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

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

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

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INTRODUCTION

OBJECTIVES OF THIS PRESENTATION

TIG torch
without filler material

Heat source

Thermo-metallo (mechanical) model for base material

Identification/validation on a simple experiment

Coupled heat transfert and metallurgical analysis
MICROSTRUCTURAL CHANGES IN T91 STEELS

✓ CHEMICAL COMPOSITION: X10CrMoVNb 9-1

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>Cu</th>
<th>Al</th>
<th>S</th>
<th>P</th>
<th>Sn</th>
<th>As</th>
<th>V</th>
<th>Nb</th>
<th>Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>% wt</td>
<td>0.099</td>
<td>0.405</td>
<td>0.216</td>
<td>0.13</td>
<td>8.305</td>
<td>0.951</td>
<td>0.054</td>
<td>0.011</td>
<td>0.002</td>
<td>0.007</td>
<td>0.006</td>
<td>0.003</td>
<td>0.201</td>
<td>0.075</td>
<td>0.004</td>
</tr>
</tbody>
</table>

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

- Liquid
- \( \gamma \) austenite, \( \delta \) ferrite and L
- \( \gamma \) austenite and \( \delta \) ferrite
- \( \gamma \) austenite
- \( \gamma \) austenite and \( M_{23}C_6 \) carbides
- \( \alpha \) ferrite and \( M_{23}C_6 \) carbides

Fe-0.1wt % C Chromium in %

Temperature in °C

\( T_m \)

L

\( L+\delta+\gamma \)

\( L+\delta+C \)

\( \gamma+\delta \)

\( \gamma+C \)

\( \alpha+\gamma+C \)

\( \alpha+\delta+C \)

\( \delta+C \)

\( \alpha+\delta+C \)

\( \gamma+\delta+\gamma \)

\( \gamma+\delta+\delta \)

\( \gamma+\delta+\gamma \)

\( \gamma+\delta+\gamma \)
VALID

SOME EFFECTS OF ALLOYING ELEMENTS:

Chromium equivalent factor by Ezaki:

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

$$= 10.811 > 8 \Rightarrow \text{Presence of } \delta\text{-ferrite}$$

CARBIDES PRECIPITATION:

In majority: $\text{M}_{23}\text{C}_6$

Others: $\text{M}_2\text{X}$
$\text{MX}$
$\text{M}_7\text{C}_3$

[Phase change]

[Duthilleul et al. 2003]
MICROSTRUCTURAL CHANGES IN T91 STEELS

✓ THERMAL COMPLEX LOADING INDUCED BY MULTIPASS WELDING:

Multi-austenitisation

Reheating of quenched martensite
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: $16500^\circ C/h > \dot{T} > 11000^\circ C/h$
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
- \((\text{Austenite} \leftrightarrow \delta \text{ferrite})\)
- Solid ↔ liquid
- Austenite → quenched martensite
- \((\text{quenched martensite} \rightarrow \text{tempered martensite})\)
SIMULATION OF THE THERMO-METALLURGICAL BEHAVIOUR OF T91 STEELS

✓ AUSTENITIC TRANSFORMATION ON HEATING:

- experimental evidence

\[
y(T) = \frac{CB}{CA}
\]

\[
\epsilon^{th} = \begin{cases} 0 & \text{if } y(T) < y_T \varepsilon_{th} \\ \frac{y(T) - y_T}{\varepsilon_{th}} & \text{if } y(T) > y_T \varepsilon_{th} \end{cases}
\]

Zhu and Devletian extrapolation:

\[
T(y_{eq}) = T(y, T) - C \left[ \frac{\dot{T}}{T} \exp \left( \frac{E}{RT} \right) \right]^{\frac{1}{3}}
\]
SIMULATION OF THE THERMO-METALLURGICAL BEHAVIOUR OF T91 STEELS

Non equilibrium transformation [Brachet 1998]

