IDENTIFICATION OF THERMAL BOUNDARY CONDITIONS AND THERMO-METALLURGICAL BEHAVIOUR OF X10CrMoVNb9-1 STEEL

-

APPLICATION TO A « DISK-SPOT » WELDING EXPERIMENT

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AKNOWLEDGEMENTS: AYRAULT D., KICHENIN J., BRACHET J.C., DE CARLAN Y.

OUTLINE

- INTRODUCTION
- MICROSTRUCTURAL CHANGES IN T91 STEELS
- SIMULATION OF THE THERMO-METALLURGICAL BEHAVIOUR OF T91 STEELS
- IDENTIFICATION OF THERMAL BOUNDARY CONDITIONS DURING A « DISK-SPOT » EXPERIMENT
- NUMERICAL SIMULATIONS OF THE DISK-SPOT EXPERIMENT
- PERSPECTIVES

INTRODUCTION

✓ FRAMEWORK OF THIS STUDY

Design of Very High Temperature Reactors of the future using gas coolant

nominal temperature: 450°C => martensitic steel

Numerical welding simulation

⇩

Initial state after welding

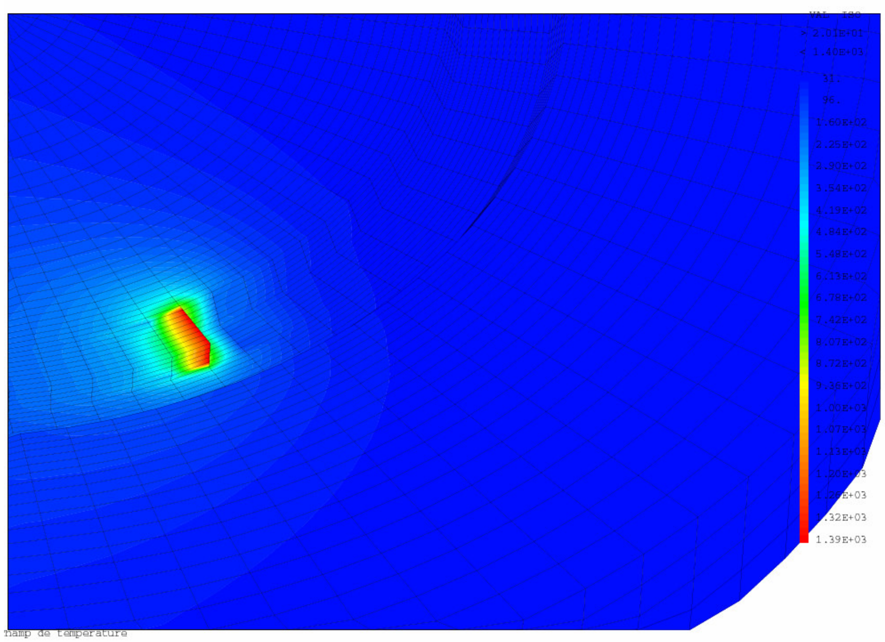
(microstructure, distorsions, residual stresses, defects, …)

⇩

Failure assessment of welds

INTRODUCTION

✓ NUMERICAL SIMULATION OF TIG WELDING



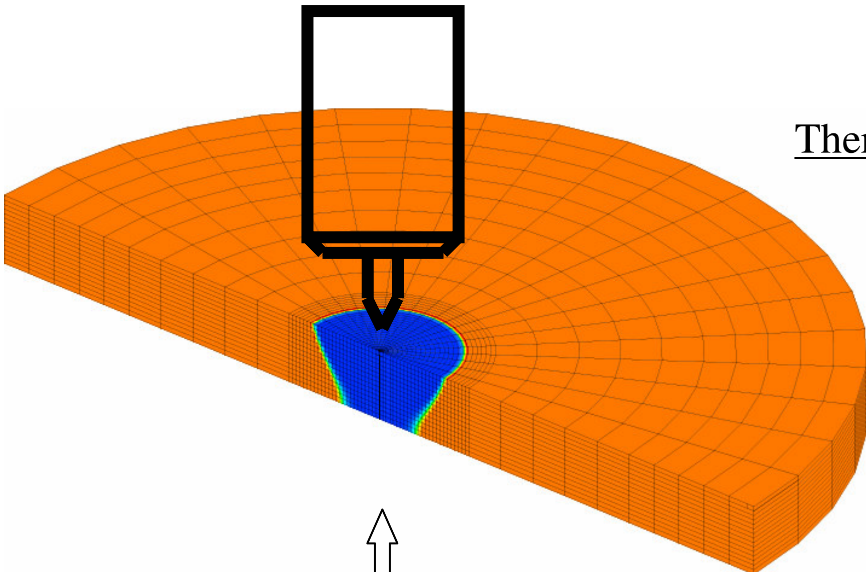
(CAST3M welding finite element simulation with an element deposit technique)

- TIG torch model (heat, plasma, metal deposit,…)
- Thermo-metallo-mechanical model for materials
- Coupled heat-transfert, metallurgical and mechanical analyses

INTRODUCTION

✓ <u>OBJECTIVES OF THIS PRESENTATION</u>

TIG torch
without filler material ⇔ Heat source



<u>Thermo-metallo</u> (mechanical) model for base material

Coupled heat transfert and
metallurgical analysis

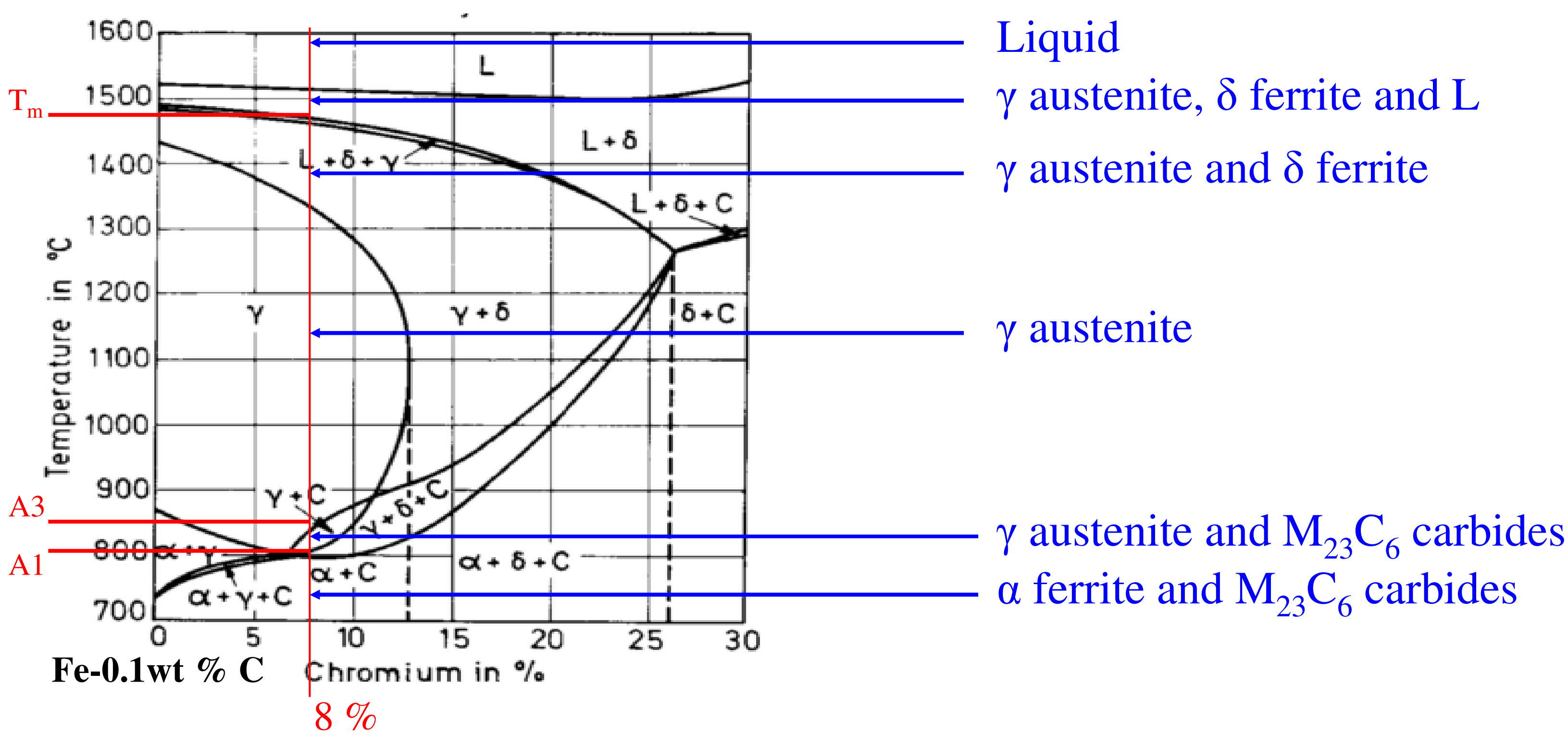
Identification/validation on a simple experiment

MICROSTRUCTURAL CHANGES IN T91 STEELS

✓ CHEMICAL COMPOSITION: X10CrMoVNb 9-1

	C	Mn	Si	Ni	Cr	Mo	Cu	Al	S	P	Sn	As	V	Nb	Ti
% wt	0.099	0.405	0.216	0.13	8.305	0.951	0.054	0.011	0.002	0.007	0.006	0.003	0.201	0.075	0.004

✓ Fe-0.1wt%C/Cr EQUILIBRIUM PSEUDO BINARY DIAGRAM:



MICROSTRUCTURAL CHANGES IN T91 STEELS

✓ SOME EFFECTS OF ALLOYING ELEMENTS:

Chromium equivalent factor by Ezaki:

$$\mathbf{Cr_{equivalent}} = \%Cr + 6.\%Si + 4.\%Mo + 1.5.\%W + 11.\%V + 5.\%Nb + 12.\%AL + 8.\%Ti - 40.\%C - 2.\%Mn - 4.\%Ni - 2.\%Co - 30.\%N - \%Cu$$

$= 10.811 > 8$ => **Presence of δ-ferrite**

✓ CARBIDES PRECIPITATION:

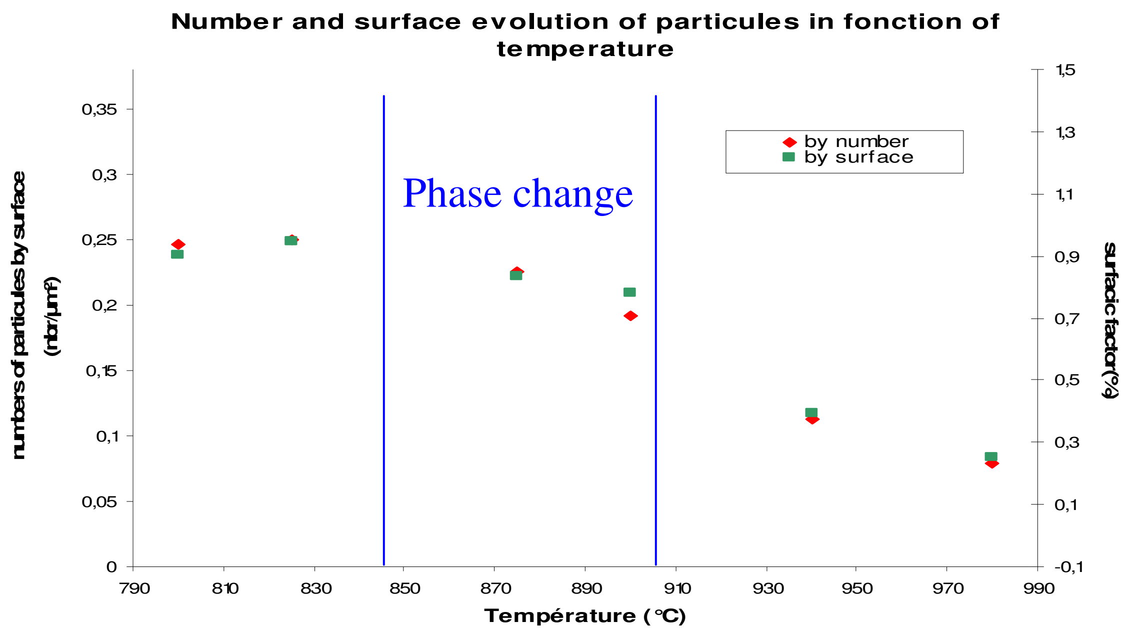
In majority : $\mathbf{M_{23}C_6}$

Others : M_2X

MX

M_7C_3

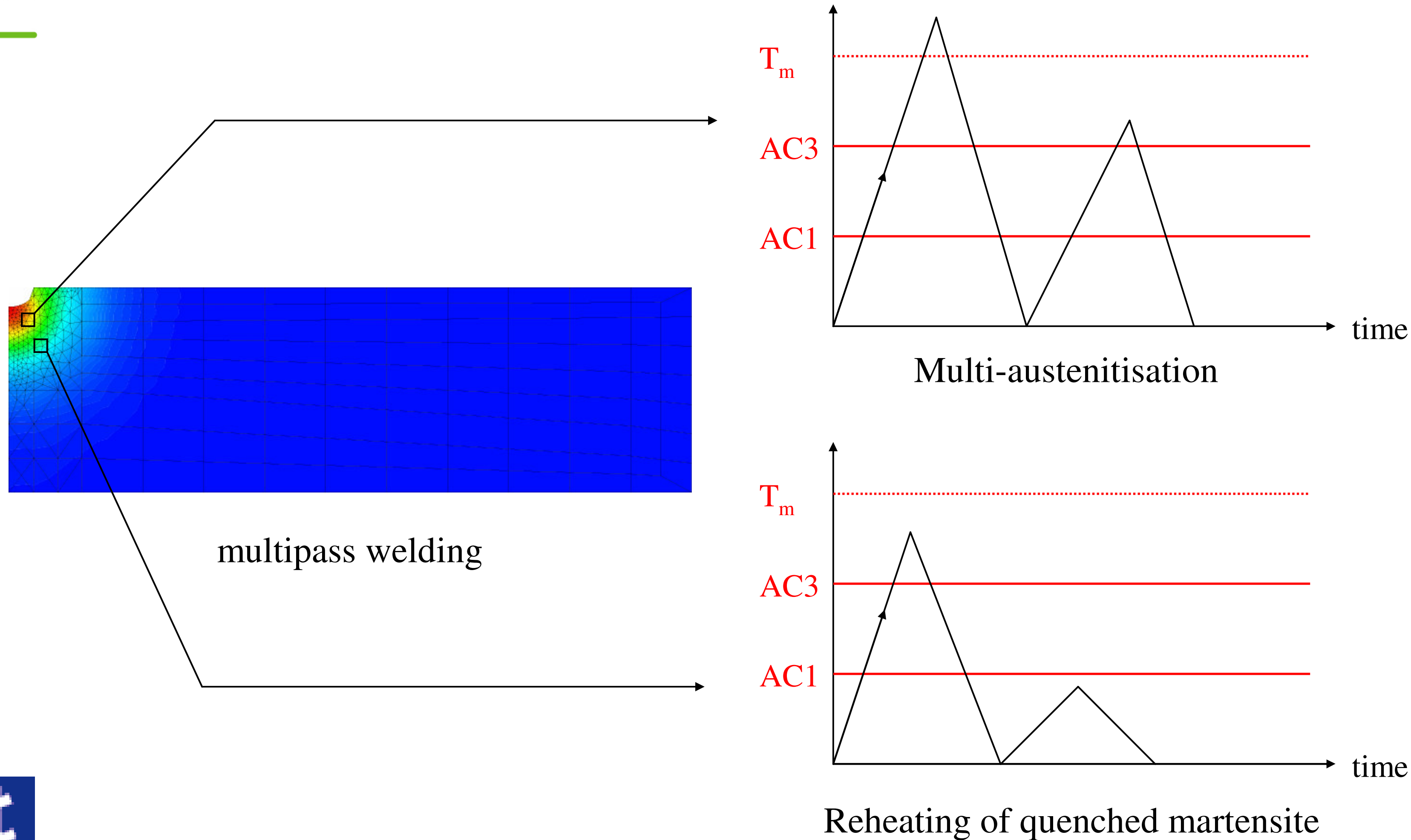
…



[Duthilleul et al. 2003]

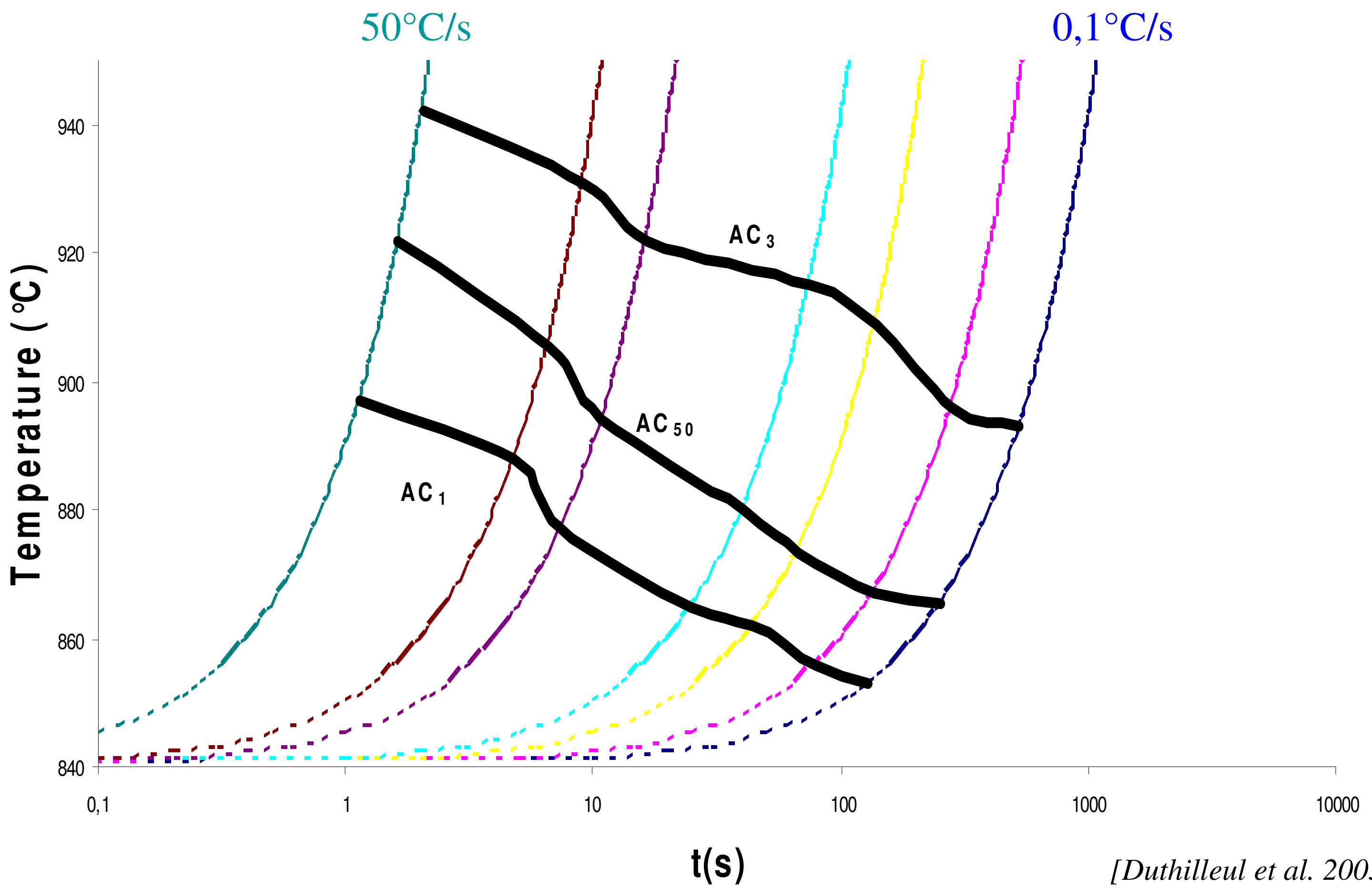
MICROSTRUCTURAL CHANGES IN T91 STEELS

✓ THERMAL COMPLEX LOADING INDUCED BY MULTIPASS WELDING:



MICROSTRUCTURAL CHANGES IN T91 STEELS

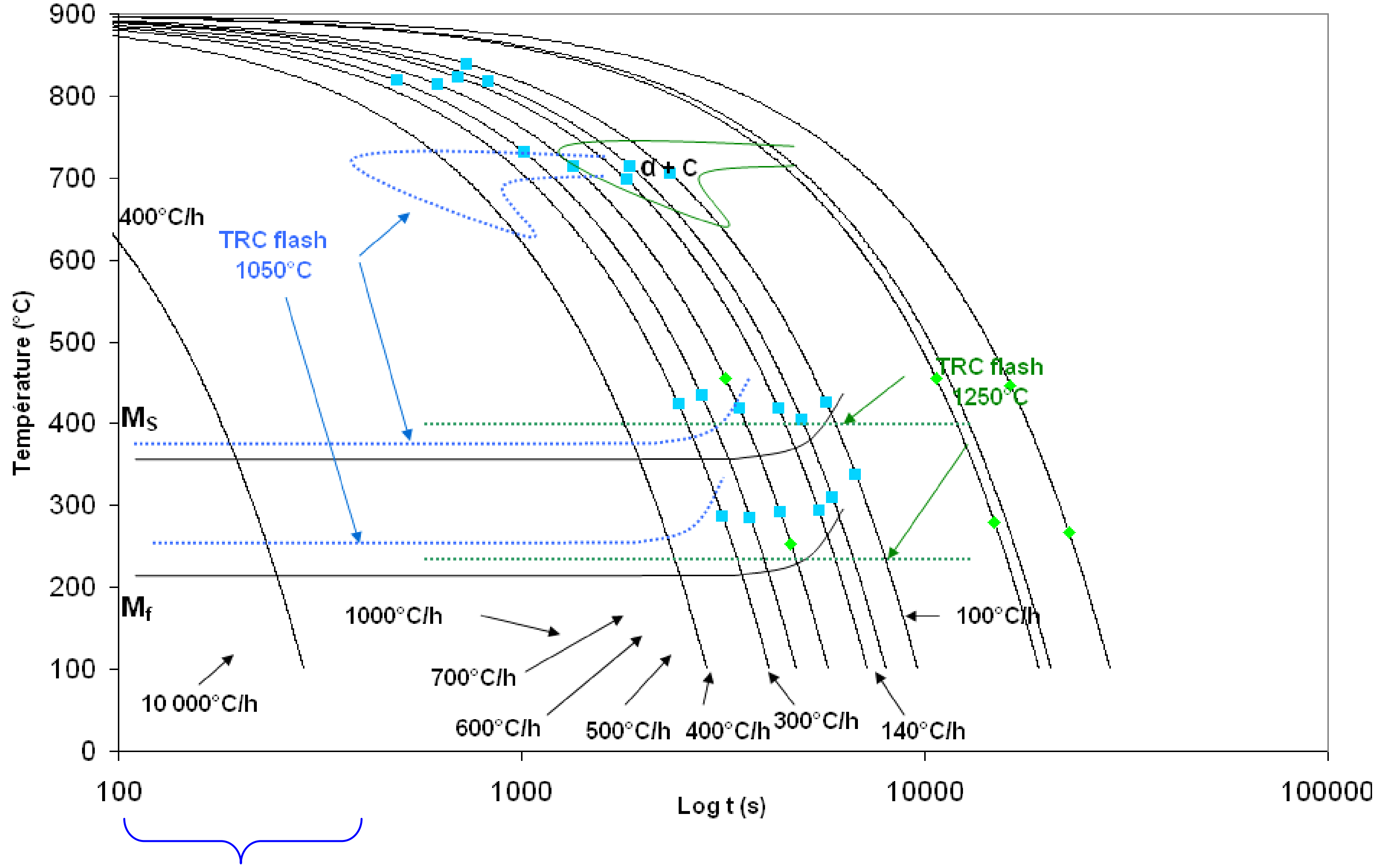
✓ NON-EQUILIBRIUM TRANSFORMATIONS ON HEATING:



[Duthilleul et al. 2003]

MICROSTRUCTURAL CHANGES IN T91 STEELS

✓ NON-EQUILIBRIUM TRANSFORMATIONS ON COOLING:



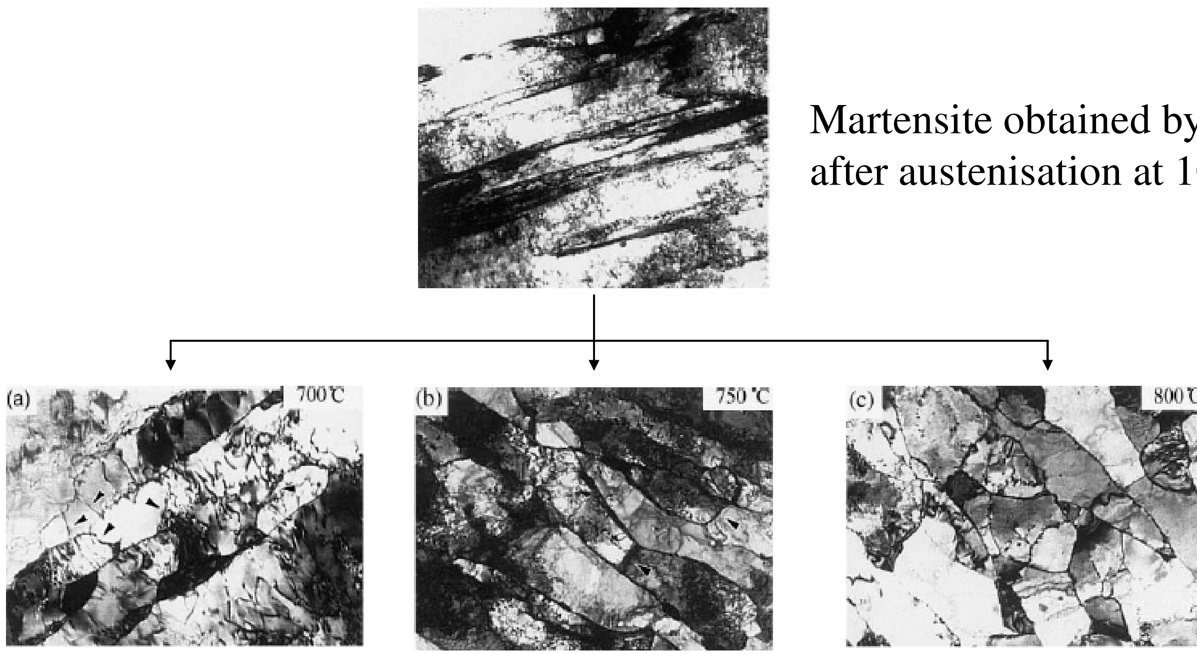
[*Duthilleul et al. 2003*]

Welding process: $16500°C/h > \dot{T} > 11000°C/h$

MICROSTRUCTURAL CHANGES IN T91 STEELS

✓ <u>REHEATING OF QUENCHED MARTENSITE</u> :

Microstructural change of quenched martensite
and carbide precipitation
=> modification of mechanical properties.



Martensite obtained by quenching after austenisation at 1050°C

Tempered at 700°C   Tempered at 750°C   Tempered at 800°C

[*Hong et al. 2001*]

SIMULATION OF THE THERMO-METALLURGICAL BEHAVIOUR OF T91 STEELS

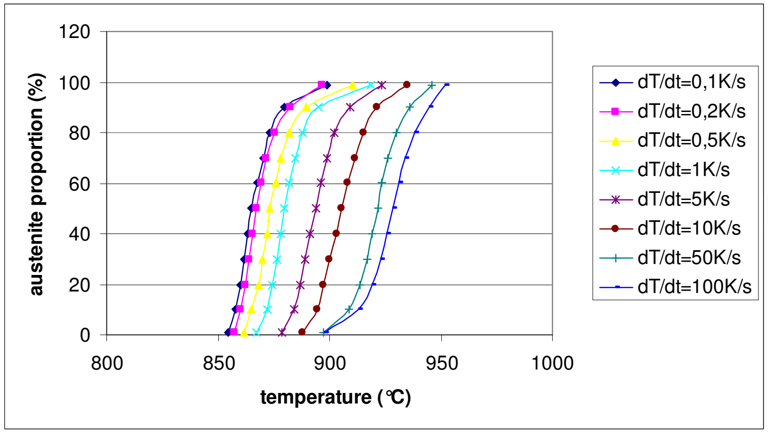
✓ CONSIDERED TRANSFORMATIONS :

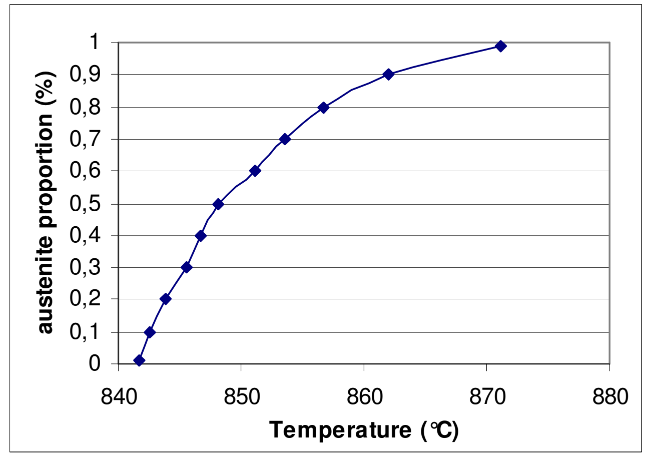
- Tempered martensite (material initial state) → austenite
- *(Austenite ↔ δ ferrite)*
- Solid ↔ liquid
- Austenite → quenched martensite
- *(quenched martensite → tempered martensite)*

SIMULATION OF THE THERMO-METALLURGICAL BEHAVIOUR OF T91 STEELS

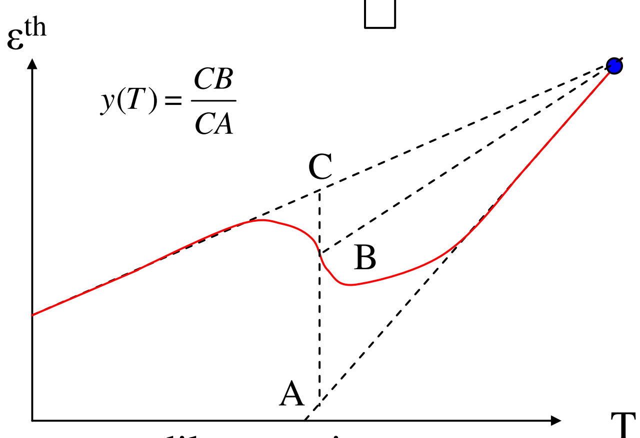
✓ AUSTENITIC TRANSFORMATION ON HEATING:

- experimental evidence





equilibrium curve



dilatometric curve

Zhu and Devletian extrapolation:

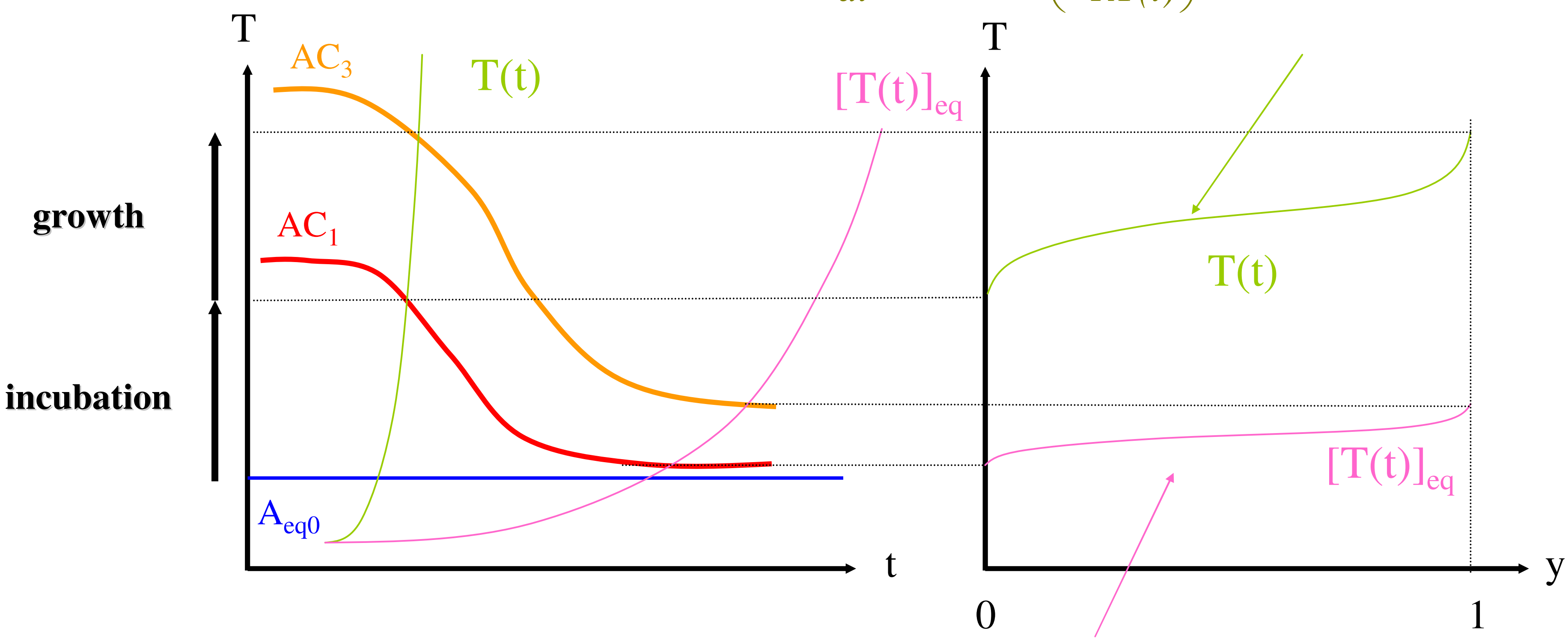
$$T(y_{eq})=T(y,\dot{T})-C\left[\dot{T}\,T(y,\dot{T})\exp\left(\frac{E}{RT}\right)\right]^{\frac{1}{3}}$$

SIMULATION OF THE THERMO-METALLURGICAL BEHAVIOUR OF T91 STEELS

- model

Non equilibrium transformation [Brachet 1998]

$$\frac{dy_\gamma(T,t)}{dt} = K\exp\left(-\frac{E}{RT(t)}\right)\left\langle T(y_\gamma)_{eq} - A_1\right\rangle_+^{n} (1 - y_\gamma)$$



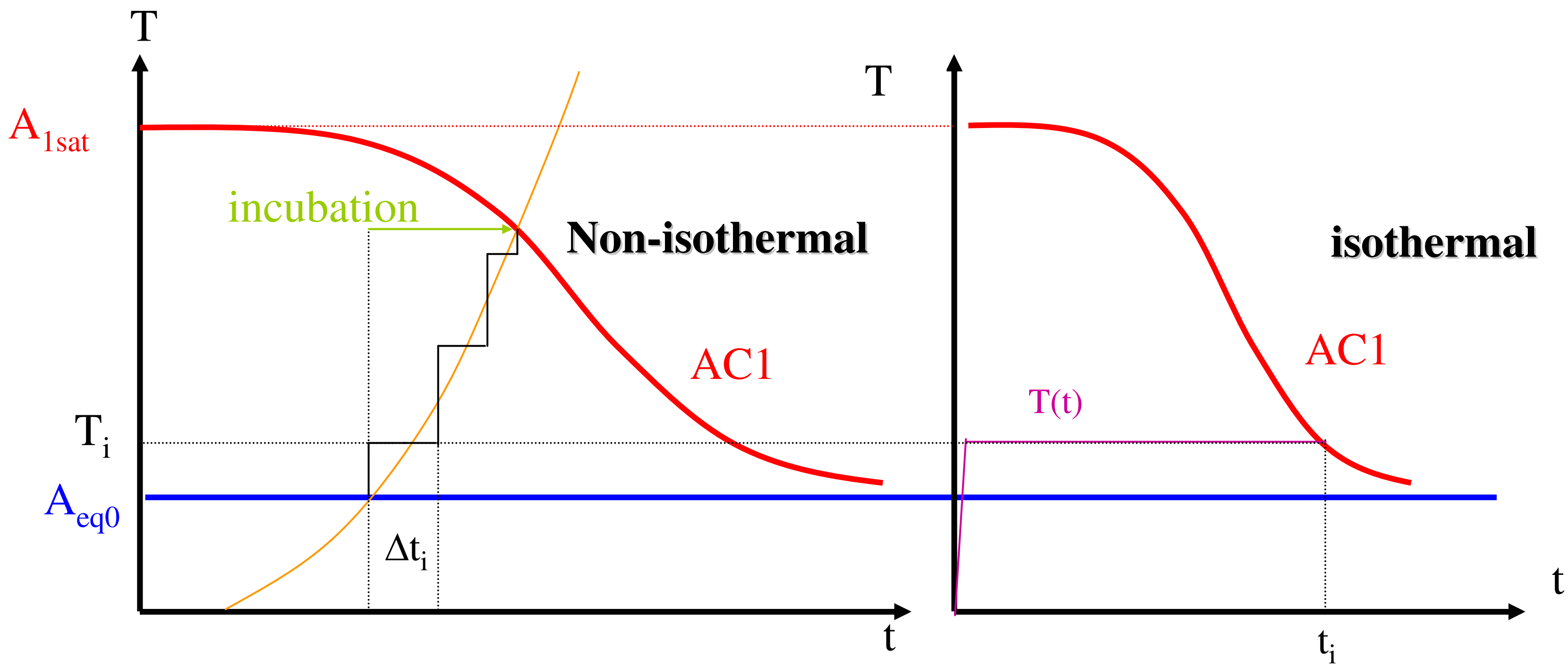
Equilibrium transformation (J.M.A. law)

$$y_{eq}(T) = 1 - \exp(-(K_0(T - A_{eq0}))^{m_0})$$

SIMULATION OF THE THERMO-METALLURGICAL BEHAVIOUR OF T91 STEELS

- incubation law

Extension of additivity Scheil rule to heating: $\sum_i \frac{\Delta t_i}{t_i(T)} = 1 \Leftrightarrow \int_{t_{eq0}}^{t} \frac{dT}{t_i(T)} \frac{dt}{dT} = 1$



Phenomenological model: $t_i(T) = A(A_{1sat} - T)exp\left(\frac{C}{T - A_{eq0}}\right)$

SIMULATION OF THE THERMO-METALLURGICAL BEHAVIOUR OF T91 STEELS

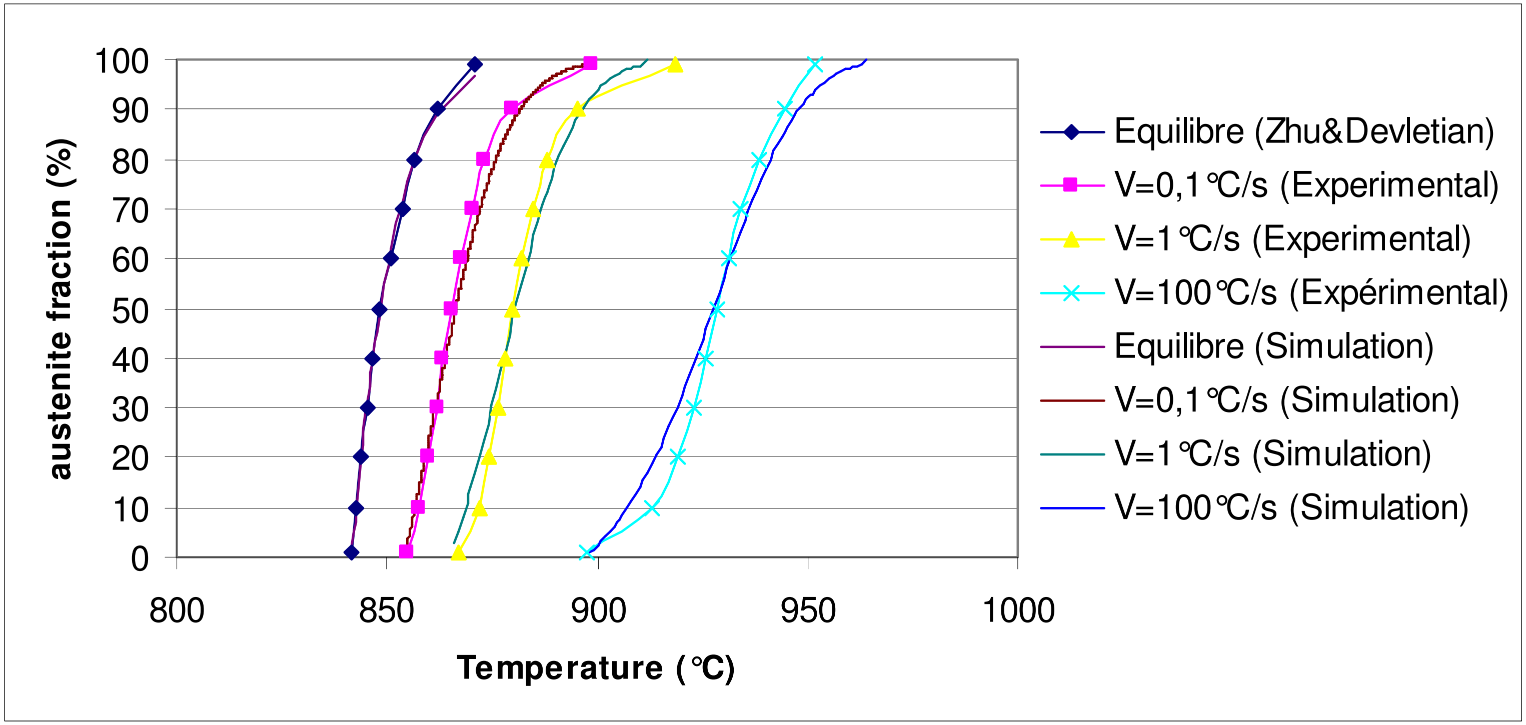
- identification

Inverse identification with Matlab©

(A_{eq0}, K_o and m_o), (A, A_{1sat} and C) and (K, W and n)

equilibrium incubation growth

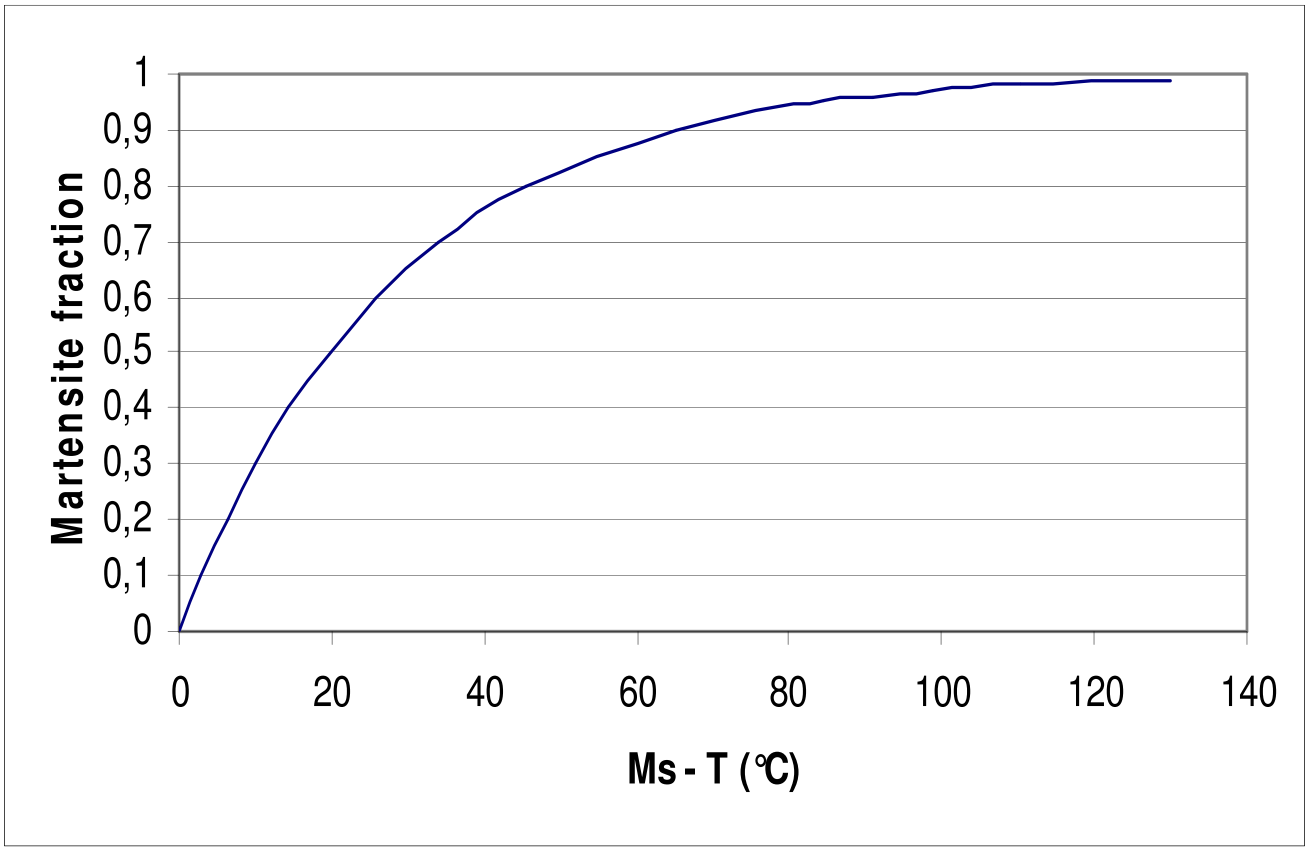
First order Runge-Kutta scheme with Δt_{step}=1°C:



SIMULATION OF THE THERMO-METALLURGICAL BEHAVIOUR OF T91 STEELS

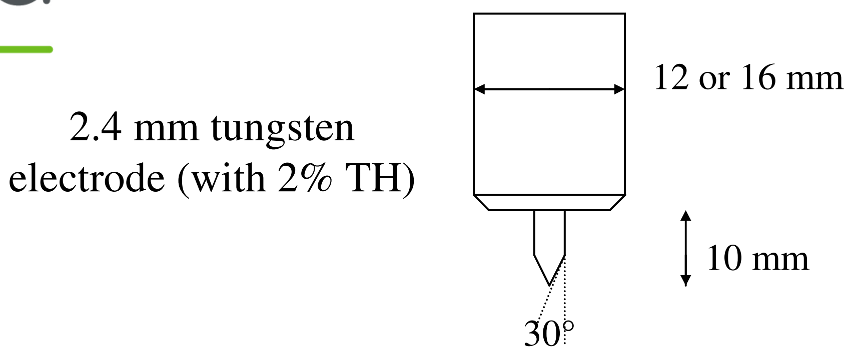
✓ <u>MARTENSITIC TRANSFORMATION</u> :

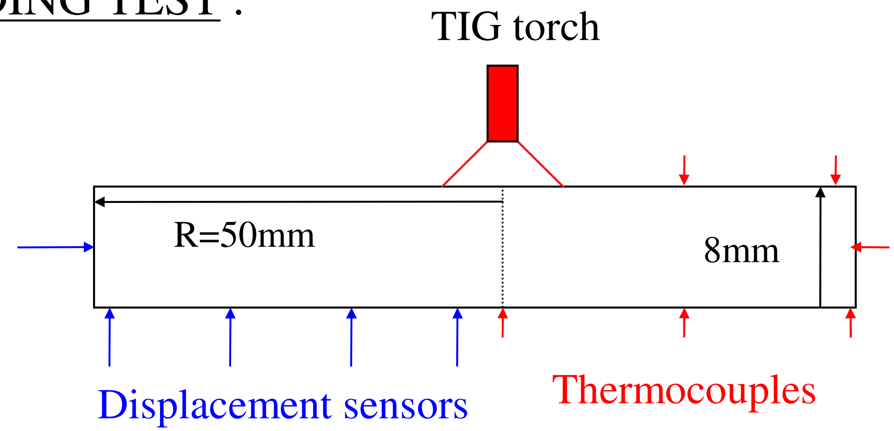
Koistinen-Marburger model: $y_m(T) = y_{\gamma 0}(1 - exp(-K_m(M_S - T)))$

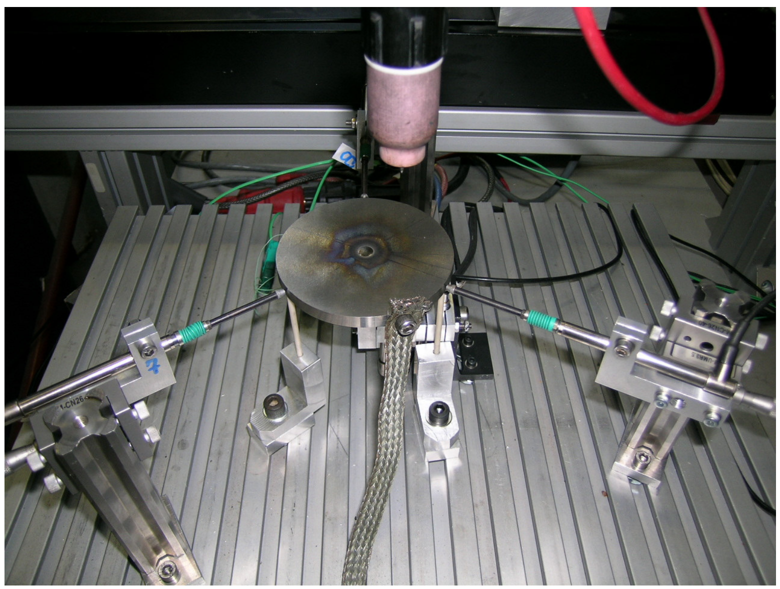


IDENTIFICATION OF THERMAL BOUNDARY CONDITIONS DURING A « DISK-SPOT » EXPERIMENT

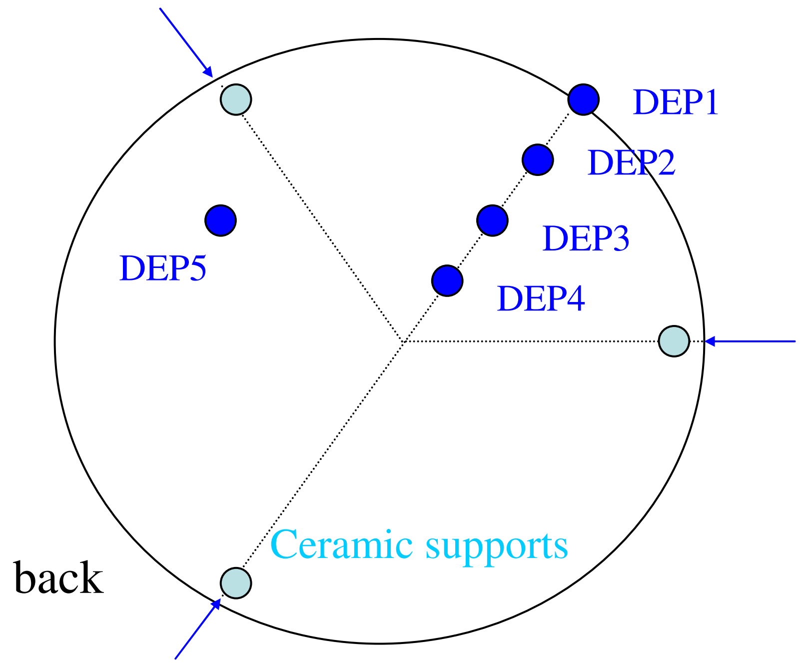
✓ DISK-SPOT SIMPLE TIG WELDING TEST :





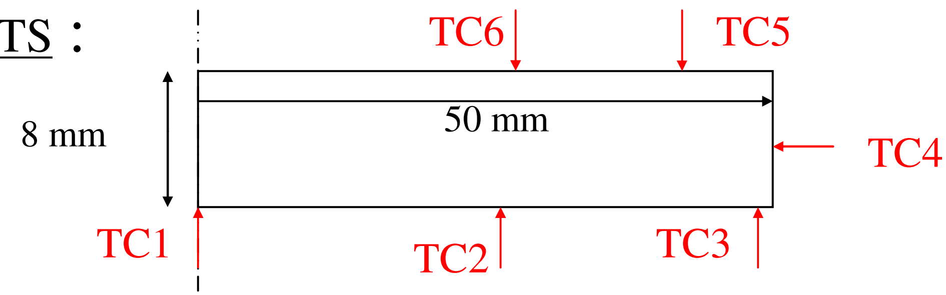


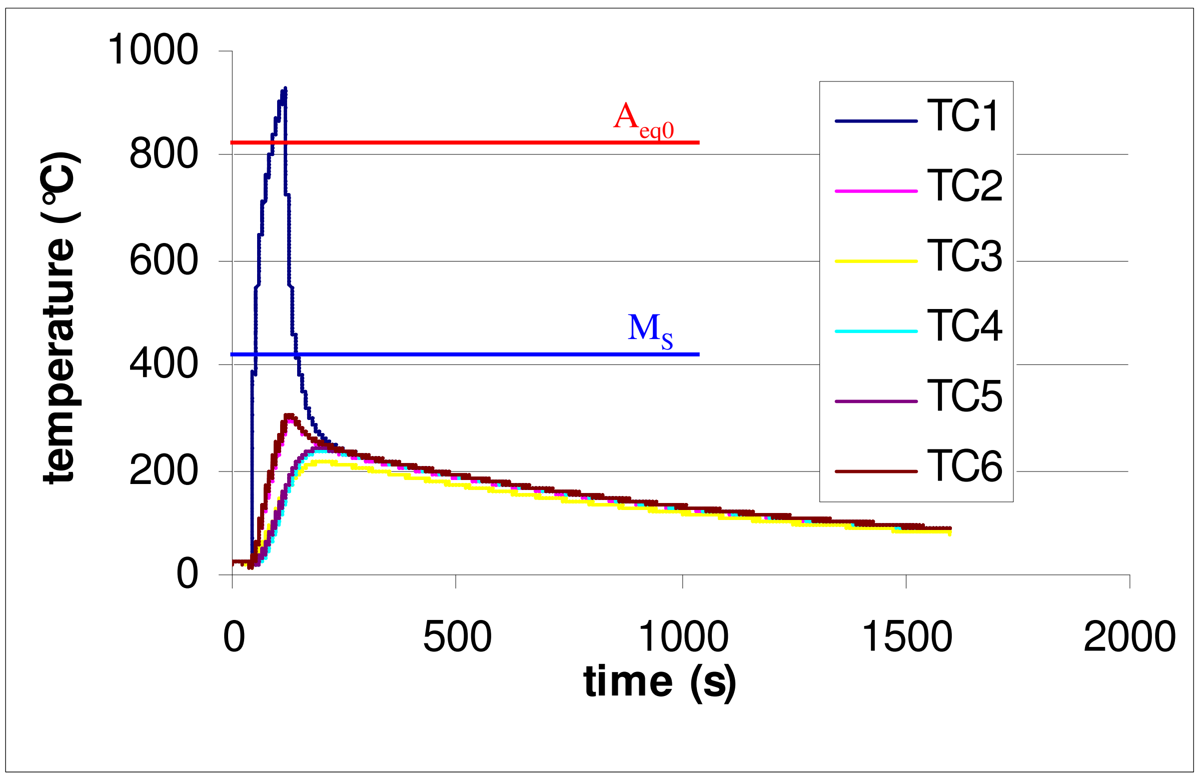
experimental set up at DRT/UTIAC



IDENTIFICATION OF THERMAL BOUNDARY CONDITIONS DURING A « DISK-SPOT » EXPERIMENT

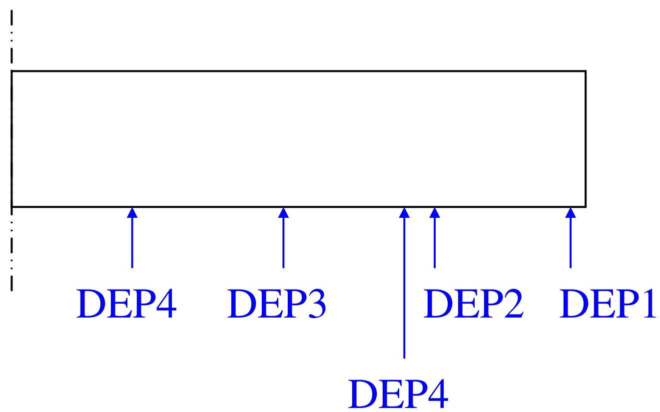
✓ TEMPERATURE RESULTS :

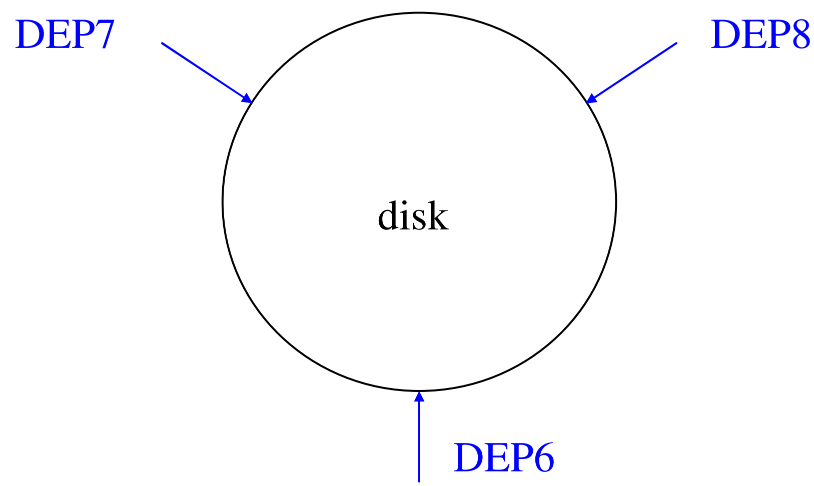


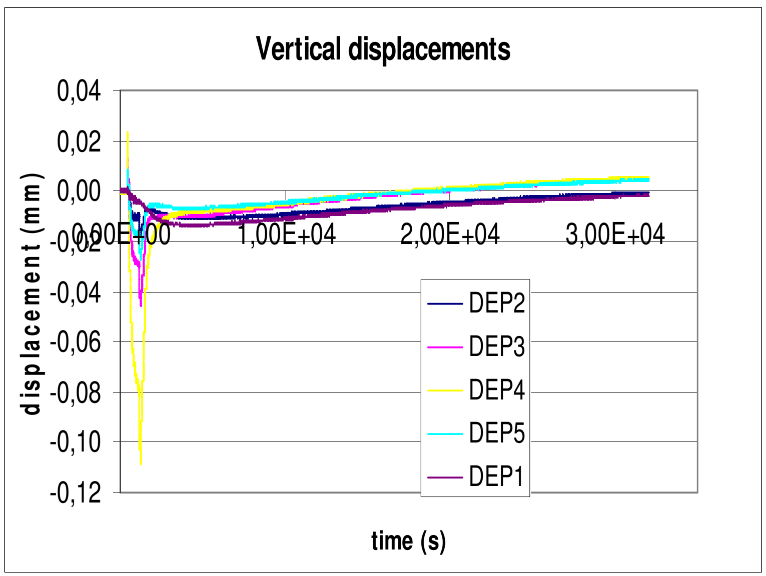


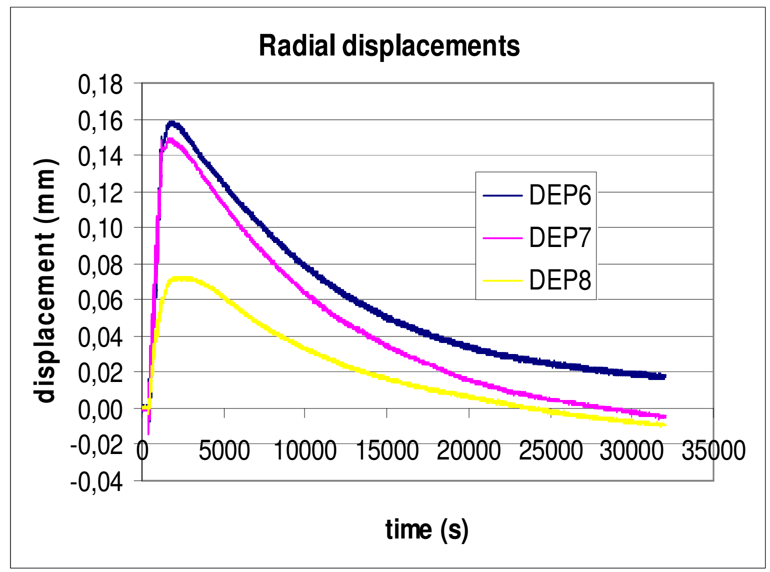
IDENTIFICATION OF THERMAL BOUNDARY CONDITIONS DURING A « DISK-SPOT » EXPERIMENT

✓ DISPLACEMENT RESULTS :









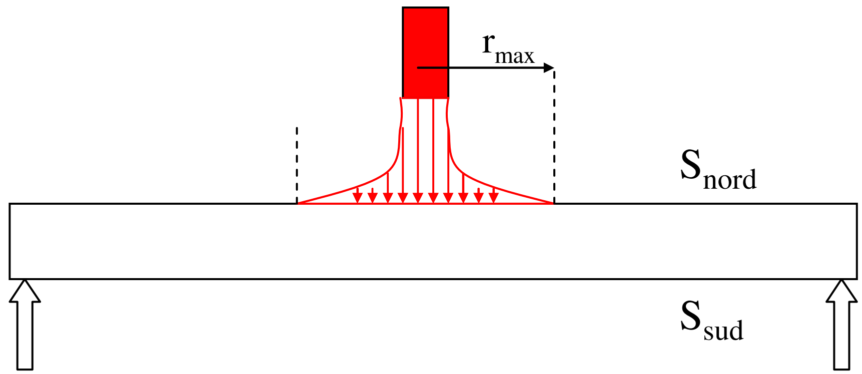
IDENTIFICATION OF THERMAL BOUNDARY CONDITIONS DURING A « DISK-SPOT » EXPERIMENT

✓ BOUNDARIES CONDITIONS TO IDENTIFY :

Hypothesis:

Low uncertainties on ρ, Cp and λ

- Heat source parameters

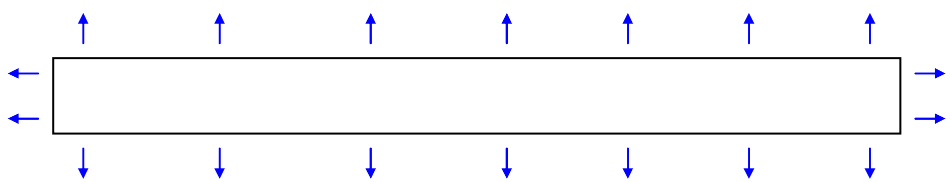


Infinite Gaussian heat source:

$$P_S = Q e^{-3\frac{r^2}{ro^2}}$$

$$0 < r < r_{max}$$

- Convection and radiation



Convection/radiation model:

$$q_v = -h(T - T_{ext})$$

h=h(T) on S_{nord} and S_{sud}

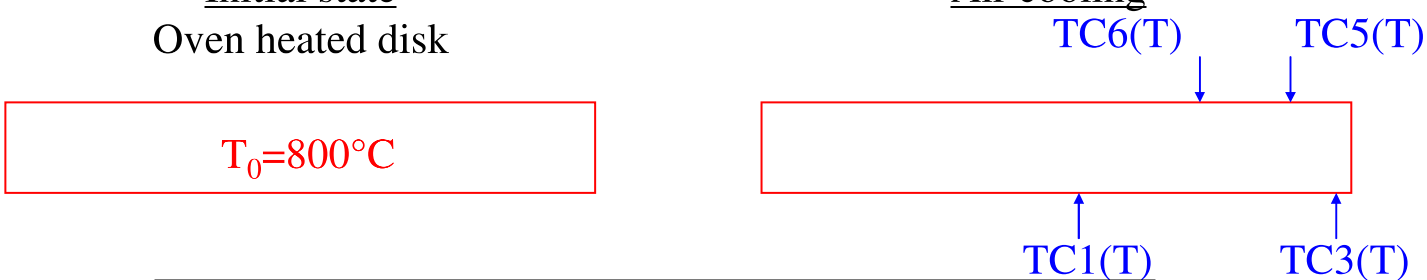
IDENTIFICATION OF THERMAL BOUNDARY CONDITIONS DURING A « DISK-SPOT » EXPERIMENT

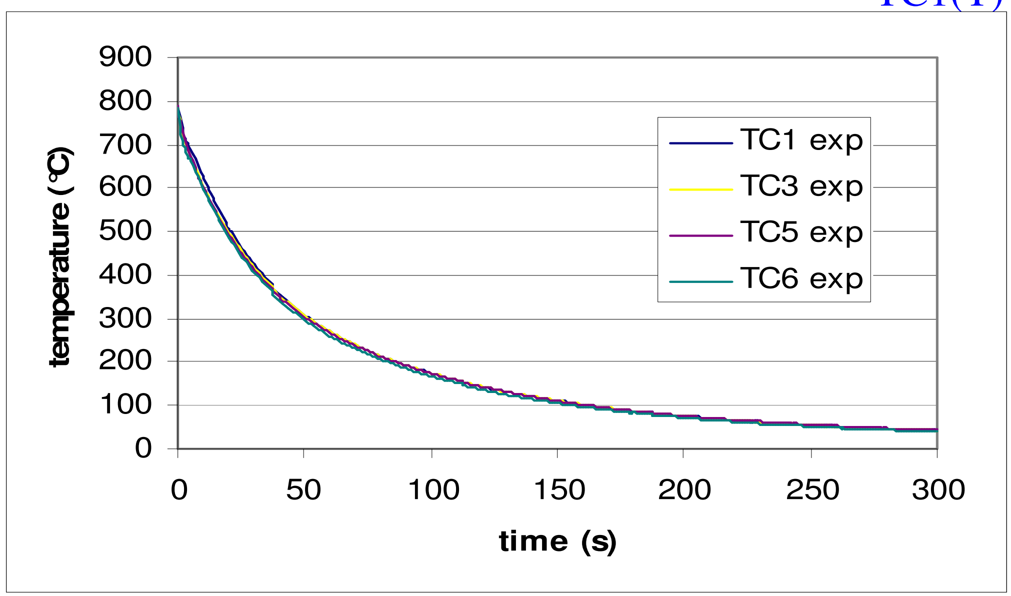
✓ IDENTIFICATION OF h(T) FOR LOW TEMPERATURES :

❑ Experiment

Initial state
Oven heated disk

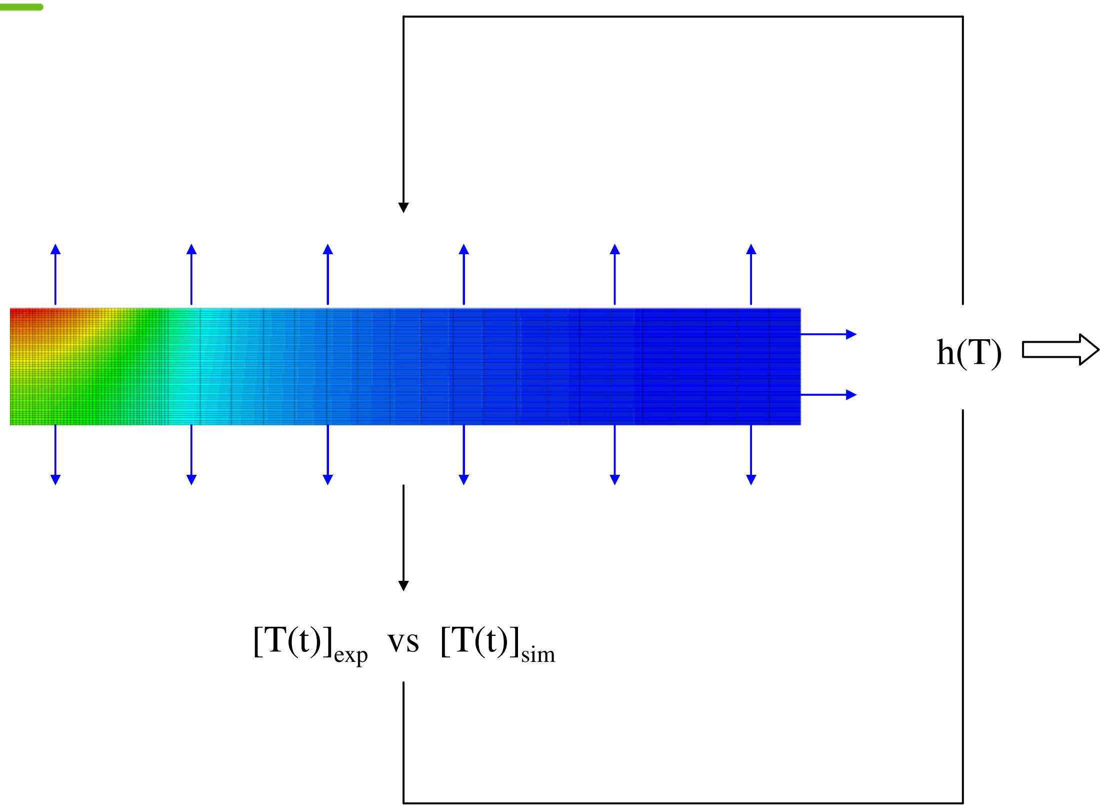
Air cooling



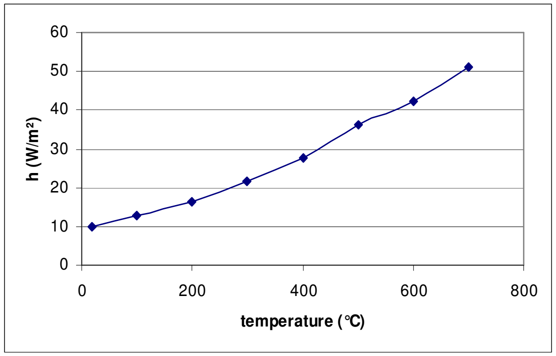


IDENTIFICATION OF THERMAL BOUNDARY CONDITIONS DURING A « DISK-SPOT » EXPERIMENT

- Inverse identification



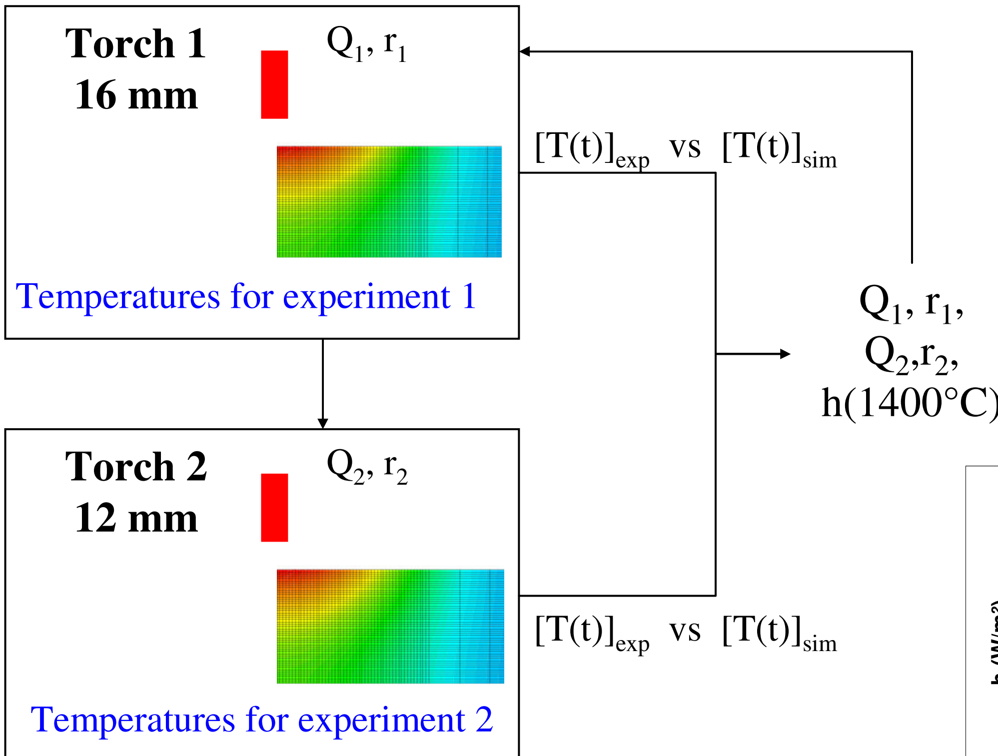
Results:



IDENTIFICATION OF THERMAL BOUNDARY CONDITIONS DURING A « DISK-SPOT » EXPERIMENT

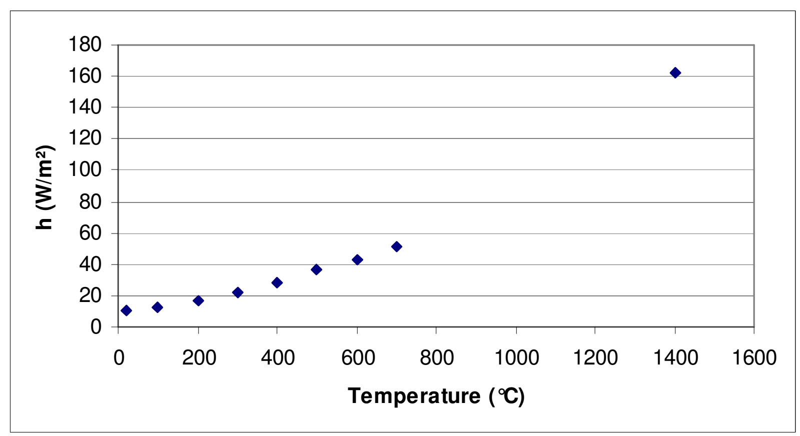
Two different experiments with same h(T) => convex problem

- Presentation of the new experimental protocol



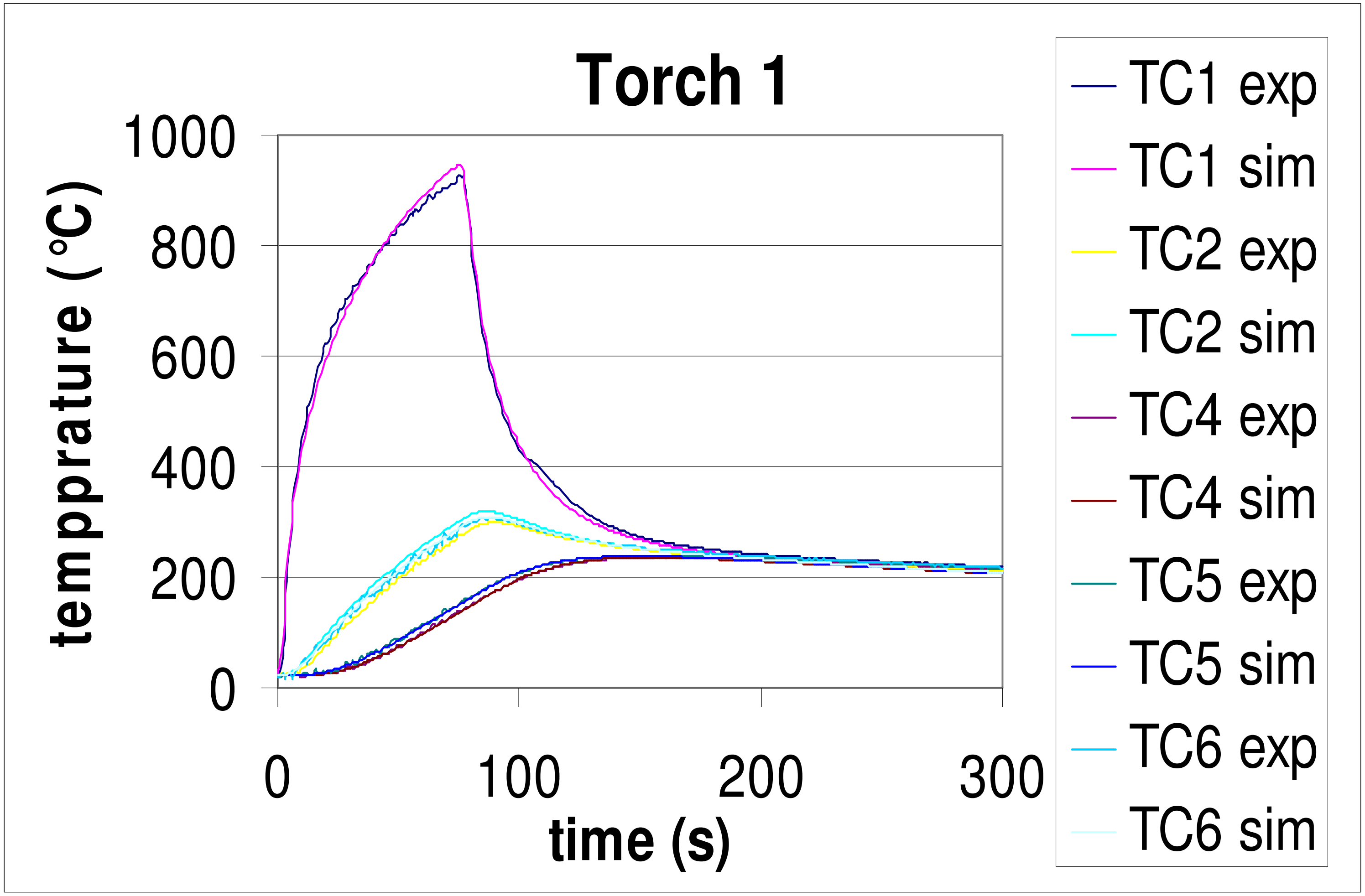
Results:

Q_1=865.65 W
r_1=1.09E-03 m
Q_2=816.42 W
r_2=3.959E-03 m

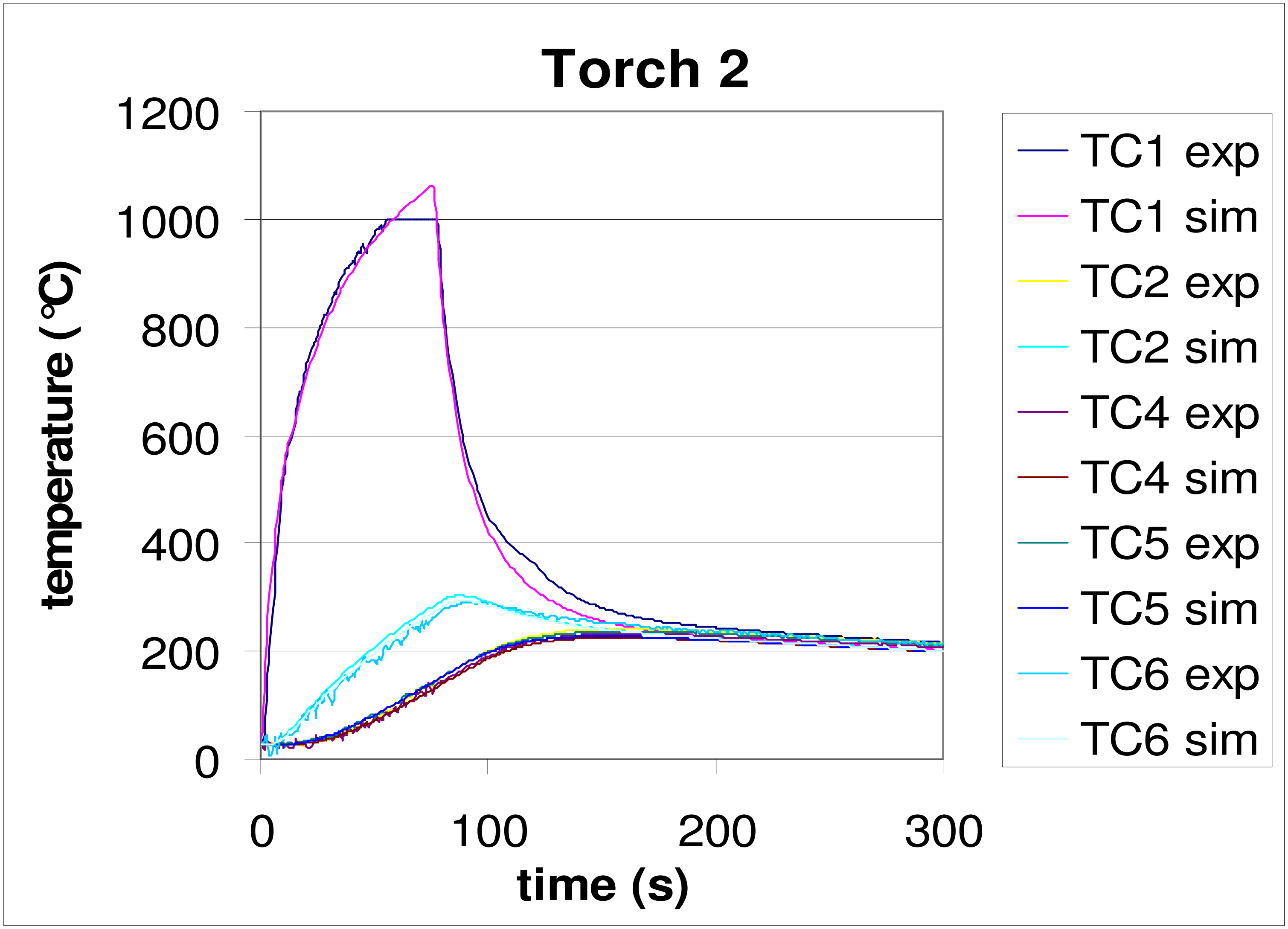


IDENTIFICATION OF THERMAL BOUNDARY CONDITIONS DURING A « DISK-SPOT » EXPERIMENT

- Comparaison between experimentations and simulations



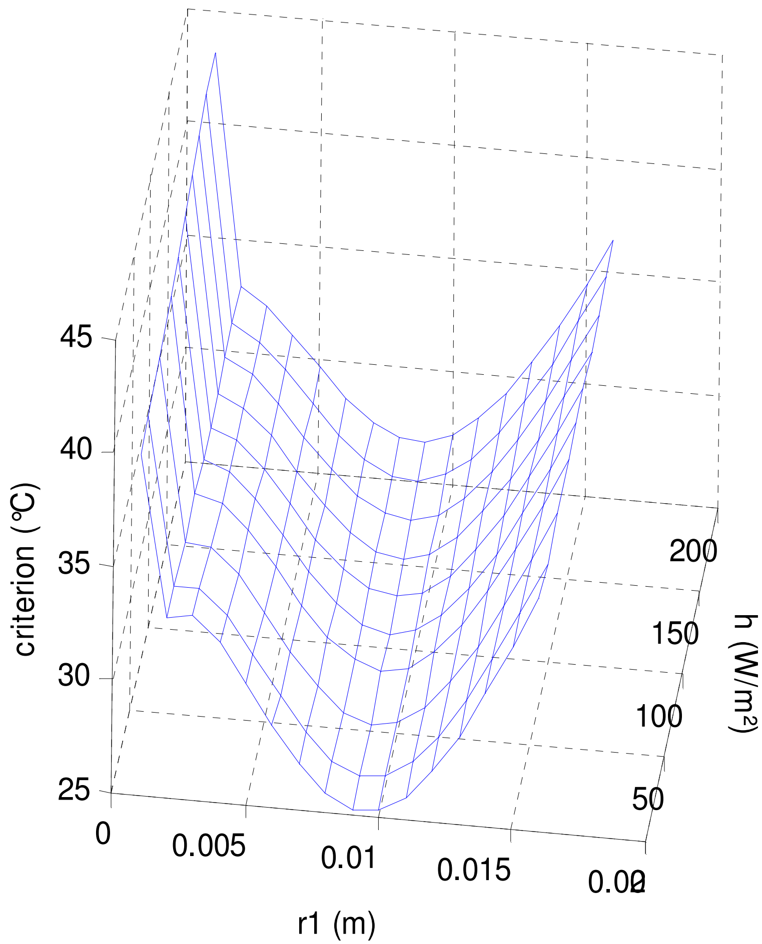
IDENTIFICATION OF THERMAL BOUNDARY CONDITIONS DURING A « DISK-SPOT » EXPERIMENT



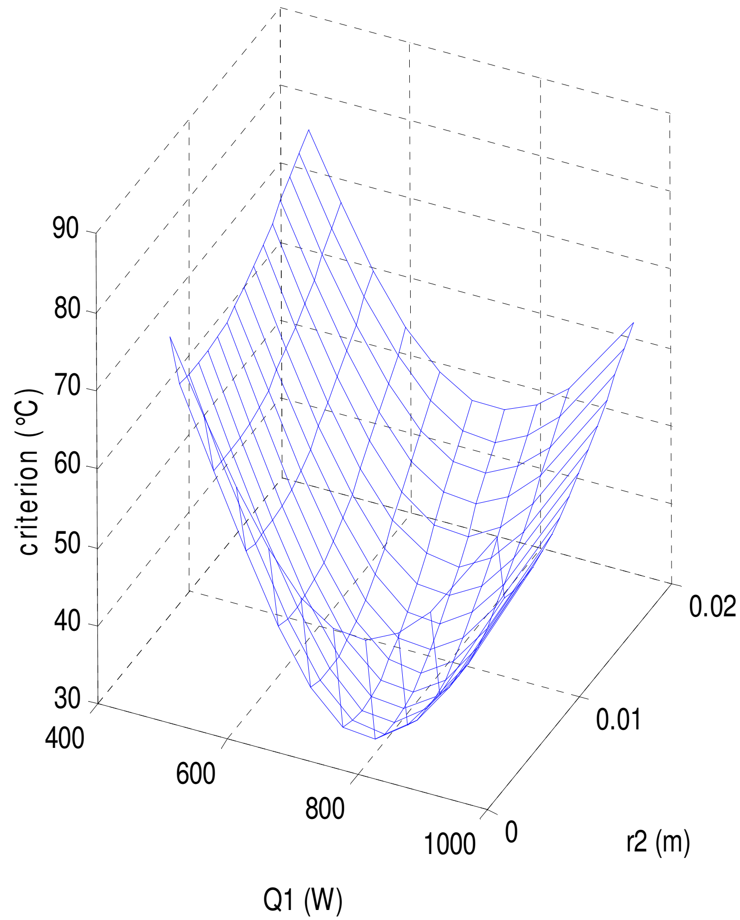
IDENTIFICATION OF THERMAL BOUNDARY CONDITIONS DURING A « DISK-SPOT » EXPERIMENT

- Verification of the critererion's convexity

In the $\{r_1,h\}$ plane

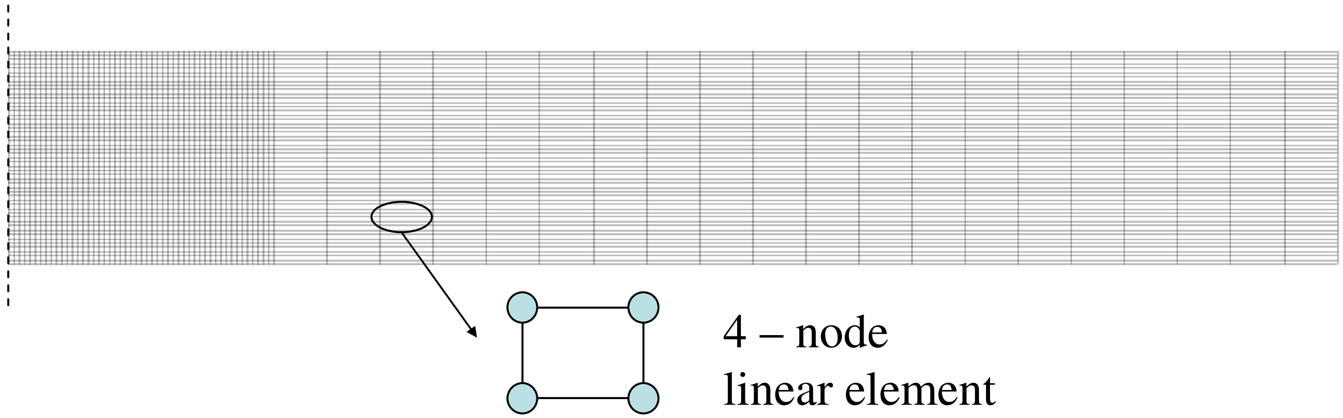


In the $\{Q_1,r_2\}$ plane



NUMERICAL SIMULATIONS OF THE DISK-SPOT EXPERIMENT

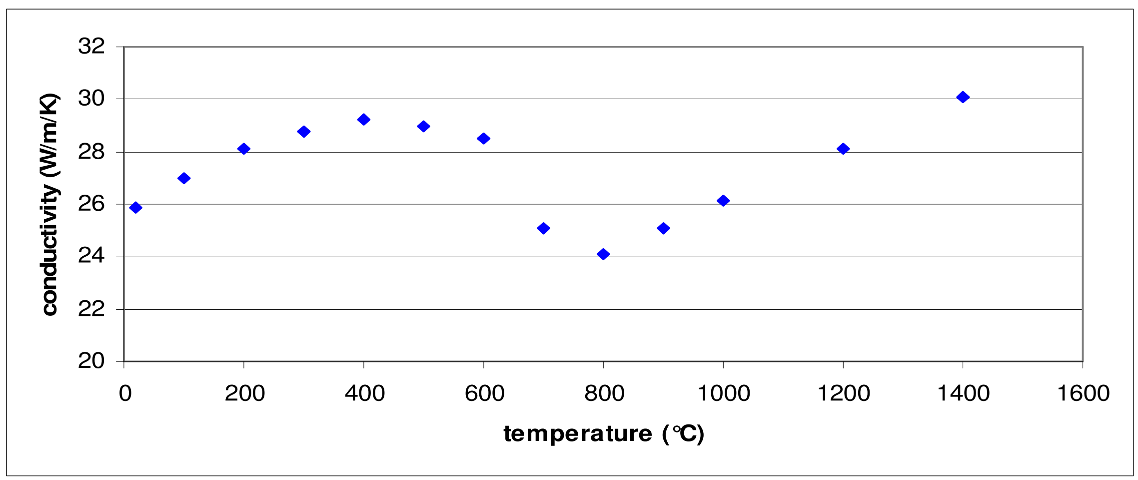
✓ CAST3M MESH



4 – node
linear element

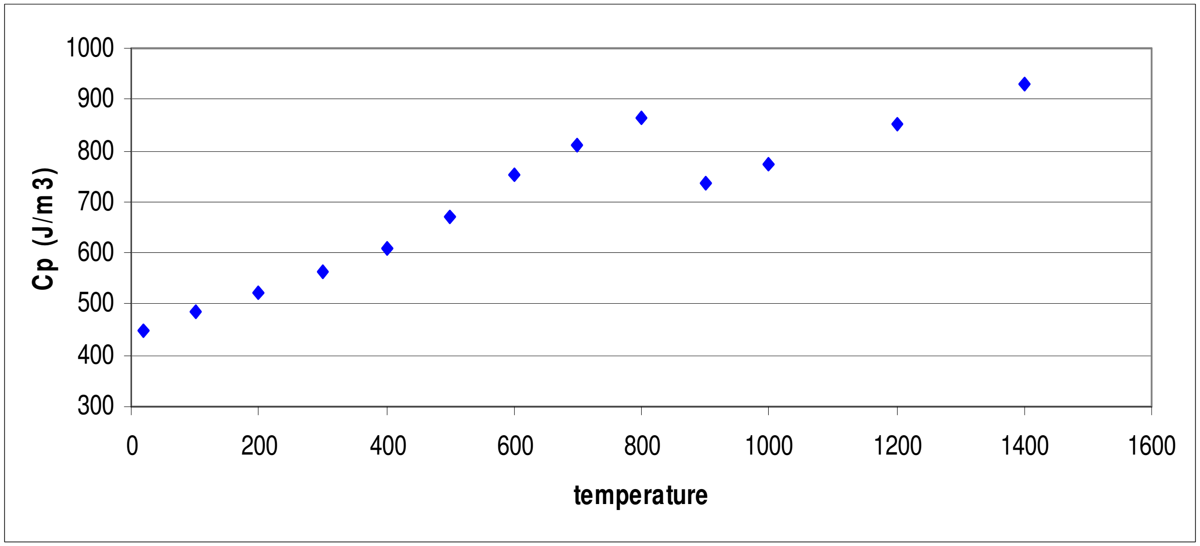
✓ THERMAL PROPERTIES

- thermal conductivity

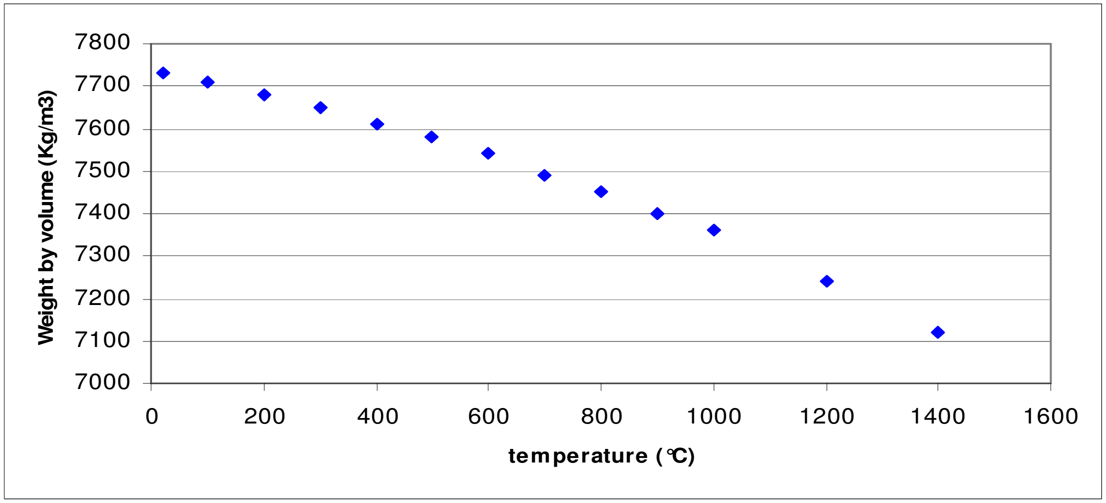


NUMERICAL SIMULATIONS OF THE DISK-SPOT EXPERIMENT

- specific heat



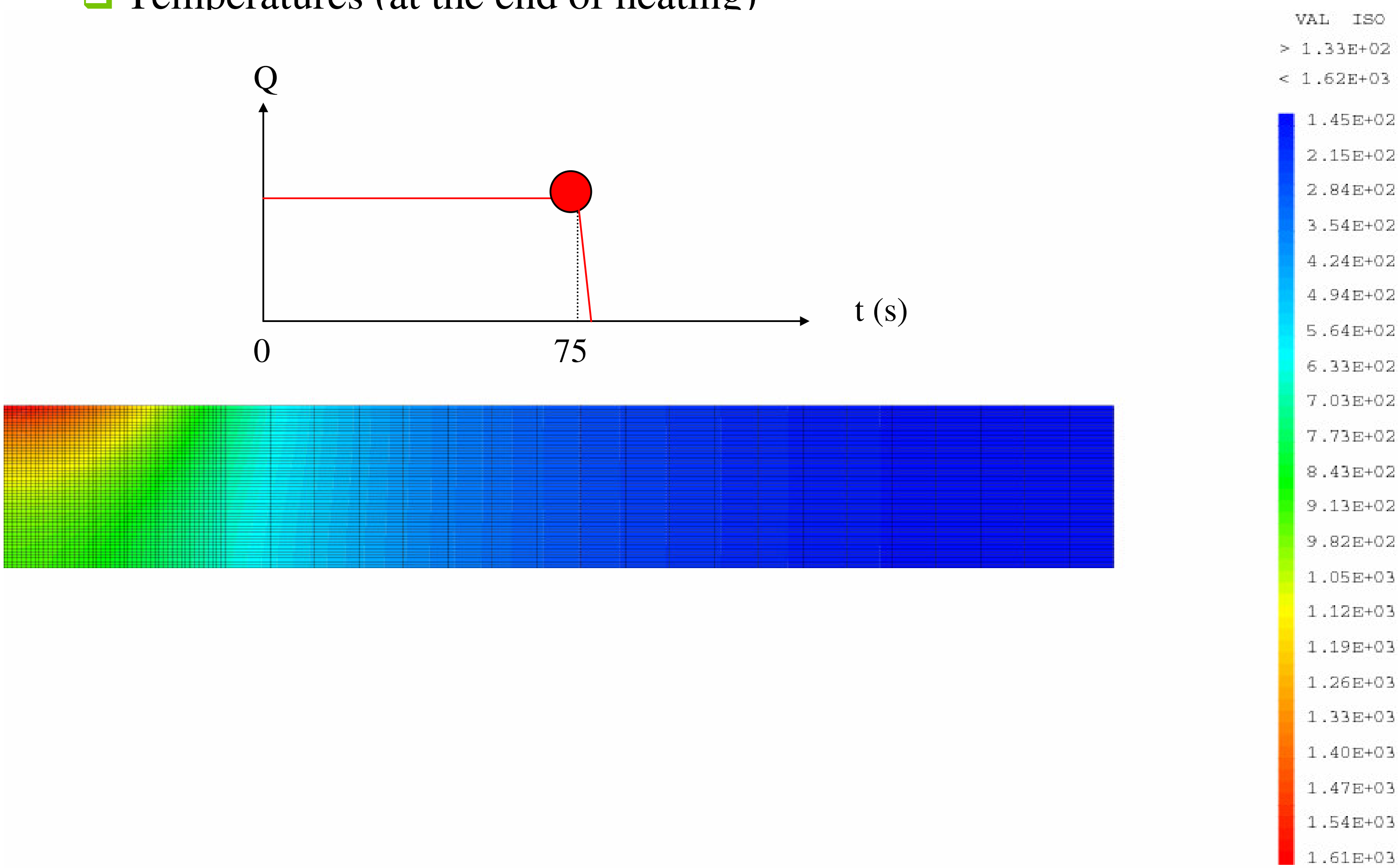
- specific mass



NUMERICAL SIMULATIONS OF THE DISK-SPOT EXPERIMENT

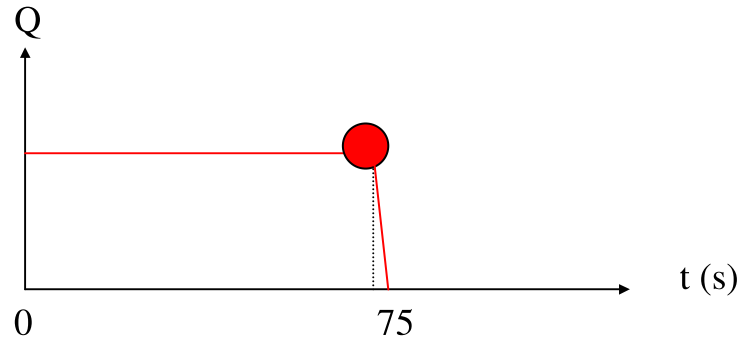
✓ SIMULATIONS FOR TORCH 1 DISK-SPOT EXPERIMENT

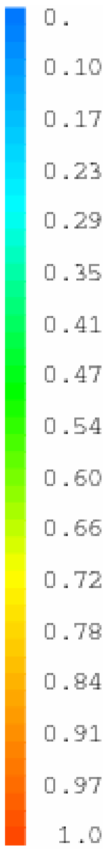
- Temperatures (at the end of heating)



NUMERICAL SIMULATIONS OF THE DISK-SPOT EXPERIMENT

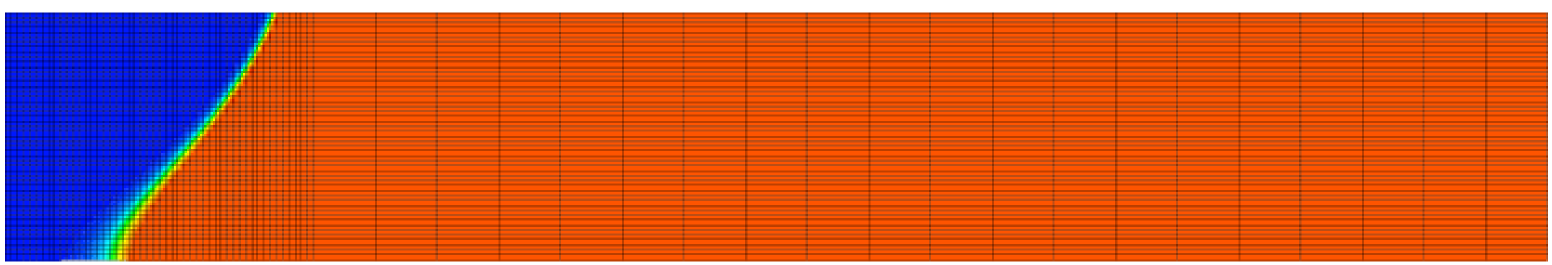
- Phases



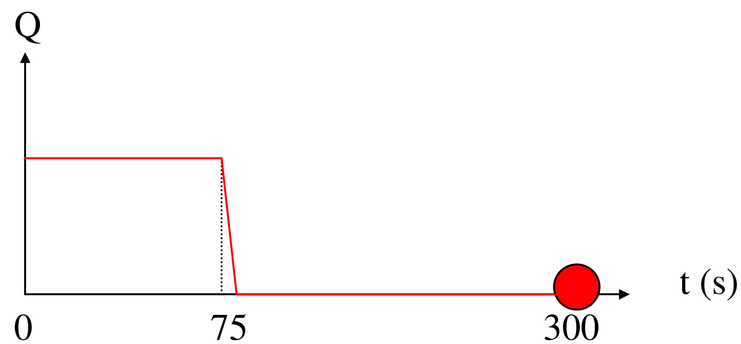


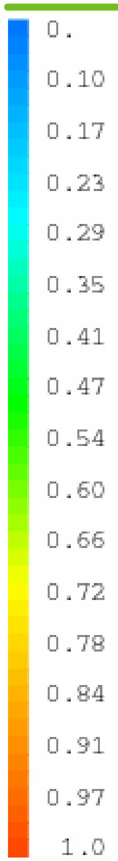
Austenite

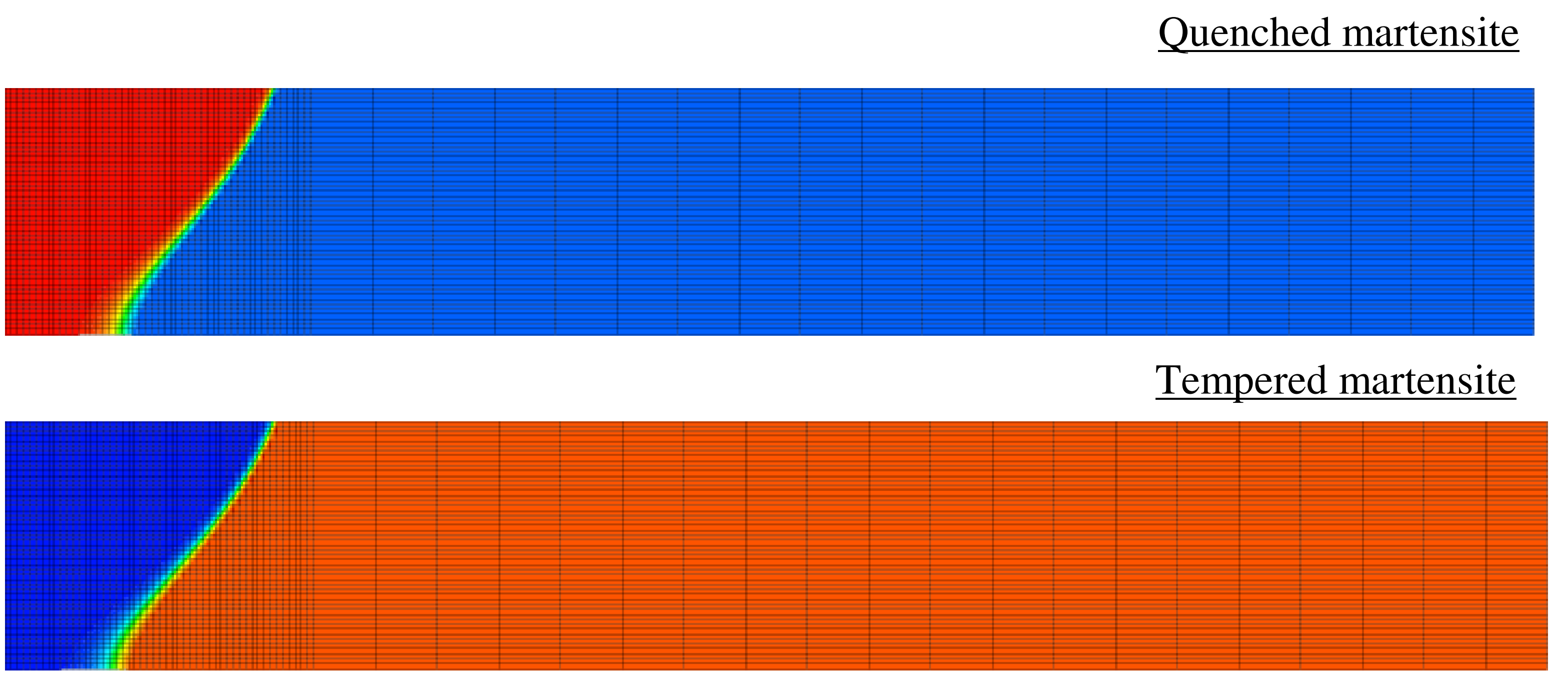
Tempered martensite



NUMERICAL SIMULATIONS OF THE DISK-SPOT EXPERIMENT





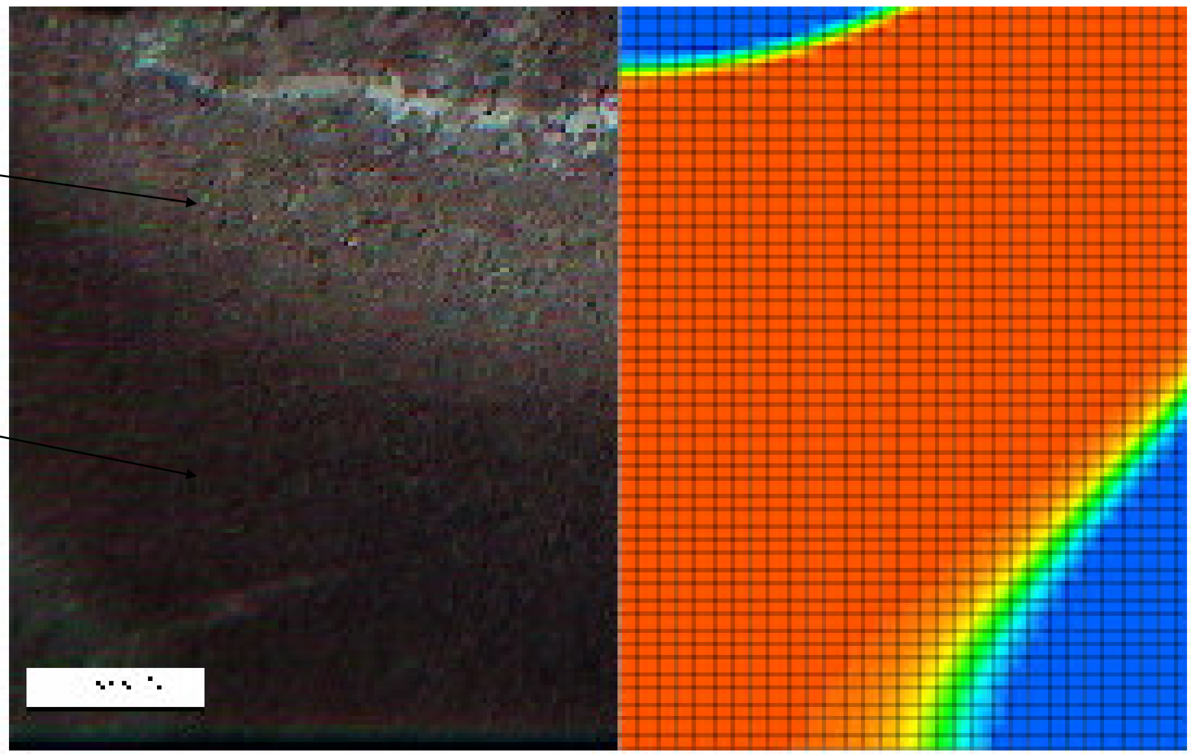


NUMERICAL SIMULATIONS OF THE DISK-SPOT EXPERIMENT

- Comparison between experiment and simulation

Fine grains

Larger grains

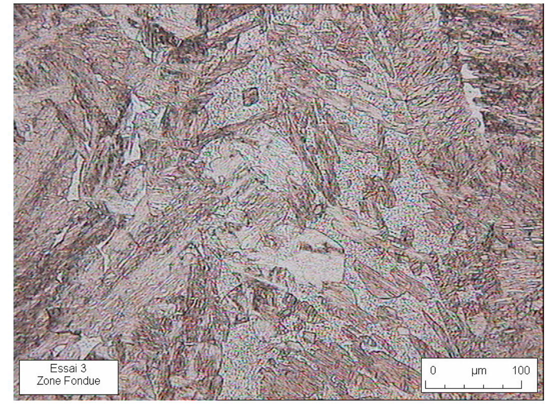


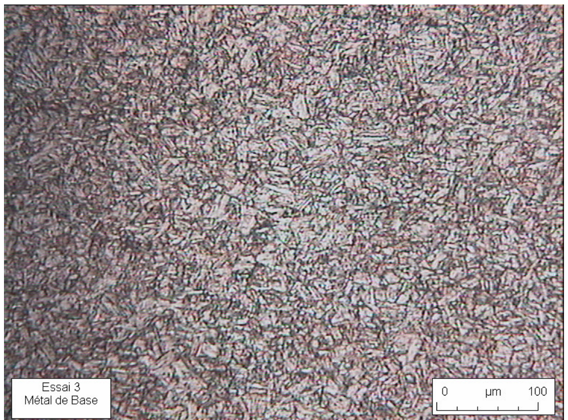
⇒ Models to be improved:

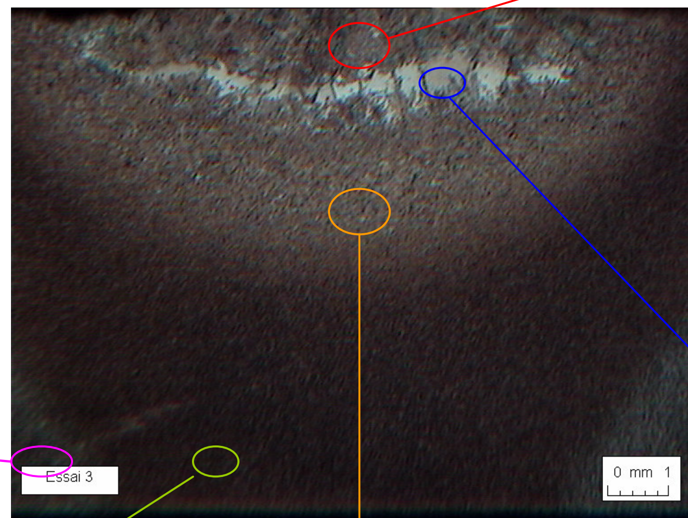
- Austenite ↔ δ ferrite
- Solid ↔ liquid
- Grain growth

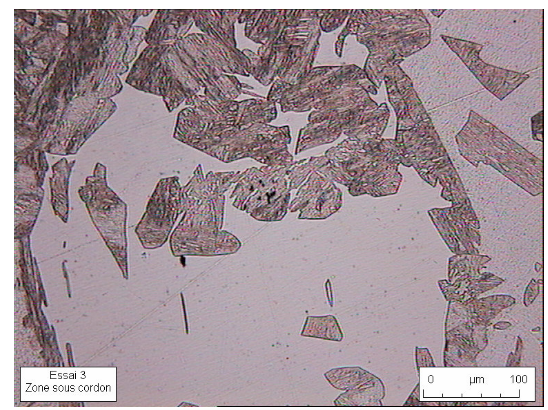
NUMERICAL SIMULATIONS OF THE DISK-SPOT EXPERIMENT

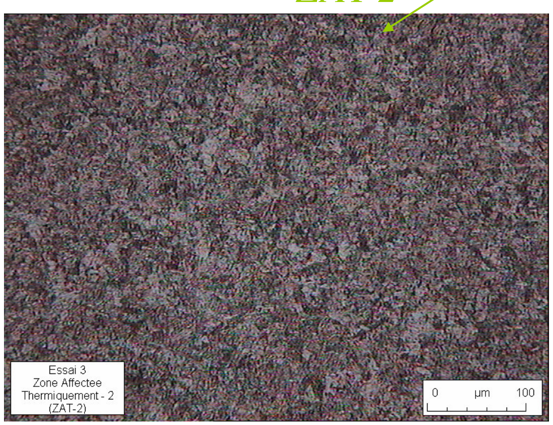
- Macrographies

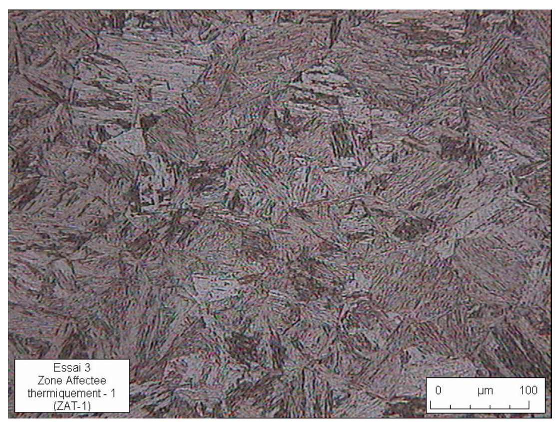












PERSPECTIVES

- ✓ VALIDATION OF THERMO-METALLURGICAL MODEL

  FOR NON CONSTANT $\dot{T}$ ANISOTHERMAL LOADING

- ✓ γ GRAIN GROWTH MODEL

- ✓ THERMO-MECHANICAL BEHAVIOUR

- ✓ MULTIPASS SIMPLE TEST

  DISK-CYCLE experiment: