Fernandes, C. Basso, J.P. Josserand, D. Farias, F. Saliou, M. Boufoussi, J.F. Ganghoffer, Y. Wen, L. Massicart, M. Zandona, A. Mey, P. Brunet, C. Aubry, J. Ch. Louin, M. Veaux, Y. Wang, Y. Renault, J.F. Douce, M. Haering, L. Mangin, S. Devynck, S. Catteau…

In the frame of industrial collaborations

CETIM, ARBED, UNIMETAL RECHERCHE, PSA, RENAULT, Creusot Loire Industrie, French Programme SIMULFORGE, European programme VHT, Ascometal, Air Liquide SNR, Vallourec, ...