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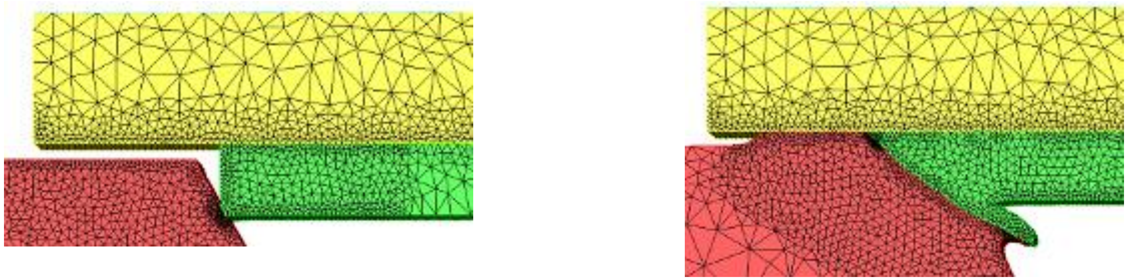

Numerical Modeling of Fuel Rods Resistance Butt Welding

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AFM - 11ème colloque modélisation et simulation numérique du soudage

28/04/2013, Maison de la Mécanique, Paris La Défense

MINES ParisTech

Cemef
CENTRE DE MISE EN FORME DES MATERIAUX

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Outline

- **Introduction**
  - **The Resistance Butt Welding (RBW) process**
  - **Numerical modeling of Zr manufacturing processes**
- **The RBW model**
  - **Meshing of the parts**
  - **Mechanical, thermal and electrical formulations**
  - **Validation of the model**
- **Application to RBW process optimization**
- **Conclusion**

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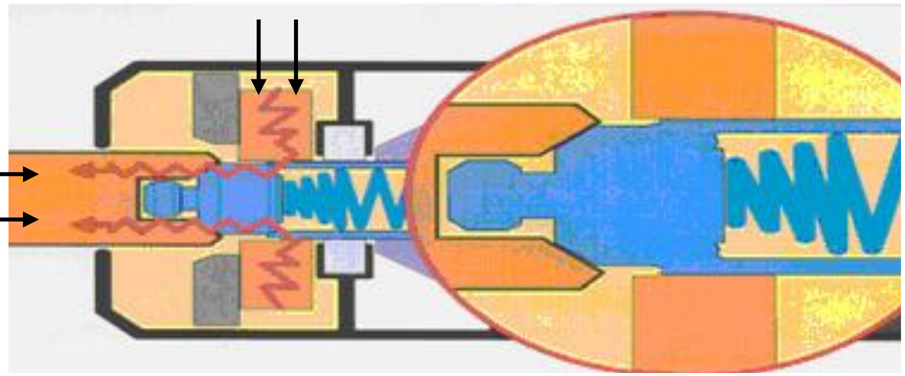
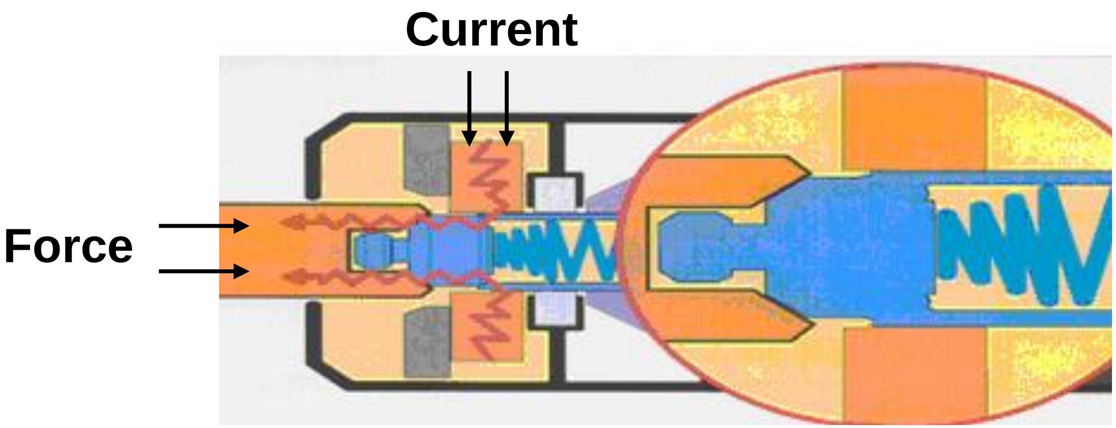
The Resistance Butt Welding (RBW) process



- **RBW : A solid state welding process**
  - **Application of a constant force on the plug**
  - **Injection of a current, going from cladding electrode to plug electrode, through the tube / plug interface**
  - **The tube / plug contact resistance acts as a heat source that allows to deform and weld the two parts**

Introduction

The Resistance Butt Welding (RBW) process

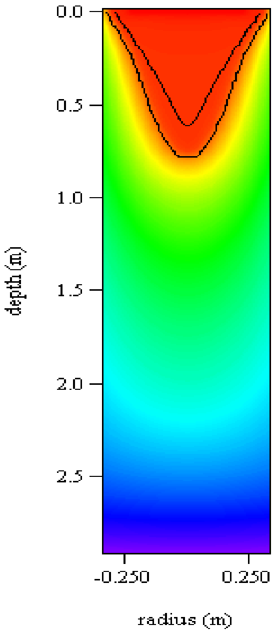


- **RBW process main advantages**
  - **Very good corrosion behavior of the welds, not affected by any potential pollution of welding atmosphere**
  - **No volumetric defects due to solidification shrinkage, X-rays examinations are then useless**

Introduction

Numerical modeling of Zr manufacturing processes

- **Since the 1990's, CEZUS uses numerical modeling for a mastering of the whole processes, together with microstructure expertise at each step of the manufacturing route**
  - **Extractive metallurgy**
  - **Melting**
  - **Forming processes**
    (Forging, Extrusion, Rolling, …)
  - **Heat treatments, Quenching**
  - **US Inspections**



VAR Melting

Temperature map

ASTM STP 1529, Chengdu 2010

Quenching

ASTM Hyderabad 2013

Cold Pilgering

ASTM STP 1354, Toronto 1998

J. Mater. Process. Technol., Vol. 117, 2006

Introduction

Numerical modeling of Zr manufacturing processes

- **For RBW process, the purpose of numerical modeling is to offer a tool for:**
  - **A better understanding of this multi-physical and very brief process**
  - **The definition of the process parameters for optimized welds**
  - **The reduction of welding tests for new configurations**

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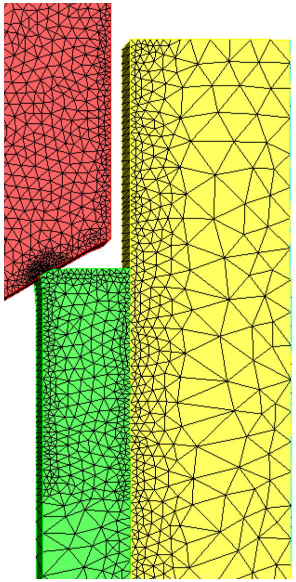
The RBW model

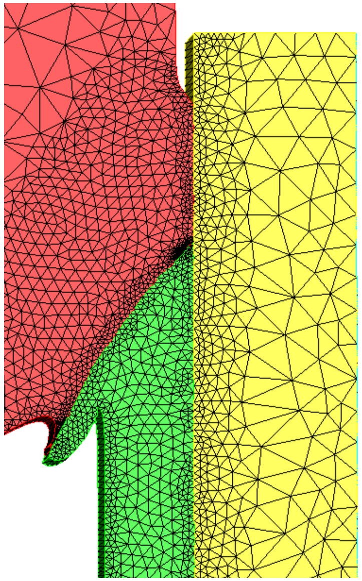
Meshing of the parts

- **FORGE™**
  - **Finite element software**
  - **Remeshing as the strain increases**

  → Accurate results for large deformations



Initial meshing of the parts

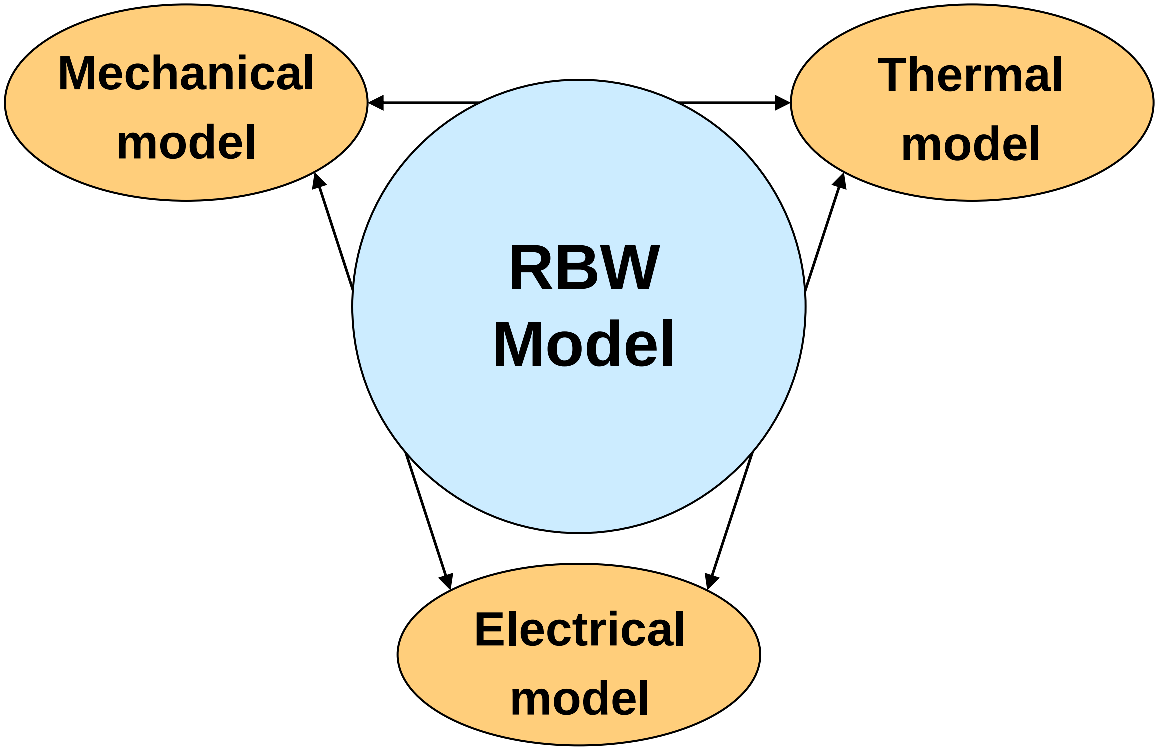


Final meshing of the parts

The RBW model

Mechanical, thermal and electrical formulations

- **Electrical phenomena were fully coupled with thermal and mechanical ones (collaboration with CEMEF / Mines ParisTech)**



The RBW model

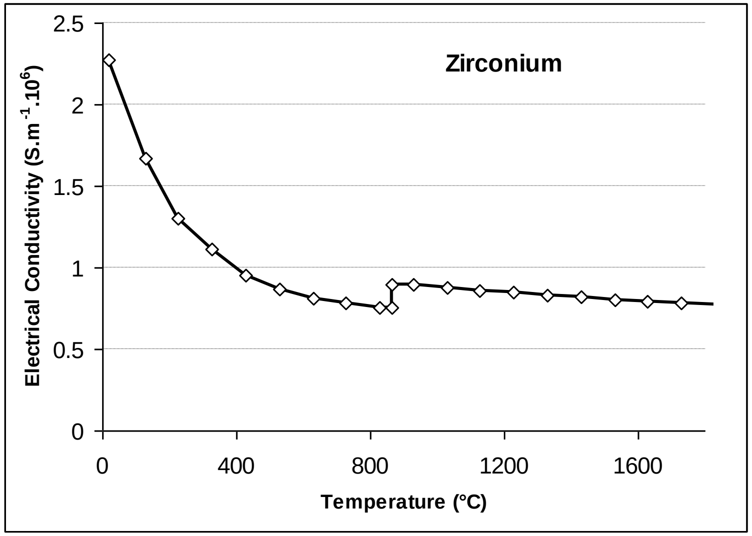
Mechanical, thermal and electrical formulations

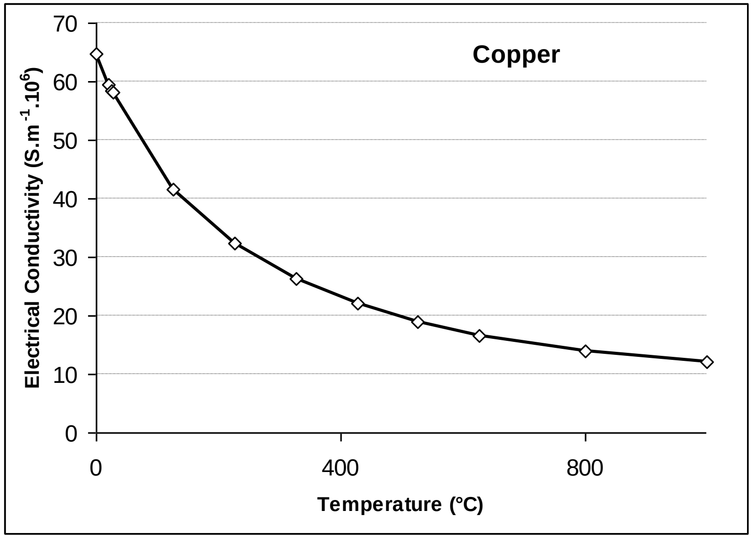
- **Electrical formulations and material properties**

<u>Volume</u>: Poisson equation

$$-div\left(\sigma_{elec}(T)\,grad(V)\right) = 0$$

- **Electrical conductivity is a function of Temperature**





Electrical conductivity as a function of temperature

The RBW model

Mechanical, thermal and electrical formulations

- **Electrical formulations and material properties**

Cladding electrode contact

Neumann condition

$$\sigma_{elec}(T)\,\overrightarrow{grad}(V).\vec{n} = \vec{J}.\vec{n}$$

Plug electrode contact

Dirichlet condition

$$V = 0$$

Free surfaces

$$\sigma_{elec}(T)\,\overrightarrow{grad}(V).\vec{n} = 0$$

- **Surfaces and interfaces :**
  - **Current applied with a Neumann condition on the cladding electrode**
  - **Dirichlet condition applied on the plug electrode for the current exit**
  - **At the free surfaces, normal current flux is set to zero**
  - **At the plug / tube interface, the electrical resistance is a function of pressure and temperature**

The RBW model

Mechanical, thermal and electrical formulations

- **Thermal formulations and material properties**

Volume

$$\rho C(T)\frac{\partial T}{\partial t} - div\left(k(T)\,grad(T)\right) = P_{mech} + P_{elec}$$

$$P_{mech} = \sigma : \dot{\varepsilon}$$

$$P_{elec} = \sigma_{elec}(T)\left\| grad(V) \right\|^2$$

Free surface

$$-k(T)\frac{dT}{dn} = h\left(T - T_{ext}\right) + \varepsilon_T \sigma \left(T^4 - T_{ext}^4\right)$$

Contact surface

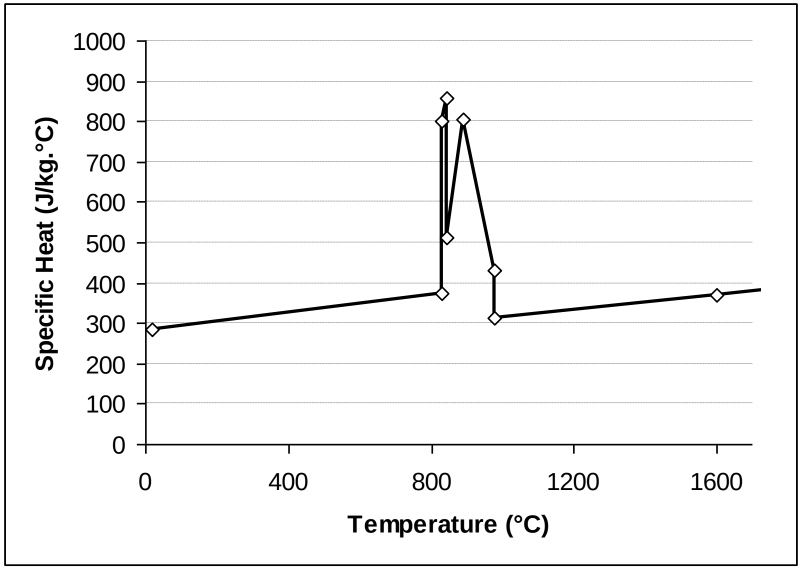
$$-k(T)\frac{dT}{dN} = \frac{1}{R_{c\_therm}}\left(T_1 - T_2\right) + \frac{1}{R_{c\_elec}}\left(V_1 - V_2\right)^2$$

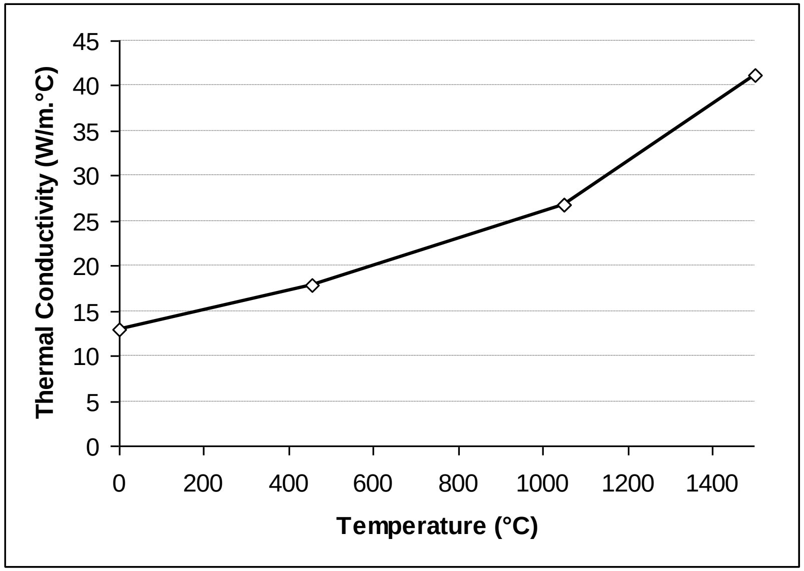
- **Mechanical and Electrical dissipated energy act as a heat source**
- **At free surfaces, convection and radiation are taken into account**
- **At contact surfaces, a thermal resistance is taken into account, as well as the heat source due to electrical contact resistance**

The RBW model

Mechanical, thermal and electrical formulations

Thermal formulations and material properties



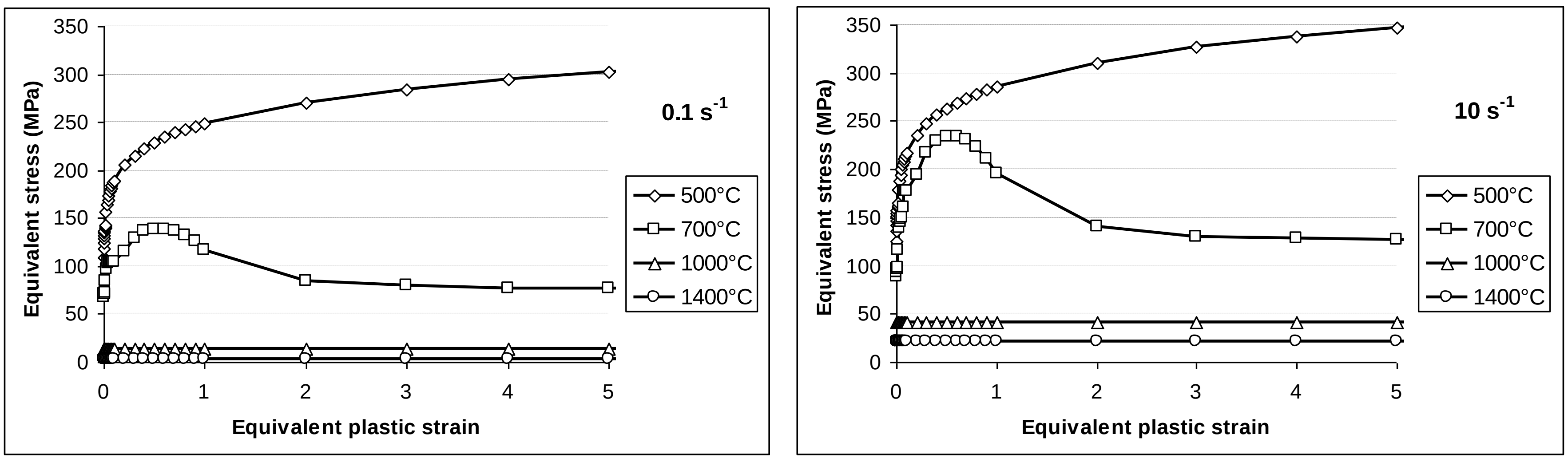


- **Specific Heat and Thermal Conductivity are a function of temperature**
- **α→β phase change is taken into account for Specific Heat**

The RBW model

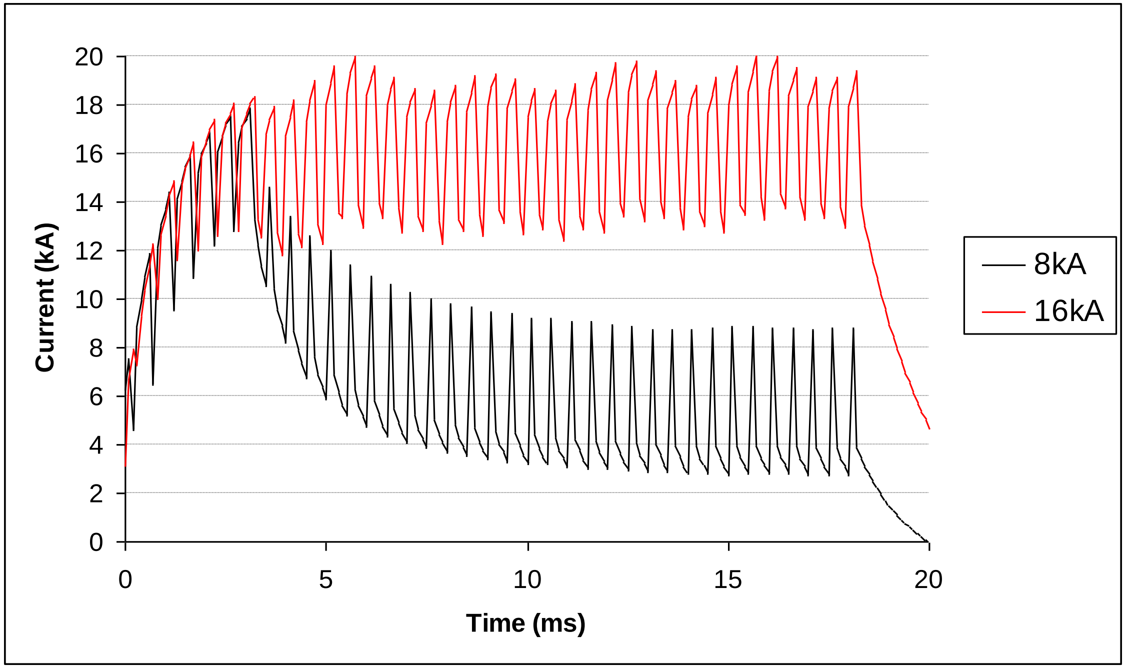
Mechanical, thermal and electrical formulations

- **Mechanical formulations and material properties**
  - **The solid mechanics model: Classical virtual work principle**
  - **Tube and Plug behavior:**
    Flow stress is a function of strain, strain rate and temperature
  - **Electrodes behavior: A rigid behavior is assumed**
  - **Friction behavior at the tube / plug interface: Sticking contact**
  - **Friction behavior with electrodes: Sliding contact**



Flow stress, as a function of strain, strain rate and temperature

- **The model was first tested on two welding configuration, and validated by comparison with experimental results**

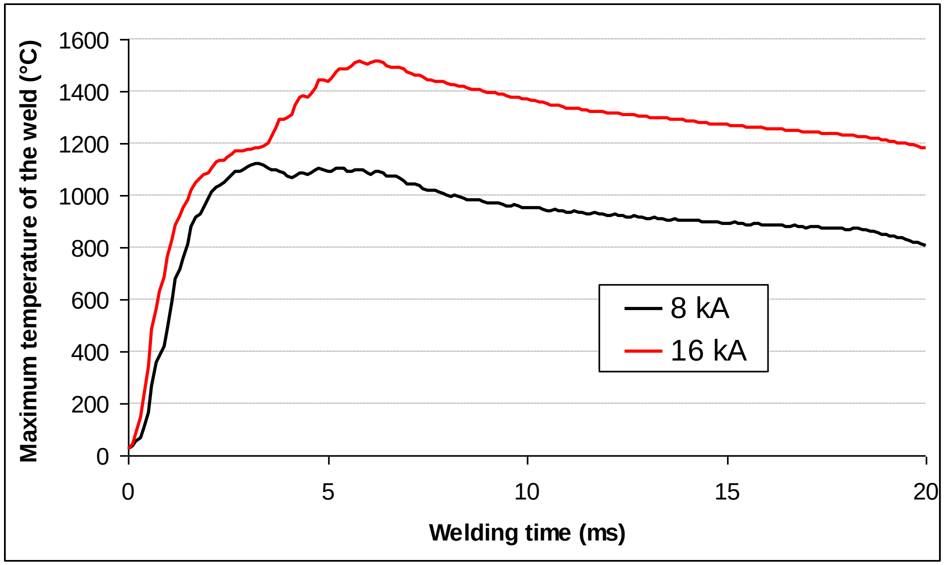


Applied current for the two validation cases

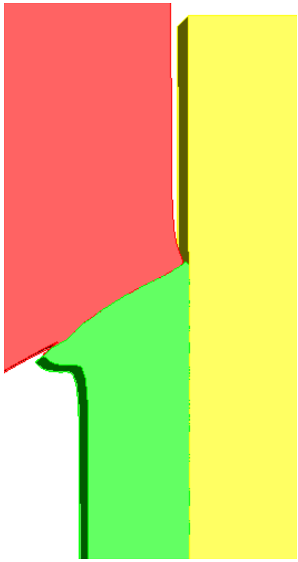
The RBW model

Validation of the model

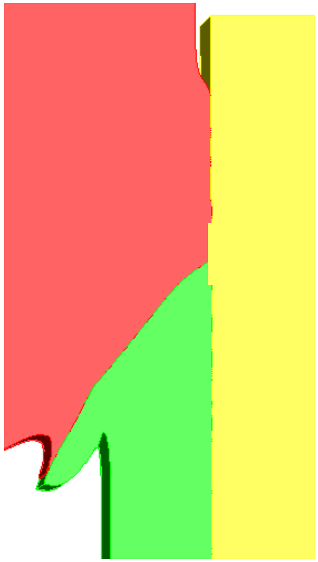
- **As a result of a higher reached temperature for higher current, the 16kA weld is larger than the 8kA one**



Maximum temperature during welding



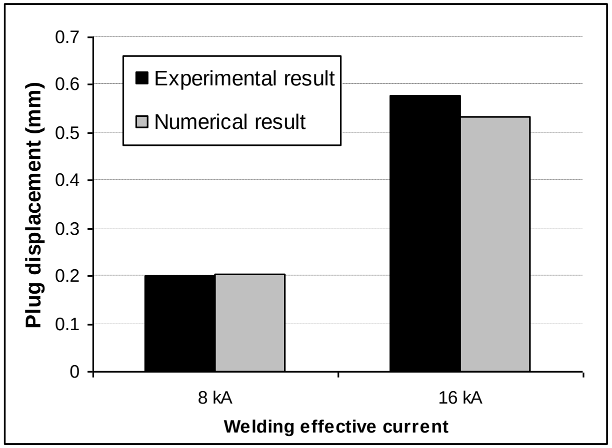
8kA weld geometry

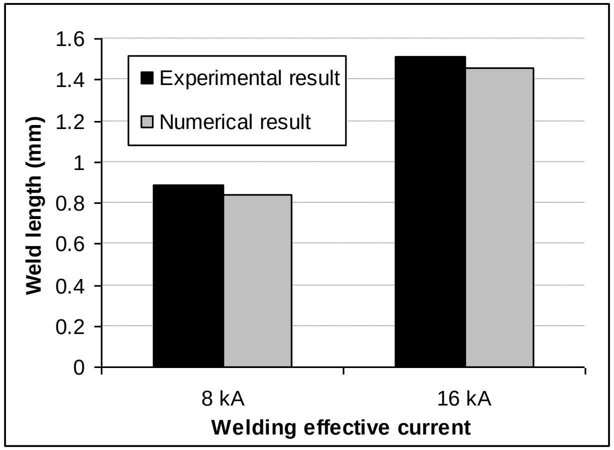


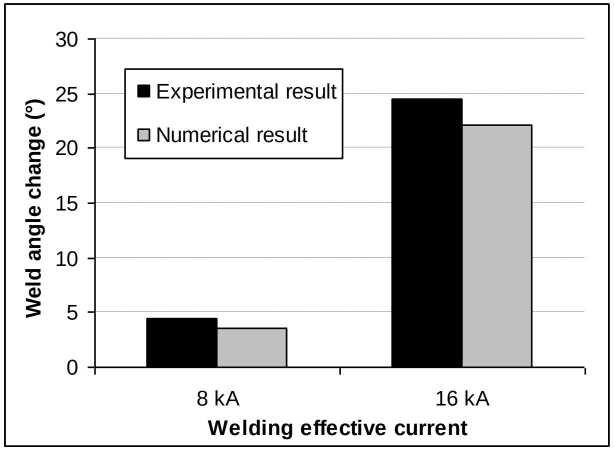
16kA weld geometry

The RBW model

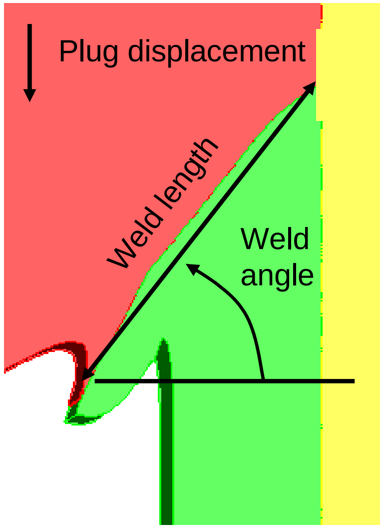
Validation of the model







- **Validation of the model, without any adjustment of the parameters (neither boundary conditions nor material parameters)**



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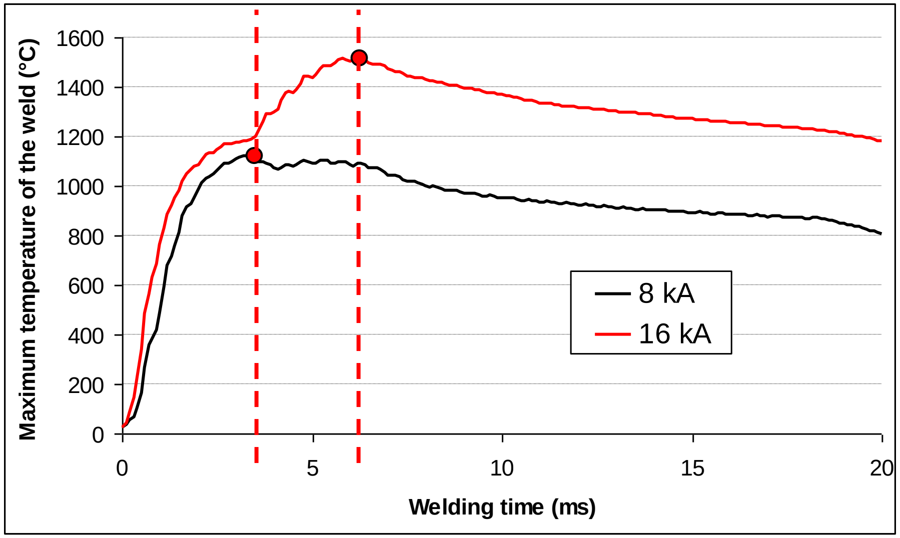
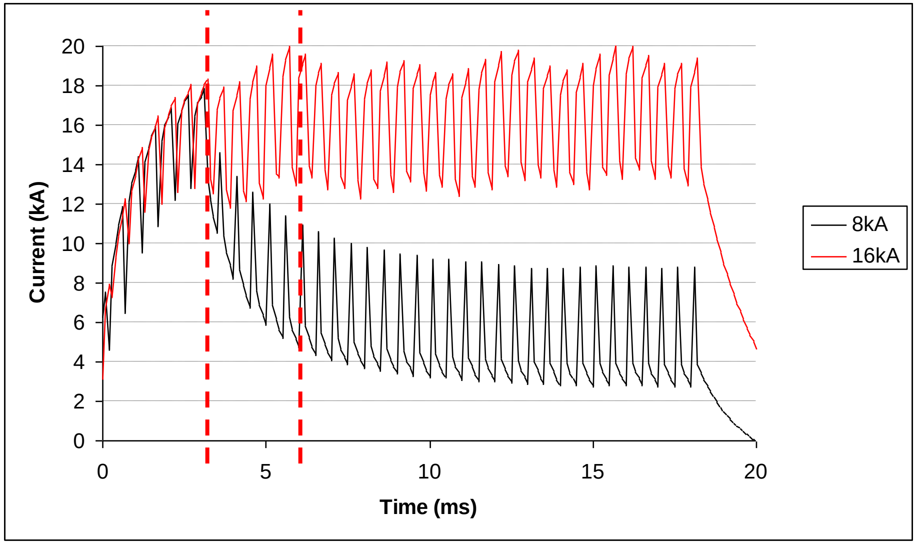
Application to RBW process optimization

- **Understanding the resistance butt welding process**
  - **For the 8kA current, maximum temperature is reached after 3 ms. This time corresponds to the maximum current value**
  - **For the 16kA current, maximum temperature is reached after 6 ms. This time does not correspond to the maximum current value, which is quite constant up to 18 ms**



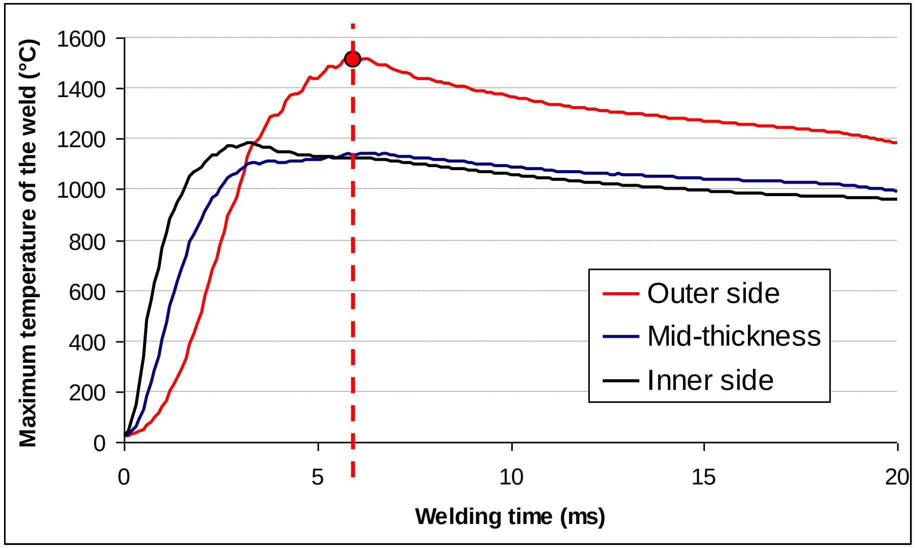
Maximum temperature during welding



Applied current for the two validation cases

Application to RBW process optimization

- **Temperature recorded by 3 sensors**
  - **Up to 3 ms, the maximum temperature is located at the inner side of the weld**
  - **Then the maximum temperature moves to the outer side of the weld**
  - **The maximum temperature is reached after 6 ms**
  - **Then, the temperature decreases whereas the current is still high**
  - **The temperature is finally decreasing faster when current decreases after 18 ms**



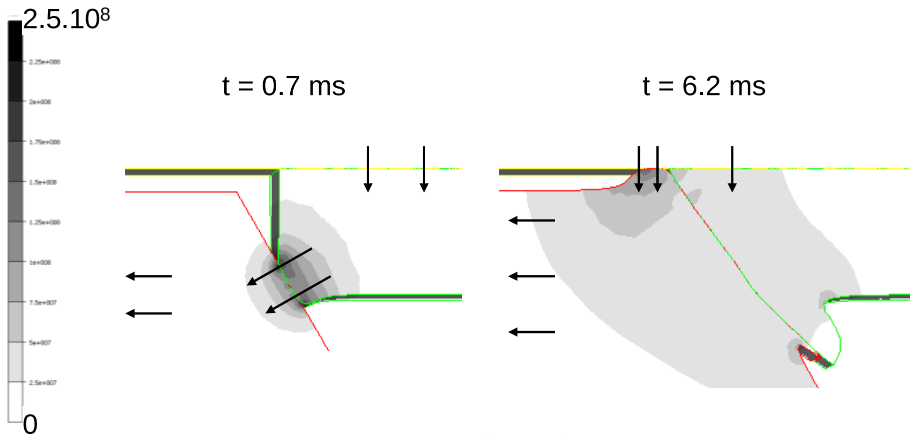
Temperatures at outer side, mid-thickness and inner side during welding for the 16kA current

- **What happens at 6 ms ?**

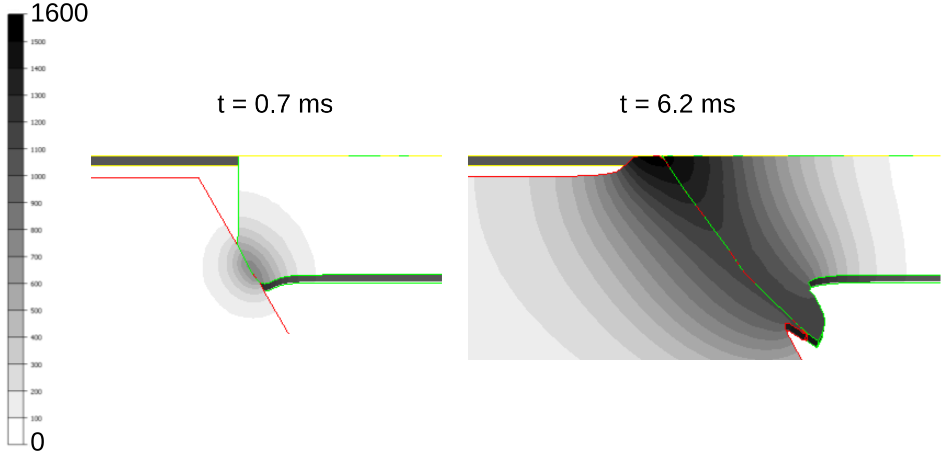
FUEL

Application to RBW process optimization

- **Understanding the temperature cycle during welding**
  - **Beginning of welding: Temperature increases at the inner part of the weld, where the tube is in contact with the plug**
  - **As the weld increases, the current goes by the shorter way, at the outer side of the weld. Temperature is thus increasing at the outer side**
  - **At 6 ms, plug comes in contact with tube electrode. A short-circuit is formed and temperature starts to decrease slowly, as electrode / plug contact resistance still heat the weld**
  - **After 18 ms, current turns down and temperature decreases faster up to the end of welding**



Current density



Temperature

Application to RBW process optimization

- **Going further for an optimization of RBW process**
  - **Since its validation, this model, coupled with a burst test model, is now used to optimize the welds quality**
- **On going studies deals with:**
  - **Definition of a weld quality criterion, based on the thermo-mechanical history of the weld and relevant experimental test matrix**
  - **Optimization of the welding process (current type and amplitude, welding time, initial geometry of the parts, …)**
  - **Definition of welding parameters for new configurations and new alloys**

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Conclusion

- **Development of the RBW model**
  - **Use of FORGE™ software, which allows large deformations with remeshing**
  - **Coupling between Mechanical, Thermal and Electrical phenomena**
- **Validation of the model**
  - **Model validated regarding to experimental data without any adjustment of the model parameters (neither boundary conditions nor material parameters)**
- **Application to RBW process optimization**
  - **The first application of the model on standard configurations explained the influence of current on the temperature cycle and the geometry of the weld**
  - **Since its validation, this model, coupled with a burst test model, is now used to optimize the welds quality**

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Thanks for your attention

Any question ?