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Comparison of two hot cracking tests JWRI and CRW

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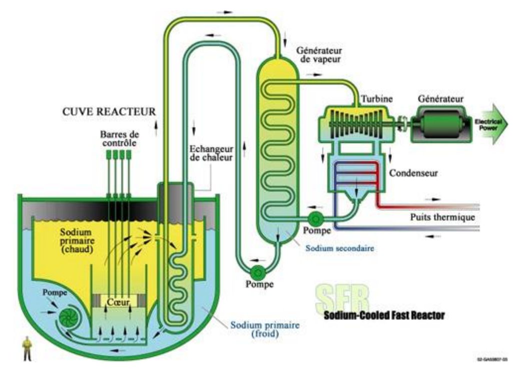
Context



IV generation nuclear reactor SFR (Sodium Fast Reactor)

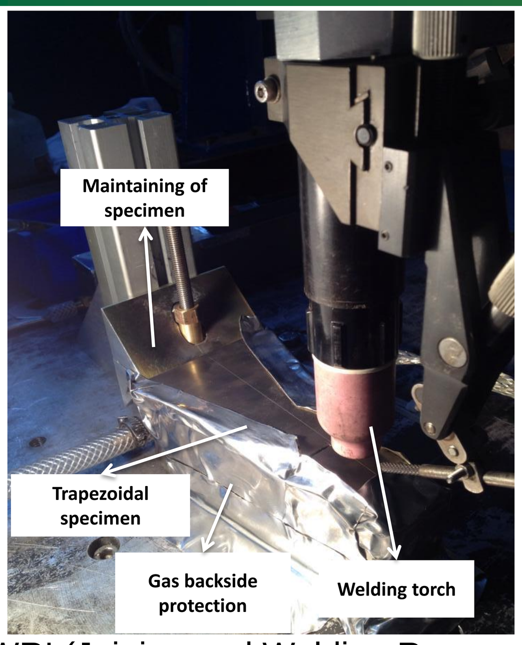
Solidification hot cracking may be encountered when welding 316L(N) using its filler metals. This material is used for the reactor vessel.

Hot cracking in welding

Hot cracking is not allowed in welds according to the rules of construction and design of nuclear components

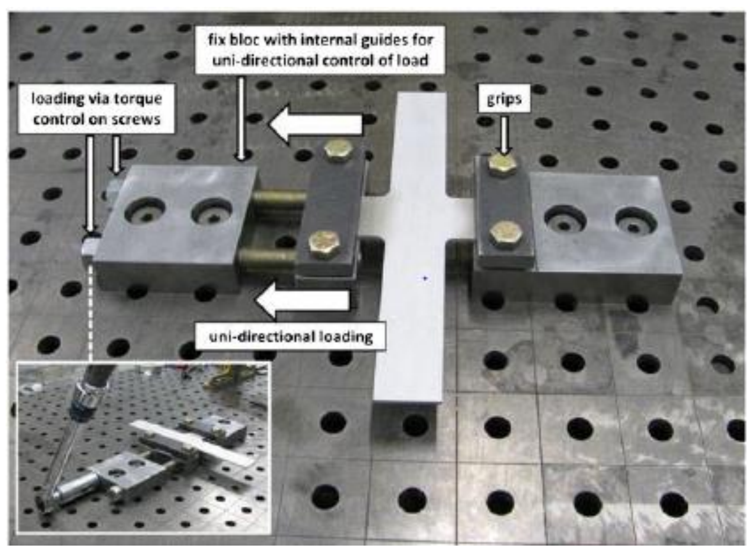
It requires :
- to prevent this risk
- to ensure that the material exhibits a satisfactory weldability

Objectives



JWRI (Joining and Welding Research Institute) test

- Propose a hot cracking test which realizes the tradeoff between sensitivity and robustness :
  sensitivity to differentiate the nuances of the material and to propose a thermomechanical hot cracking criterion ;
  robustness to avoid the operatives uncertainties and **get in repeatability conditions**.
- Improve the **understanding of hot cracking mechanisms** and **to identify a thermomechanical hot cracking criterion by means of the numerical simulation of hot cracking tests**.
- Characterize granular structures around the crack areas to couple multiscale **approaches such as CAFE (Cellular Automata Finite Element)** for the prediction of the grain structures with the thermomechanical behavior of the mushy zone.

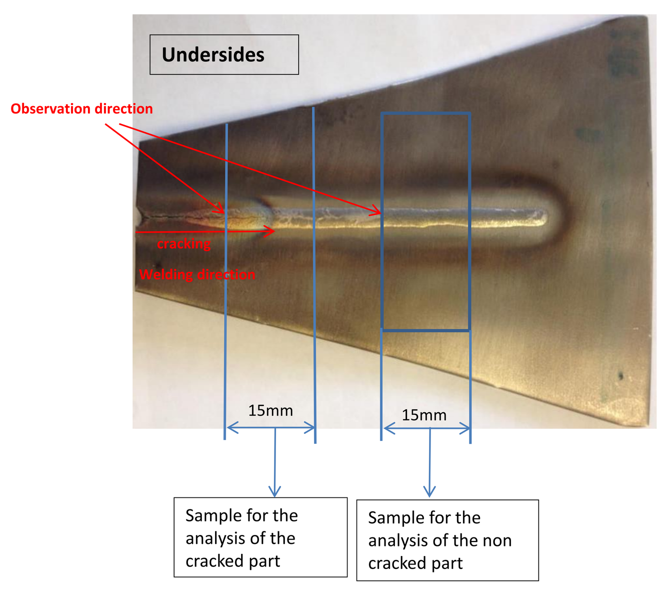


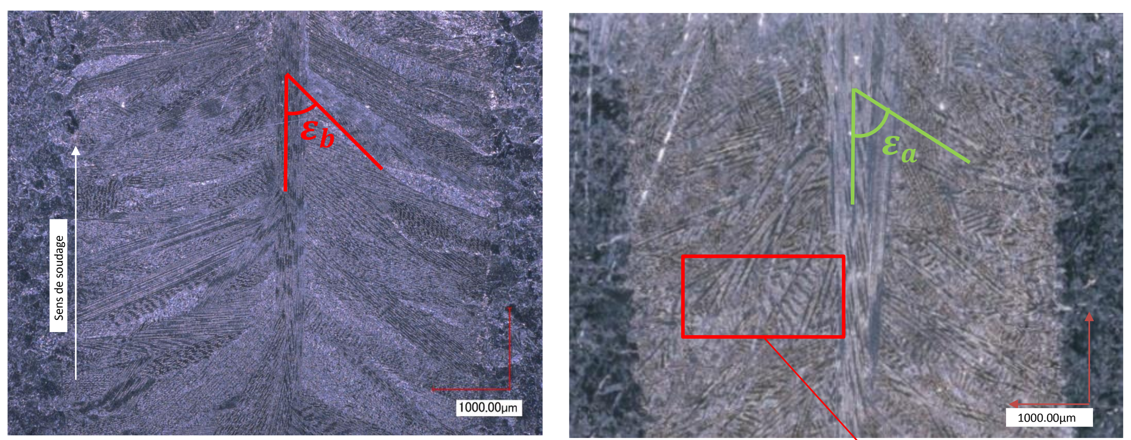
CRW (Controlled Restraint Weldability) test [1]

Advantage of CRW test
- both initiation and arresting crack

Numerical simulation of this test
- Understand local mechanisms of hot cracking and to identify a hot crack initiation criterion

Metallographic observations and experimental results



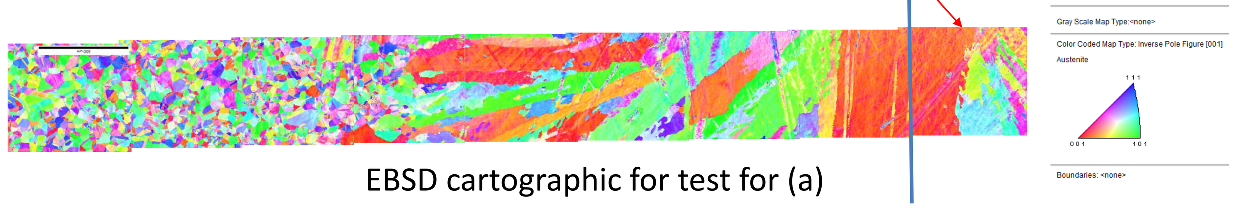


(a) (b)

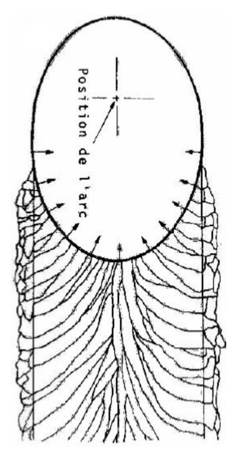
Top view : (a) $V_s = 150\ mm/min$; (b) $V_s = 80\ mm/min$

$\varepsilon_b > \varepsilon_a$, observation axial grain

Welding direction

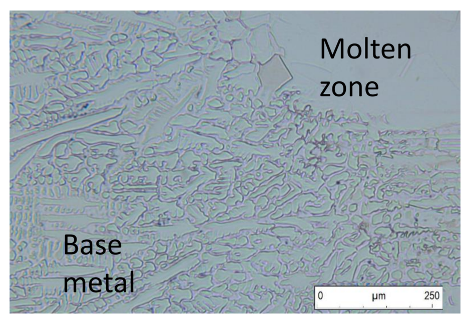


EBSD cartographic for test for (a)

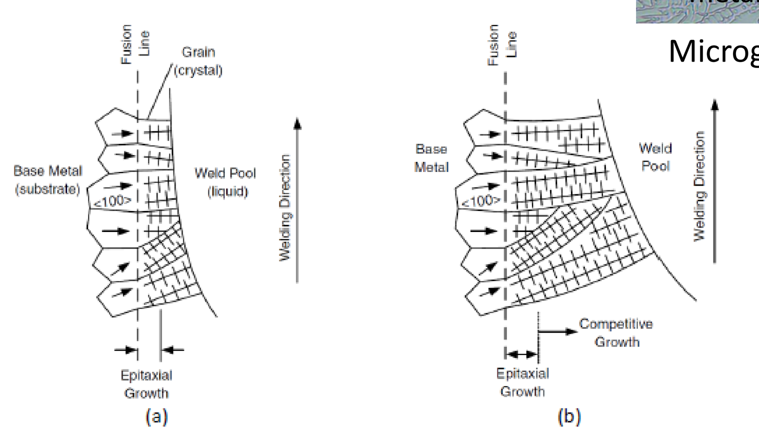


Structure of the welding seam for elliptical bath

The preferential growth direction is the <100> direction that is aligned with the temperature gradient



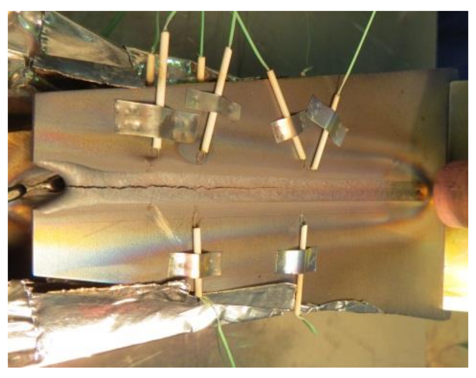
Micrograph of the epitaxial area



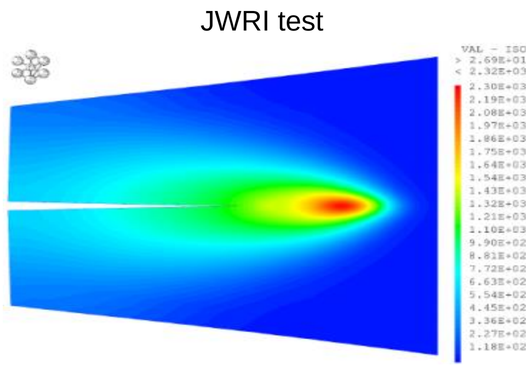
(a): epitaxial grains growing near the fusion line
(b): competitive growth between grains in the melting zone

Numerical Simulation JWRI & CRW

Free restraint test - JWRI



JWRI test

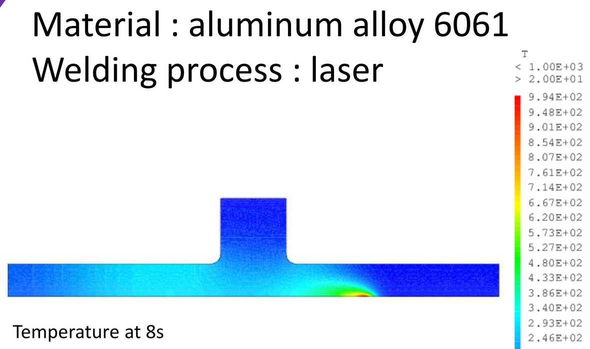


2D simulated temperature field with the hot crack

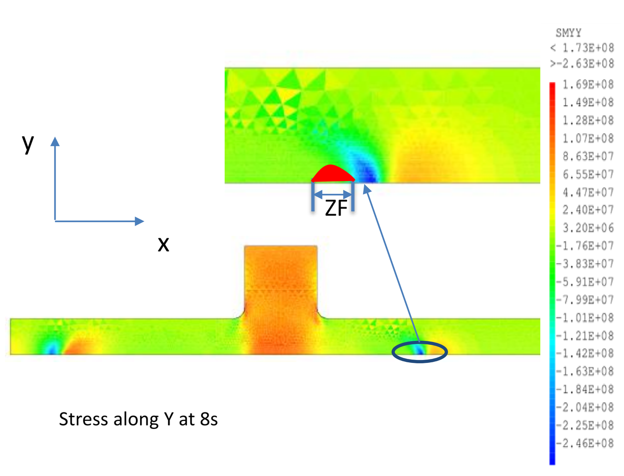
JWRI test allows :
- to observe a crack arrest
- to analyze hot cracking mechanisms
- to identify a crack arrest criterion

Restraint test - CRW

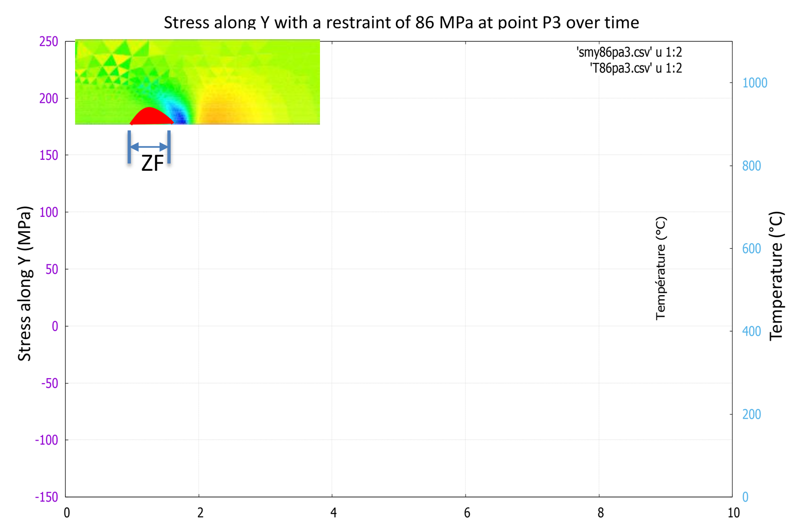
Material : aluminum alloy 6061
Welding process : laser



2D simulated temperature field



2D simulated stress field



Blue curve : temperature at point P3 over time
Violet curve: stress along Y at point P3 over time

Energy balance:

$$\rho C_p \frac{\partial T}{\partial t} = -div(-k\,gradT) + w$$

ρ : material density
C_p : specific heat capacity
T : temperature
k : thermal conductivity
w : volumic heat sources

The equivalent source :

$$w\,(m,t) = A\exp\left(-3\frac{x_f^2 + y_f^2}{r^2}\right)$$

A : power dissipated in the Gaussian
r : radius of flux distribution

Mechanical modeling (elastic -plastic constitutive law + thermal expansion) :

Hooke's law:

$$\sigma_{ij} = \mu\left[\varepsilon_{ij}^e + \frac{\upsilon}{(1-2\upsilon)} tr(\varepsilon^e)\delta_{ij}\right]$$

$$and \quad \mu = \frac{E(T)}{(1+\upsilon)}$$

Cast3M

Strain decomposition :

$$\varepsilon_{ij} = \varepsilon_{ij}^e + \varepsilon_{ij}^p + \varepsilon_{ij}^{th}$$

Plastic flow :

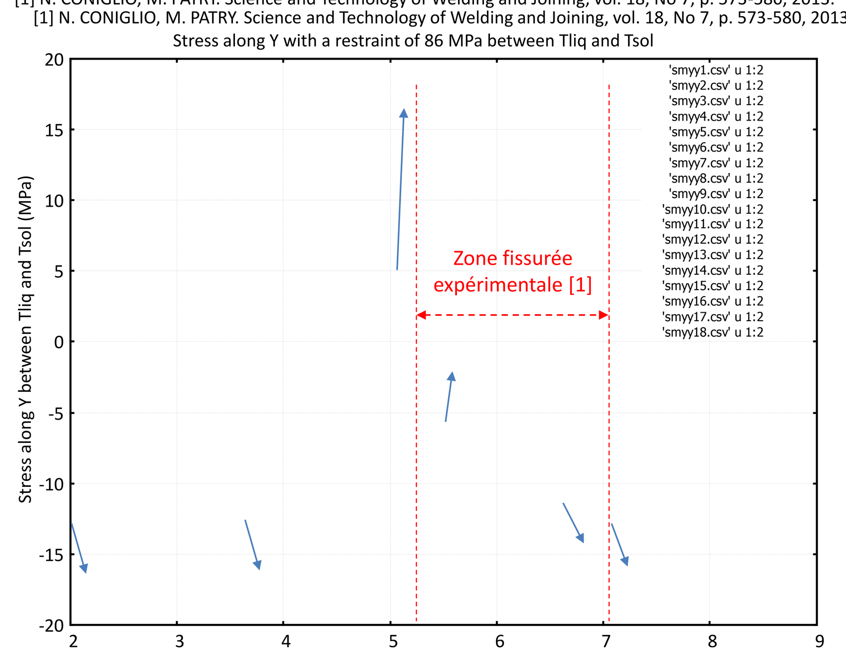
$$\dot{\varepsilon}_{ij}^p = \dot{\lambda}\frac{\partial f(\sigma_{ij})}{\partial \sigma_{ij}}$$

Thermal expansion :

$$\varepsilon_{ij}^{th} = \alpha(T - T_0)\,\delta_{ij}$$

Comparing the simulation results to the experimental data from the literature [1]

[1] N. CONIGLIO, M. PATRY. Science and Technology of Welding and Joining, vol. 18, No 7, p. 573-580, 2013.



Evolution of the stress along Y between the liquidus temperature and the solidus temperature at different points of the specimen

Conclusions and further works

- Compare hot cracking tests for different welding processes, TIG and Laser, using 316L(N) stainless steel alloy
- Develop simulation of type CAFE (Cellular Automaton Finite Element) in order to predict granular structures in welds with the help of metallographic observations + EBSD
- Identify the high temperature behavior law with the help of Gleeble simulator tests
- Develop numerical simulations of hot cracking tests to identify a hot cracking thermomechanical criterion

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