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

Equilibrium transformation (J.M.A. law)

\[
y_{eq}(T) = 1 - \exp\left(-K_0(T - A_{eq0})^{m_0}\right)
\]
SIMULATION OF THE THERMO-METALLURGICAL BEHAVIOUR OF T91 STEELS

- incubation law

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

Phenomenological model:
\[
t_i(T) = A(A_{\text{sat}} - T) \exp \left( \frac{C}{T - A_{eq0}} \right)
\]
SIMULATION OF THE THERMO-METALLURGICAL BEHAVIOUR OF T91 STEELS

- identification

Inverse identification with Matlab©

\( (A_{\text{eq}}, K_0 \text{ and } m_0) \), \( (A, A_{\text{1sat}} \text{ and } C) \) and \( (K, W \text{ and } n) \)

- equilibrium
- incubation
- growth

First order Runge-Kutta scheme with \( \Delta t_{\text{step}} = 1^\circ \text{C} \):

![Graph showing austenite fraction vs. temperature for different cooling rates and conditions](image-url)
SIMULATION OF THE THERMO-METALLURGICAL BEHAVIOUR OF T91 STEELS

MARTENSITIC TRANSFORMATION:

Koistinen-Marburger model: \( y_m(T) = y_{\gamma_0}(1 - \exp(-K_m(M_s - T))) \)

![Graph showing martensite fraction vs. Ms - T (°C)]
IDENTIFICATION OF THERMAL BOUNDARY CONDITIONS DURING A « DISK-SPOT » EXPERIMENT

DISK-SPOT SIMPLE TIG WELDING TEST:

2.4 mm tungsten electrode (with 2% TH)

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

TEMPERATURE RESULTS:

8 mm

50 mm

TC1

TC2

TC3

TC4

TC5

TC6

0 500 1000 1500 2000

time (s)

0 200 400 600 800 1000

temperature (°C)

A_{eq0}

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

DISPLACEMENT RESULTS:

Vertical displacements:

Radial displacements:

DEP1 DEP2 DEP3 DEP4 DEP5 DEP6 DEP7 DEP8
IDENTIFICATION OF THERMAL BOUNDARY CONDITIONS DURING A « DISK-SPOT » EXPERIMENT

BOUNDARIES CONDITIONS TO IDENTIFY:

- Heat source parameters
- Convection and radiation

Hypothesis:
Low uncertainties on \( \rho \), \( C_p \) and \( \lambda \)

Infinite Gaussian heat source:

\[
P_s = Q_e e^{-\frac{3r^2}{\alpha^2}}
\]

\( 0 < r < r_{\text{max}} \)

Convection/radiation model:

\[
q_v = \overline{h}(T - T_{\text{ext}})
\]

\( h = h(T) \) on \( S_{\text{nord}} \) and \( S_{\text{sud}} \)
IDENTIFICATION OF THERMAL BOUNDARY CONDITIONS DURING A « DISK-SPOT » EXPERIMENT

IDENTIFICATION OF \( h(T) \) FOR LOW TEMPERATURES:

- **Experiment**

  **Initial state**
  Oven heated disk

  \[ T_0 = 800°C \]

  **Air cooling**
  TC6(T)
  TC5(T)
  TC1(T)
  TC3(T)

  \[ \text{tc}1 \] \[ \text{tc}3 \] \[ \text{tc}5 \] \[ \text{tc}6 \]

  \[
  \begin{align*}
  \text{TC1(T)} & \quad 0 \quad 50 \quad 100 \quad 150 \quad 200 \quad 250 \quad 300 \\
  \text{TC3(T)} & \quad 0 \quad 50 \quad 100 \quad 150 \quad 200 \quad 250 \quad 300 \\
  \text{TC5(T)} & \quad 0 \quad 50 \quad 100 \quad 150 \quad 200 \quad 250 \quad 300 \\
  \text{TC6(T)} & \quad 0 \quad 50 \quad 100 \quad 150 \quad 200 \quad 250 \quad 300 \\
  \end{align*}
  \]

  \[
  \begin{align*}
  \text{time (s)} & \quad 0 \quad 50 \quad 100 \quad 150 \quad 200 \quad 250 \quad 300 \\
  \text{temperature (°C)} & \quad 0 \quad 100 \quad 200 \quad 300 \quad 400 \quad 500 \quad 600 \quad 700 \quad 800 \quad 900 \\
  \end{align*}
  \]
IDENTIFICATION OF THERMAL BOUNDARY CONDITIONS DURING A « DISK-SPOT » EXPERIMENT

- Inverse identification

Results:

[T(t)]_{exp} vs [T(t)]_{sim}
IDENTIFICATION OF THERMAL BOUNDARY CONDITIONS DURING A « DISK-SPOT » EXPERIMENT

Two different experiments with same $h(T) \Rightarrow$ convex problem

- Presentation of the new experimental protocol

Torch 1
16 mm

$Q_1, r_1$

Temperatures for experiment 1

[T(t)]_exp vs [T(t)]_sim

Torch 2
12 mm

$Q_2, r_2$

Temperatures for experiment 2

[T(t)]_exp vs [T(t)]_sim

Results:

$Q_1=865.65$ W

$r_1=1.09E^{-03}$ m

$Q_2=816.42$ W

$r_2=3.959E^{-03}$ m

\[ \frac{\text{Temperature (°C)}}{\text{h (W/m²)}} \]

\[ \frac{\text{Temperature (°C)}}{\text{Temperature (°C)}} \]
IDENTIFICATION OF THERMAL BOUNDARY CONDITIONS DURING A « DISK-SPOT » EXPERIMENT

- Comparaison between experimentations and simulations

![Graph showing temperature (°C) over time (s) for different torches and experiments vs simulations]

- TC1 exp
- TC1 sim
- TC2 exp
- TC2 sim
- TC4 exp
- TC4 sim
- TC5 exp
- TC5 sim
- TC6 exp
- TC6 sim
IDENTIFICATION OF THERMAL BOUNDARY CONDITIONS DURING A « DISK-SPOT » EXPERIMENT
Verification of the criterion'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

![Graph showing thermal conductivity vs. temperature](image-url)
NUMERICAL SIMULATIONS OF THE DISK-SPOT EXPERIMENT

- specific heat

- specific mass
Temperatures (at the end of heating)
NUMERICAL SIMULATIONS OF THE DISK-SPOT EXPERIMENT

Phases

- Austenite
- Tempered martensite

Q vs. t (s) plot:

0 75

0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

Color scale:

- Red: Austenite
- Orange: Tempered martensite
NUMERICAL SIMULATIONS OF THE DISK-SPOT EXPERIMENT

Quenched martensite

Tempered martensite

Q
0 75 300 t (s)

0. 0.10 0.17 0.23 0.29 0.35 0.41 0.47 0.54 0.60 0.66 0.72 0.78 0.84 0.91 0.97 1.0
Comparison between experiment and simulation

Models to be improved:
- Austenite $\leftrightarrow$ $\delta$ ferrite
- Solid $\leftrightarrow$ liquid
- Grain growth

Fine grains

Larger grains
NUMERICAL SIMULATIONS OF THE DISK-SPOT EXPERIMENT

- **Macrographies**

  - Molten zone
  - δ-ferrite zone
  - Base metal
  - ZAT 1
  - ZAT 2

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PERSPECTIVES

☑ VALIDATION OF THERMO-METALLURGICAL MODEL FOR NON CONSTANT $T$ ANISOTHERMAL LOADING

☑ $\gamma$ GRAIN GROWTH MODEL

☑ THERMO-MECHANICAL BEHAVIOUR

☑ MULTIPASS SIMPLE TEST

DISK-CYCLE experiment: