Residual stress: a matter of structural integrity for nuclear reactors

D. GONCALVES and co-works

Service d´Etudes Mécaniques et Thermiques (SEMT), CEA, Université Paris-Saclay, Gif-Sur-Yvette, France

Wednesday, November 16, 2022

CEA: French Alternative Energies and Atomic Energy Commission

CEA is a French public government-funded research organization, in the areas of energy, defense and security, information technologies and health technologies.

→ 9 main facilities and 8 regional platforms for technology transfer
→ over 20,000 employees
→ budget of about €5.1 billion/year

CEA is divided into four divisions:

→ Military Applications Division (DAM)
→ Fundamental Research Division (DRF)
→ Technological Research Division (DRT)
→ **Energies division (DES)**

Energy Division (DES): missions

The DES is responsible for structuring and piloting the research programmes on energy at CEA.

Production

- **Decarbonized production** (nuclear, renewable energy)

System

Tools for **Flexibility & storage** multi-energy vectors

Energy **Conversion** (efficiency, sobriety)

Resources

Circular economy **&** advanced **materials**

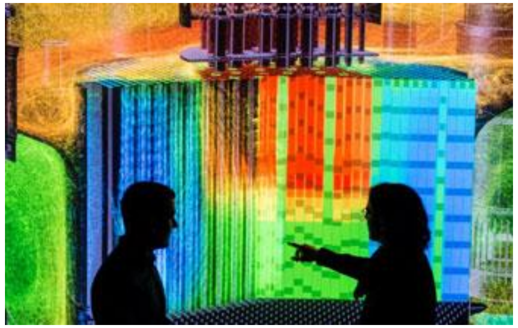
Closure of **carbon** cycle

Energy mix

Energy **Scenarios** & **tech-eco** models

Energy Division (DES): projects for nuclear energy

2^{nd} and 3^{rd} Gen. reactors program

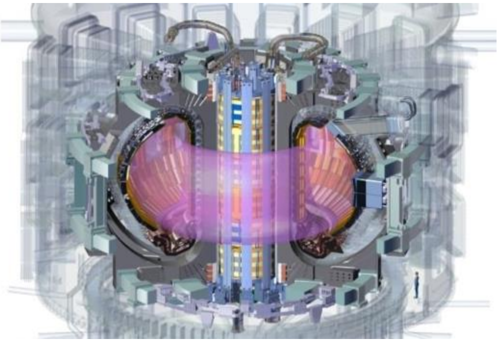


4^{th} Gen. reactors program

DES

SMR program

Fusion reactors (ITER, DEMO)



- Design studies: feasibility/performance of concepts, aiming at simplifying the architecture of the reactor;
- Extension of the operating life of reactors or files related to structural integrity;
- New fuels or management methods for fuels;
- Development of new technologies and systems for in-situ controlling;
- Evolution of codes and standards, operating rules, and safety regulations;
- New strategies in terms of incidental and accidental reaction;
- Development and improvement of numerical tools (neutronic, thermal hydraulics, mechanics, fuel, etc.)

Weld joints: the Achilles heel of nuclear reactors

NUCLEAR ENGINEERING INTERNATIONAL

Weld repairs at Flamanville 3

6 February 2020

PROBLEMS WITH EIGHT DEFECTIVE WELDS connected to the steam generators at the Flamanville 3 EPR in France were revealed during testing and future operation will depend on the success of weld repairs that will continue for at least the next three years, according to EDF.

SPIEGEL

Pannenkraftwerk in Frankreich

Atomreaktor in Flamanville läuft noch später an

Eigentlich sollte das Prestigeprojekt bereits 2012 Strom liefern – nun verzögert sich der Start des Atomreaktors im französischen Flamanville erneut. Erst 2023 soll es so weit sein. Teurer wird das Kraftwerk auch.

12.01.2022, 12.18 Uhr

Le Monde

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ÉCONOMIE

Partage

Nouveaux déboires pour l'EPR de Flamanville

L'Autorité de sûreté nucléaire juge «sérieux» les problèmes de soudure révélés par EDF.

Par Pierre Le Hir et Nabil Wakim · Publié le 22 février 2018 à 16h53 - Mis à jour le 27 février 2018 à 09h34

Lecture 3 min.

The New York Times

As Europe Quits Russian Gas, Half of France's Nuclear Plants Are Off-Line

France's state-backed nuclear operator is scrambling to overcome a monthslong crisis to get as many reactors as possible restarted before winter sets in.

An army of engineers has fanned out through nuclear power plants across France in recent months, inspecting reactors for signs of wear and tear. Hundreds of expert welders have been recruited to repair problems found in cooling circuits. Stress tests are being conducted to check for safety problems.

La energía nuclear, orgullo de Francia, flaquea en plena crisis energética

MARC BASSETS

Los problemas de corrosión en las tuberías y las tareas de mantenimiento fuerzan a parar la mitad de los reactores y a buscar alternativas, y disparan las importaciones de electricidad

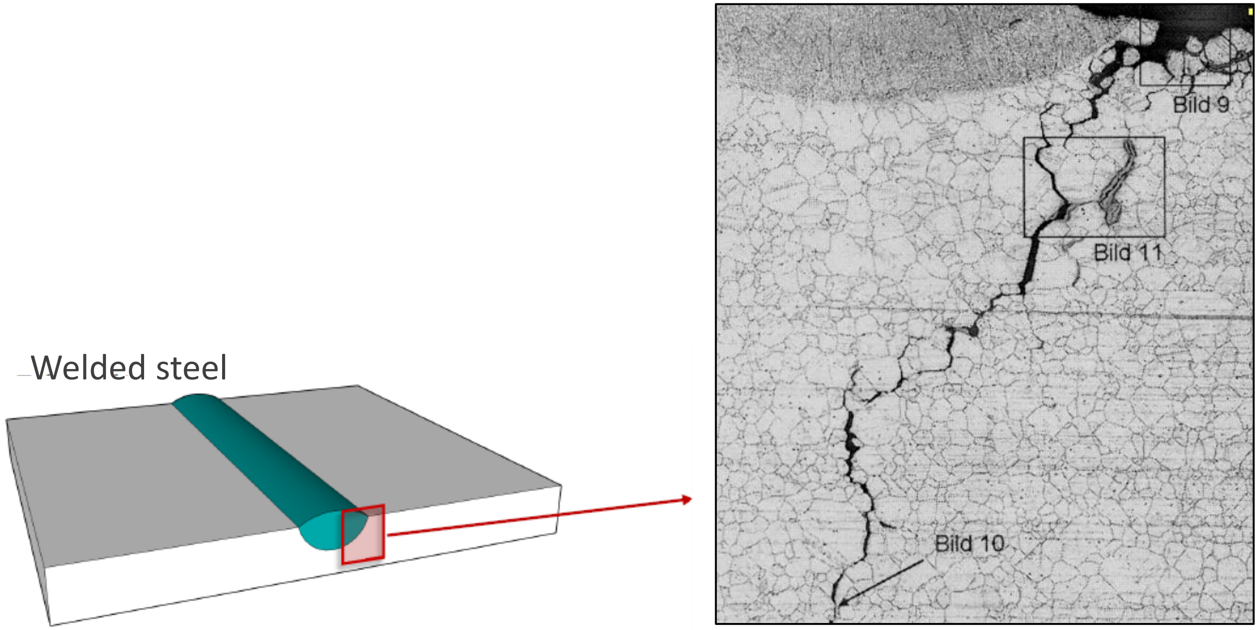
EL PAÍS

Stress corrosion phenomenon affecting nuclear power reactors: ASN considers that EDF's inspection strategy is appropriate

asn

MESSAGE /!\

Nuclear reactors may show problems related to welding (or other manufacturing process), which can be enhanced by corrosion, temperature, pressure and so-on.



Cracking in the ZAT of a welded 800H steel [Wortel, 2007]

Today, many are still to be done for understanding how welds affect the material behavior, and for improving components life time

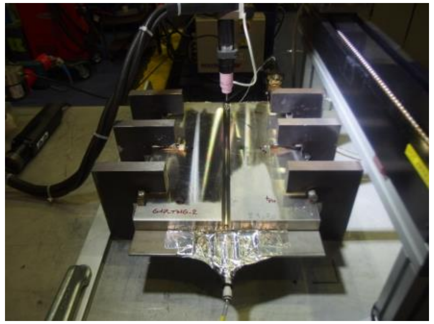
Mastery of welding and additive manufacturing processes, accounting for metallurgical weldability and welding procedure, based on experimental tests and numerical modelling.

The LTA also applies to the development of remote (cutting and repair) processes (tools and basic knowledge).

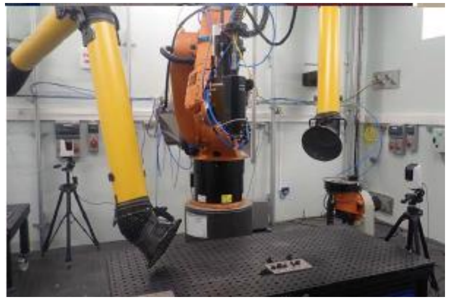
LTA members are present in groups for nuclear codes and standards (i.e RCC-MRx) of both welding and additive manufacturing.

16 employees
+ ~2 PhD students/year
+ post-doc fellows and interns

Experimental and numerical platform



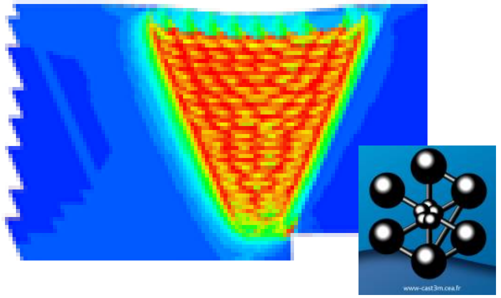
Welding



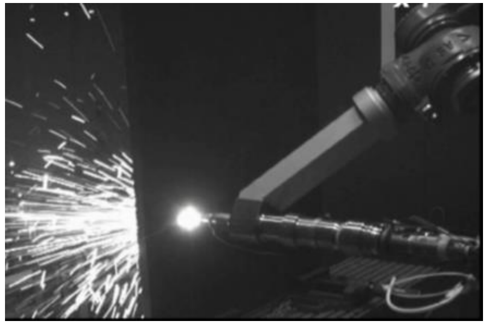
Additive manufacturing

LTA

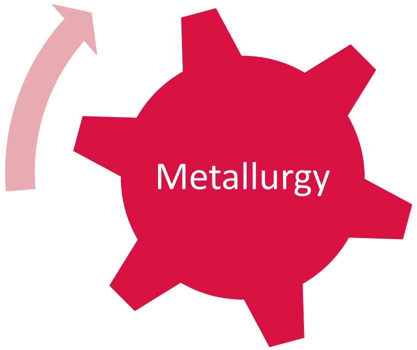
Modelling



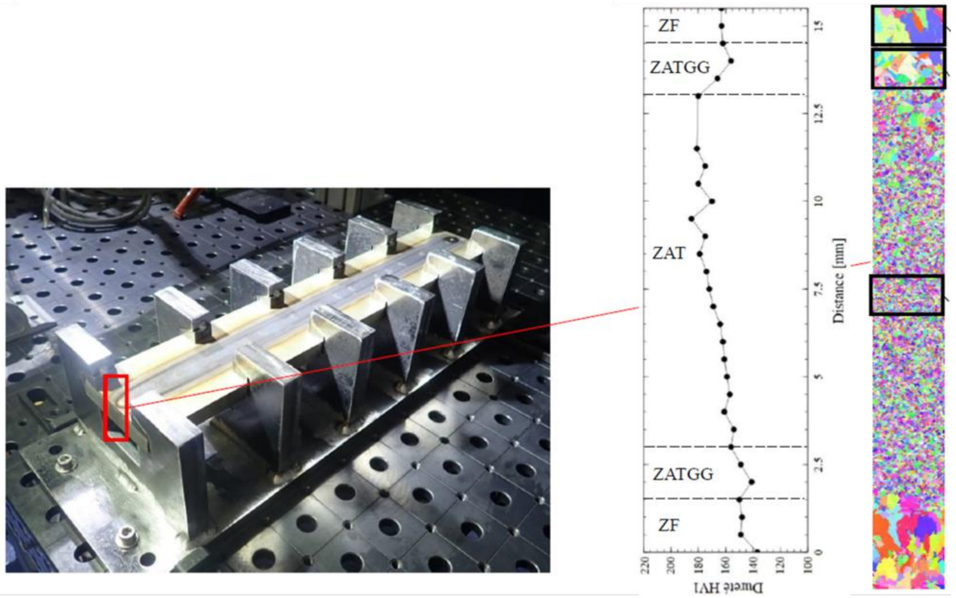
Remote cut processes



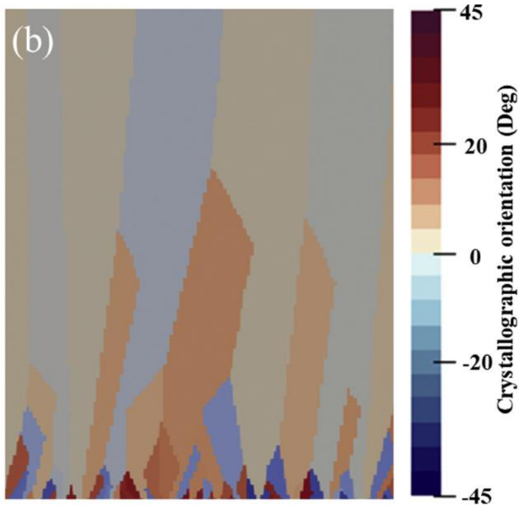
Weld joints: a complex problem



Effect of welding on the microstructure, affecting the mechanical properties
(microscopy and mechanical tests and numerical simulations)

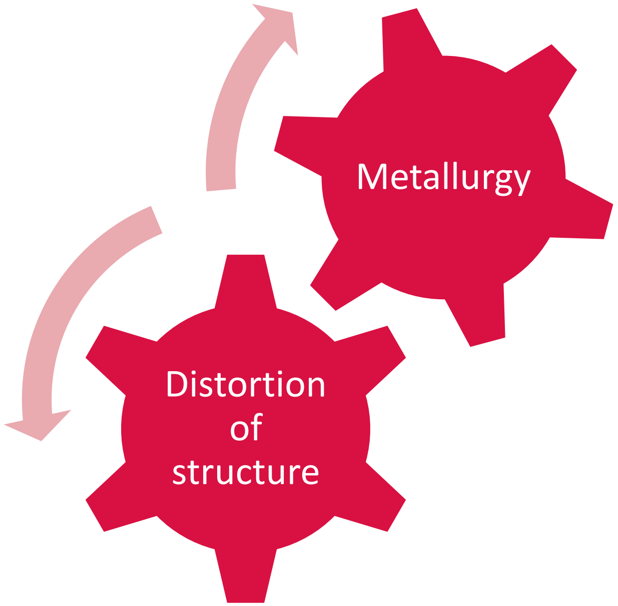


Hardness profile and EBSD of welded 316L(N) steel [Py-Renaudie, 2022]

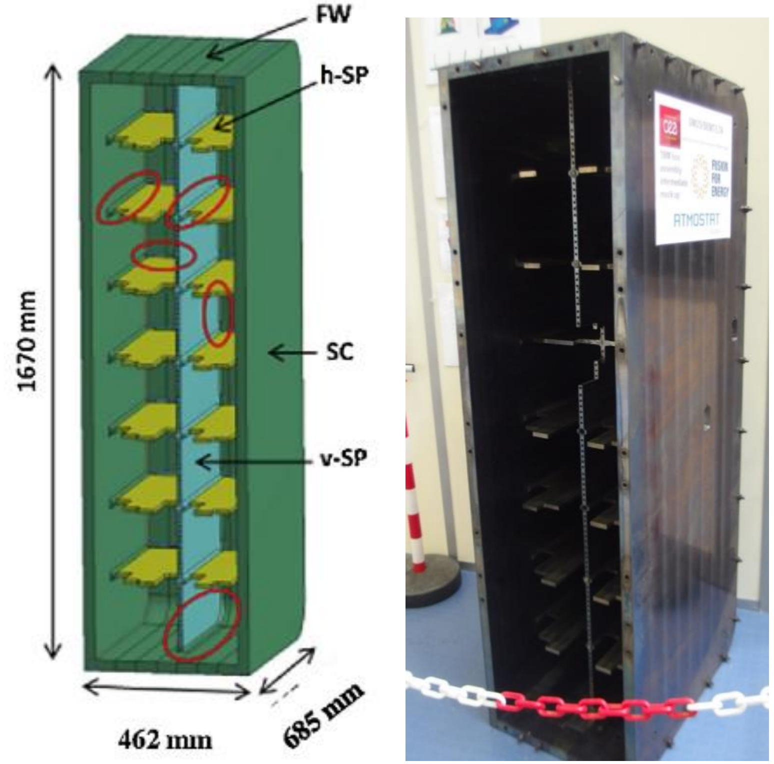


Numerical results of the competition growth of crystals obtained using a CA-FE model [Baumard et al., 2021]

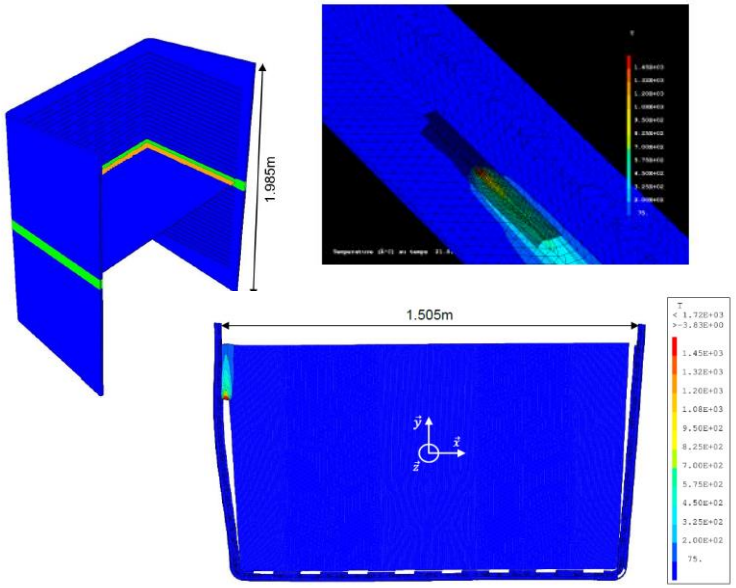
Weld joints: a complex problem



Effect of welding on the components dimensions
(prototypes for the industry assisted by numerical simulations)

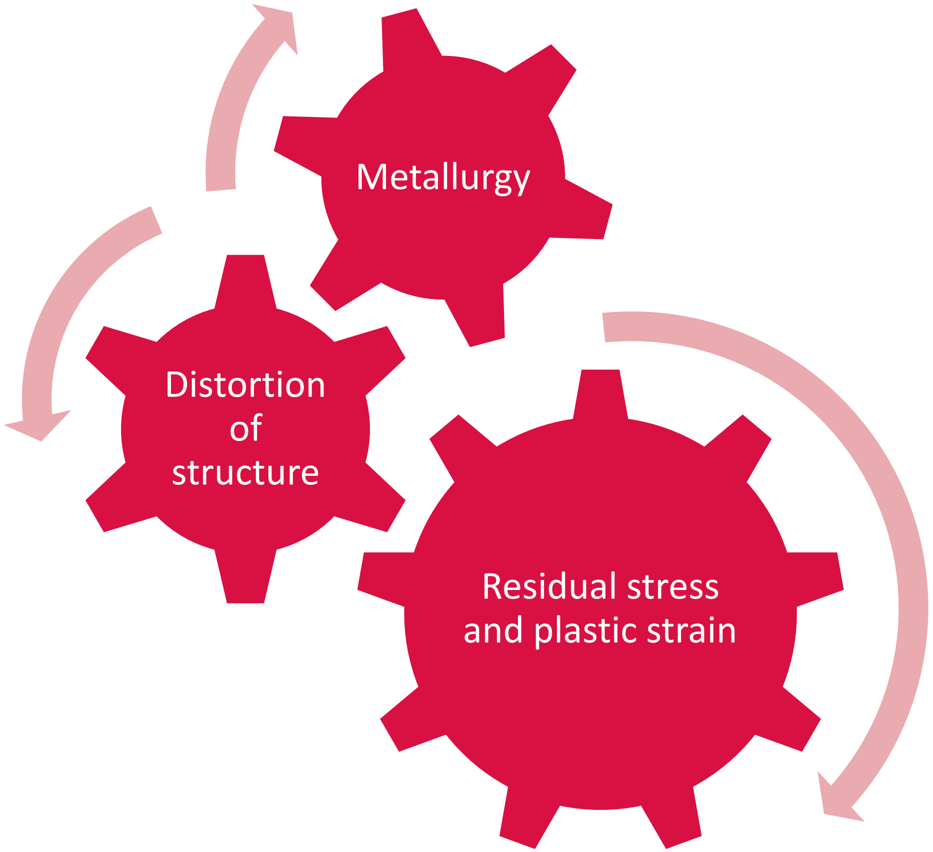


Feasibility study of European ITER Test Blanket Modules (full scale) [Forest et al., 2018, 2021]

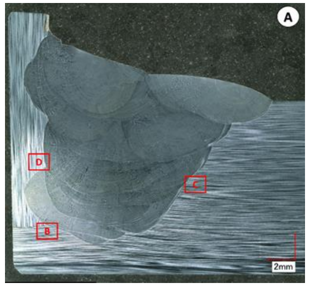


Simulation of the welding deformation, Breeding blanket (full scale) [S. PASCAL, 2020]

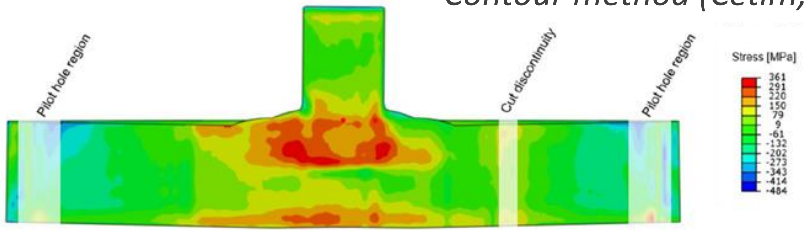
Weld joints: a complex problem

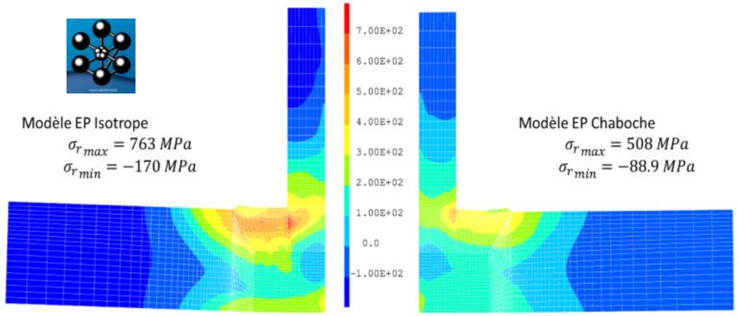


Effect of welding on components properties (experimental measurements and numerical simulations)



Contour method (Cetim, France)





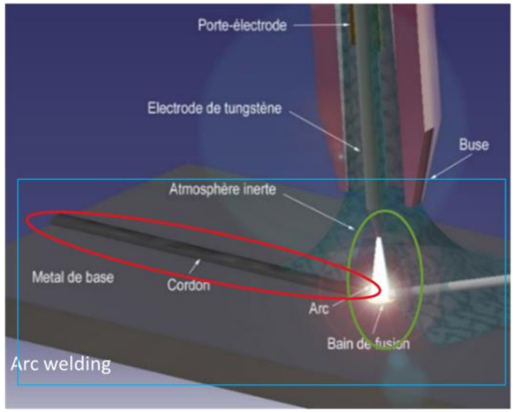
Borland specimen: experimental measurements and numerical predictions of residual stress [Gonçalves, 2019]

Welding and additive manufacturing processes

- **Shield Metal Arc Welding (SMAW)**
- **Gas Tungsten Arc Welding (GTAW)**
- **Laser Welding (LW)**
- **Pressure Resistance Welding (PRW)**
- **Wire-Arc Additive Manufacturing (WAAM)**
- **Wire-Laser Additive Manufacturing (WLAM)**
- **Laser Powder Bed Fusion (LPBF)**

Coupled experimental simulation approach

Numerical simulations at different scales



Multi-physics modeling

Simulation of electric arc and weld pool
- Physical mechanisms of plasma
- Thermohydraulics

Welding bead modeling

Simulation of the solidified microstructure
- Material properties (isotropy, anisotropy)

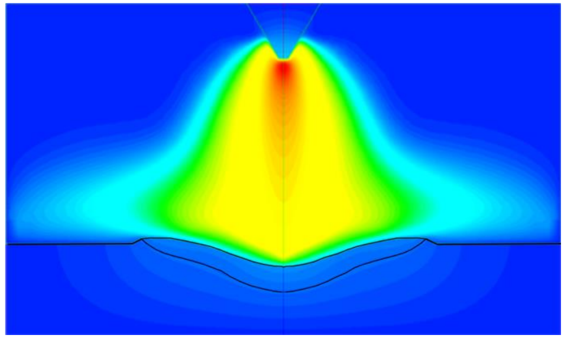
Welded assembly modeling

Thermo-metallo-mechanical simulation
- Influence of thermal loading on metallurgy and behavior of assemblies

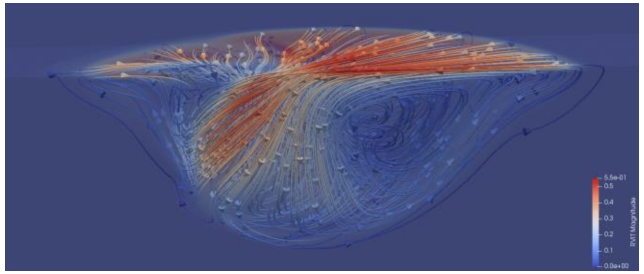
Data input → Material response → Mechanical consequences → Structure lifetime

Numerical simulations at different scales

Multi-physics modelling

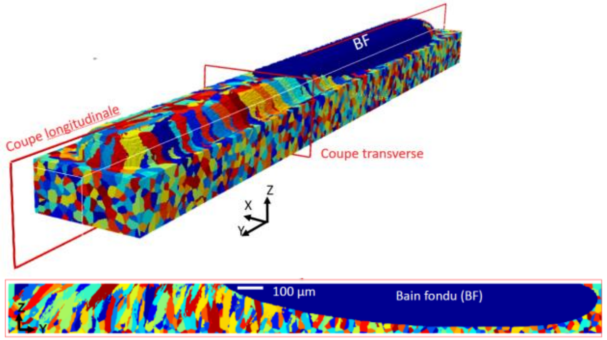


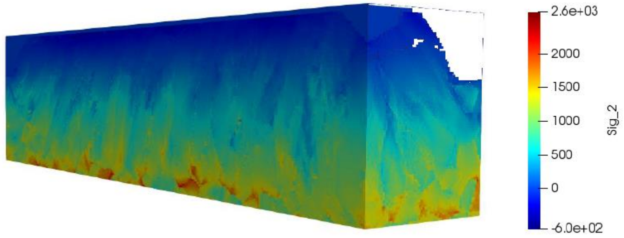
Temperature field in an electric arc [Nahed, 2021]



Flow of the liquid metal in the weld pool [Gounand, 2017]

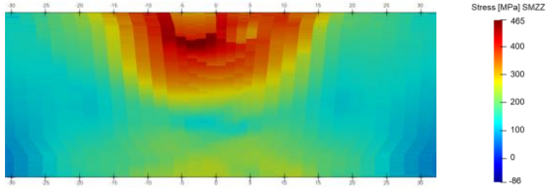
Welding bead modelling



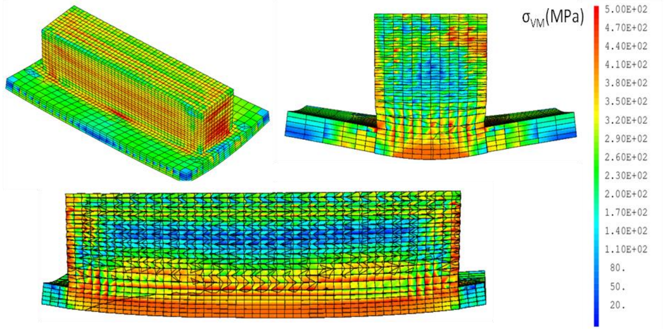


Crystalline microstructure and stress field (elastic behavior) resulted from the LPBF process (316L steel) [Baumard, 2021]

Welded assembly modelling



Longitudinal stress simulated for the GEMMA project (narrow gap, GTAW, 316LN steel) [Gonçalves, 2021]



Stress field of an additive manufactured block (WAAM, 316L steel) [Artières, 2021]

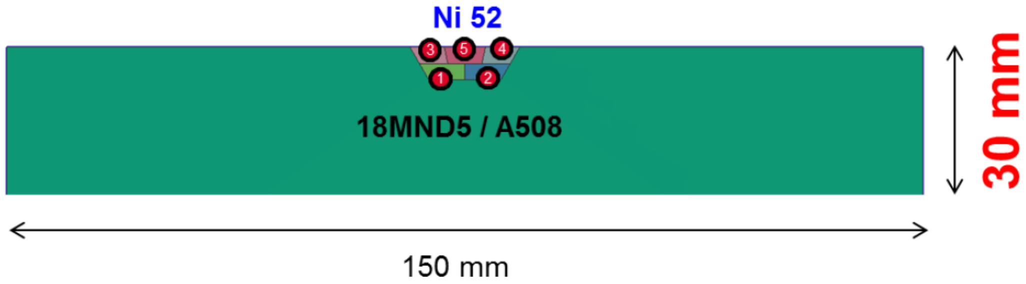
Experimental data, but also computation results (benchmark), are required for validating these simulations!!

Numerous problems examined, resulting in a large experimental and numerical database since its formation

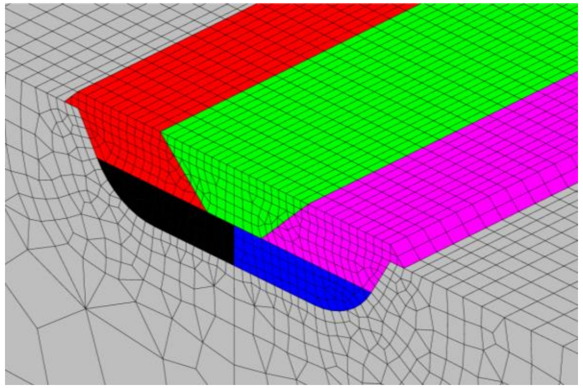
- Validation of welding residual stress distributions predicted by CEA's numerical welding models (finite element code Cast3M).
- Improvement of existing material property databases and fruitful discussions on suitable constitutive material behavior for welding simulations.
- Gain a better knowledge on residual stress profiles in multipass welded components thanks to neutron diffraction and other measurement methods.
- Access to open results of residual stresses measurements, welding experiments, or simulations that are very useful for benchmarking

Numerous problems examined, resulting in a large experimental and numerical database since its formation

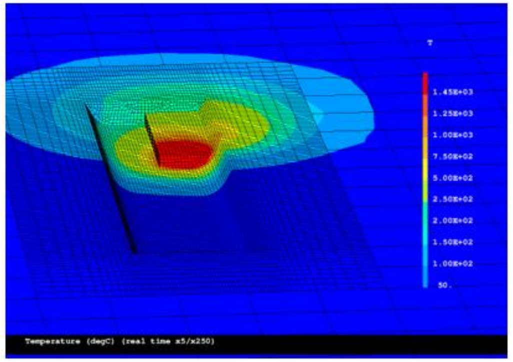
NeT TG8 simulation Protocol with Cast3M [S. Pascal, 2021]



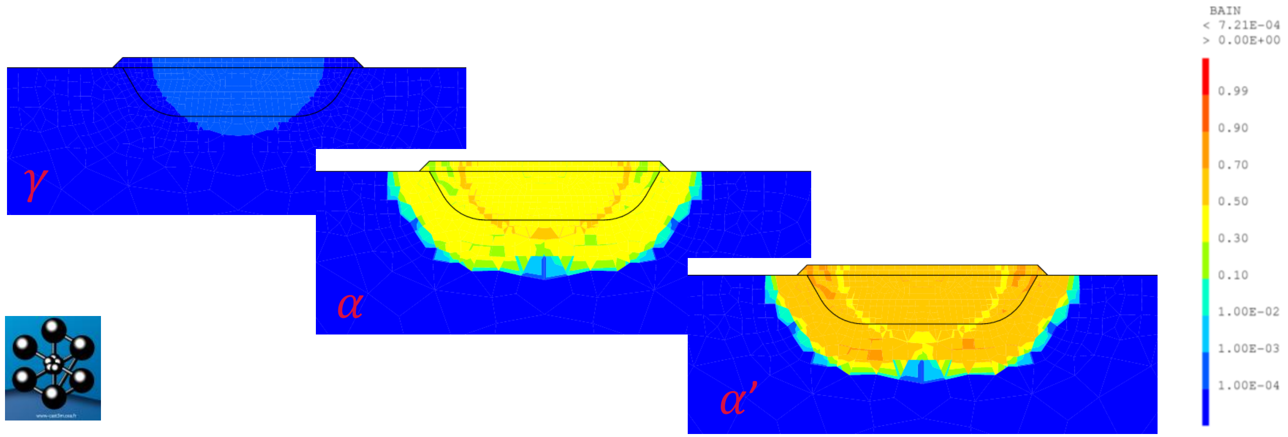
Base Metal: 16MND5 steel / Filler metal: Ni alloy
5 finite lenght weld bead (~80 mm)
First simulations → validation to be done using NeT database



Mesh detail



Temperature field

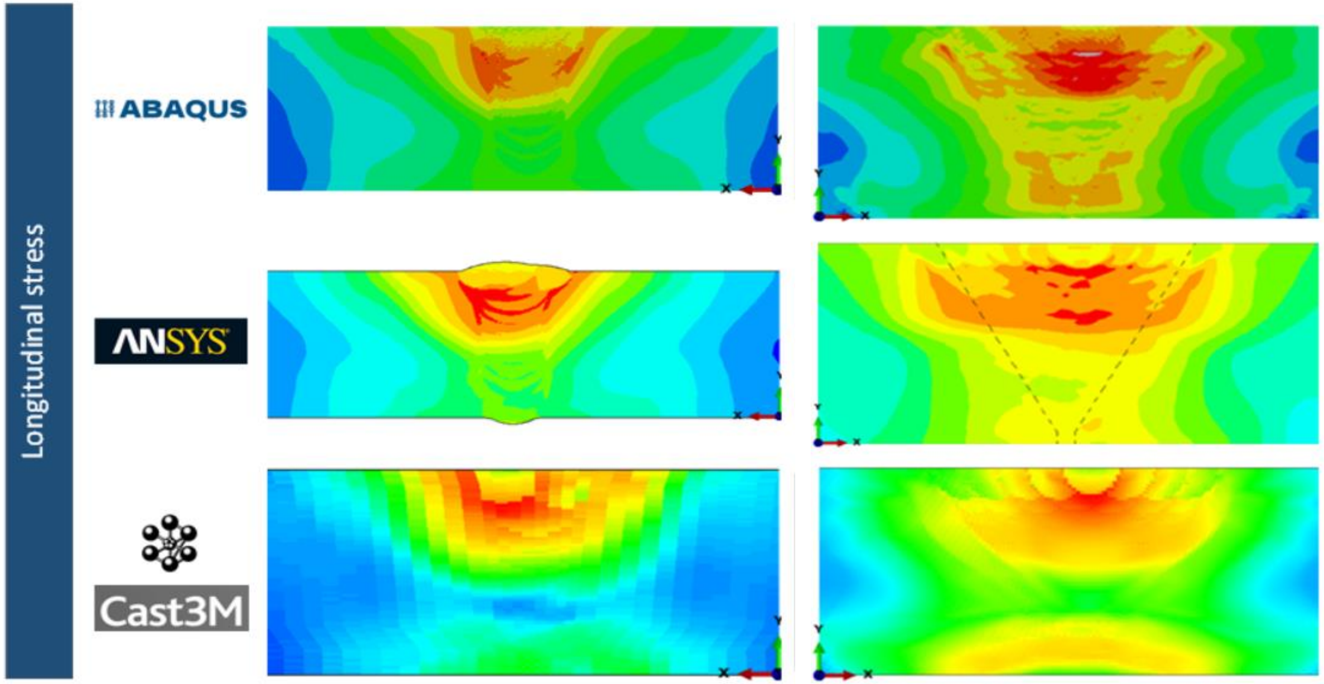


Fraction of phases: austenite, ferrite and martensite.

Numerous problems examined, resulting in a large experimental and numerical data base since its formation

GTAW specimen (11 weld runs)

SMAW specimen (65 weld runs)



GEMMA PROJECT

Specimens manufactured (GTAW and SMAW processes)

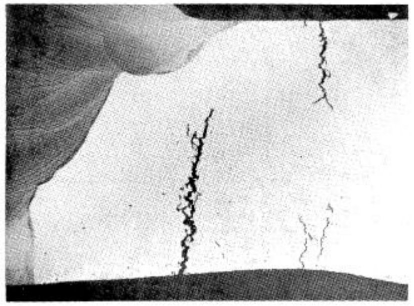
Numerical benchmark → **numerical parameters taken from NeT** [Murásnky et al, 2012]

Validation of predicted residual stresses in respect to experimental measurements (neutron diffraction and contour method)

This study was **developed according to NeT mission**: undertakes measurement and modelling studies, followed by the interpretation of results

Occurrence of cracks between two repair welds in a 347H piping systems joints of a steam turbine after operation at 565 °C [Curran and Rankin, 1957]

Experimental and numerical results are essential to improve safety of the of nuclear reactors, allowing the continuous updating of design and construction rules in respect to <u>welding operations and their implementation</u>



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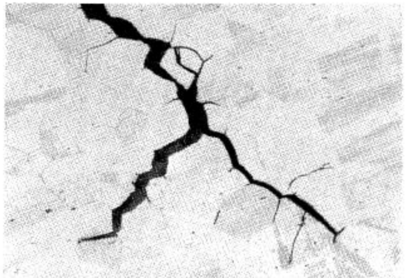


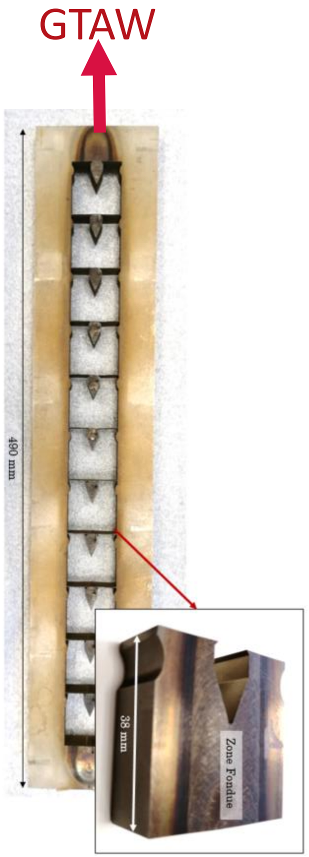
Intergranular cracks in type 304 steel pipe [Kass et al., 1980]

Integrate the manufacturing history → Know the material behavior → Welded components integrity

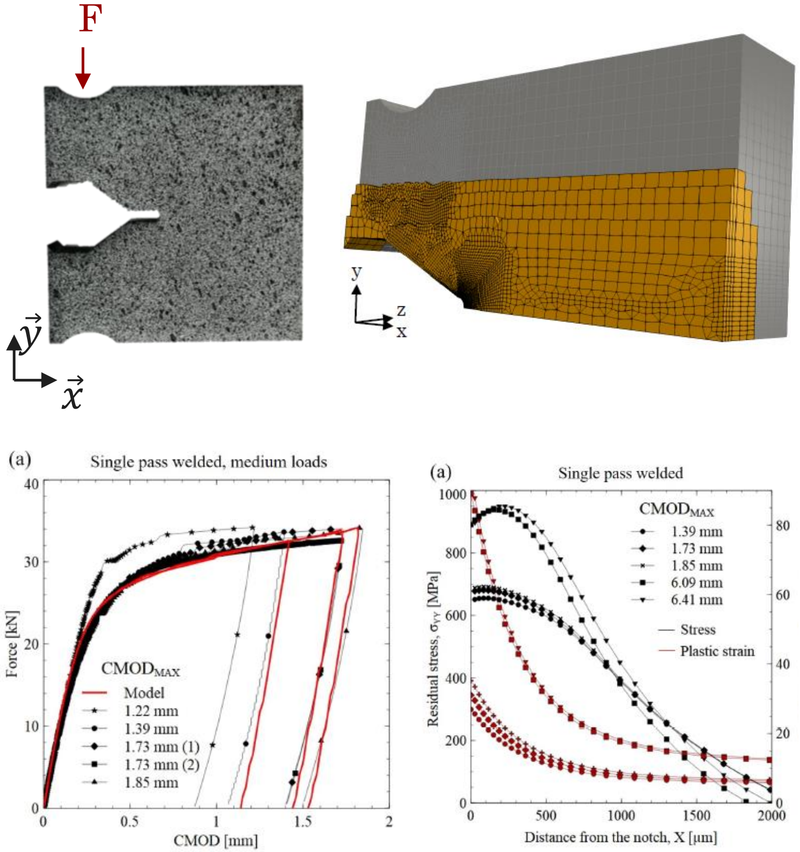
Scientific computing results can be used for assisting the welding operation, and predict materials changings related to the welding process (temperature gradients, material deformation, residual stresses, etc.)

Validation using reliable experimental data

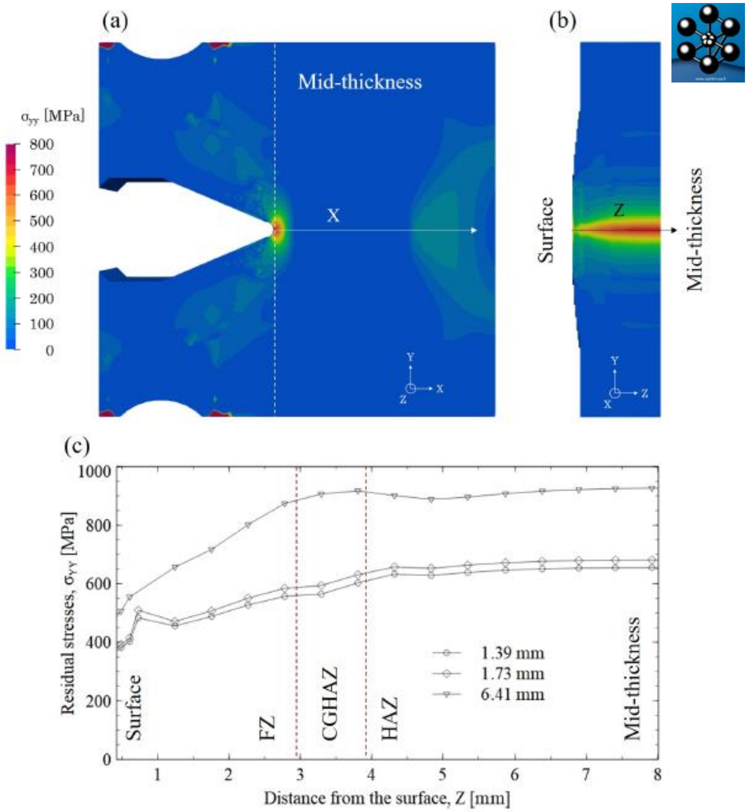
Study of the sensitivity of steels to stress relaxation cracking (reheat cracking) [Py-Renaudie, 2019-2022]
→ Relaxation of residual stresses during service or PWHT, resulting in intergranular cracking



Welding of 316L(N) sheets and CT-like specimens machining [Py and Robidet, 2020]

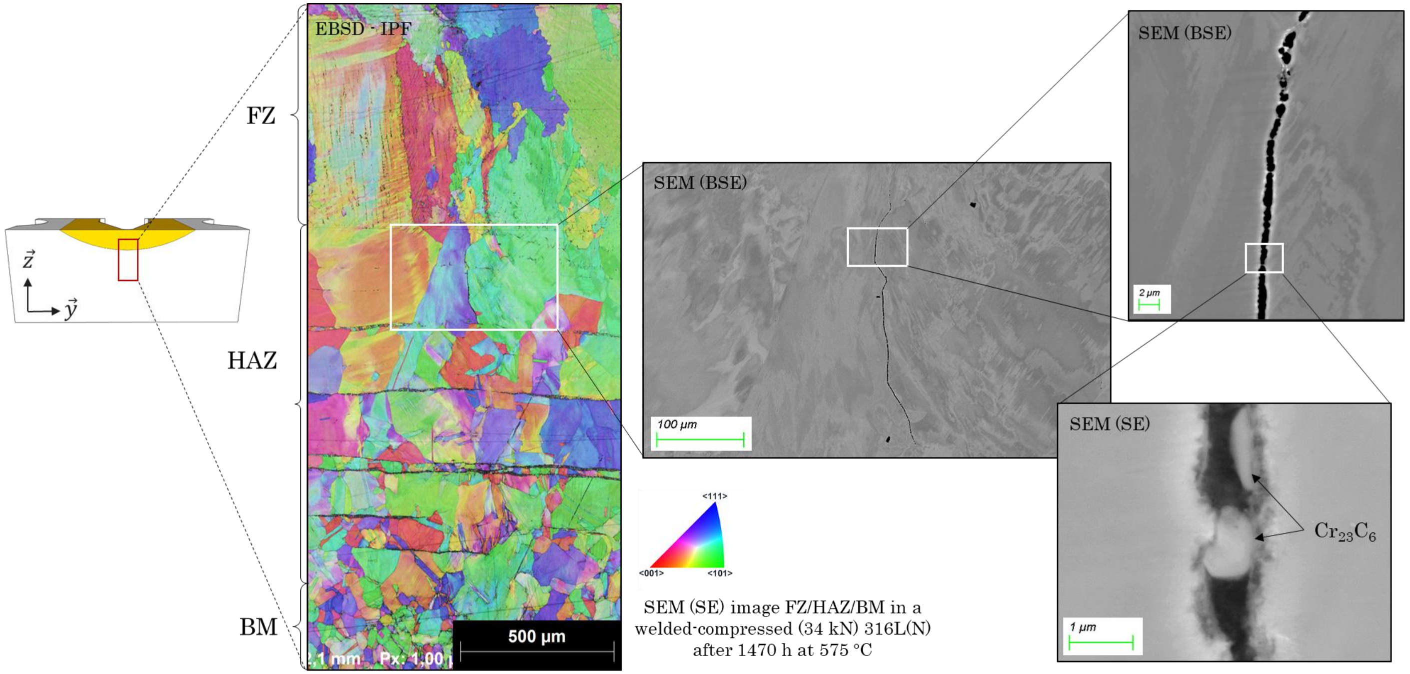


Experimental compression at RT and numerical simulation using the Chaboche Model [Py-Renaudie, 2021]



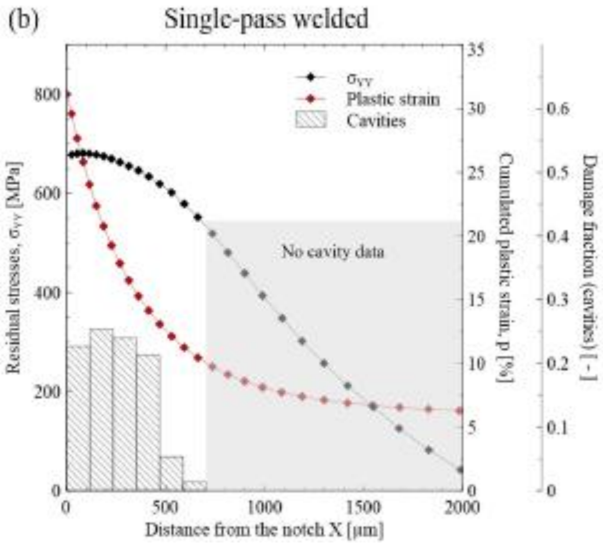
Predicted residual stress within the CT specimen [Py-Renaudie, 2021]

Study of the sensitivity of steels to stress relaxation cracking (reheat cracking) [Py-Renaudie, 2019-2022]
→ Relaxation of residual stresses during service or PWHT, resulting in intergranular cracking



Observation of cavities and cracks, mainly in the HAZ: effect of plastic strain, residual stress, grain size and absence of ferrite [Py-Renaudie, 2022]

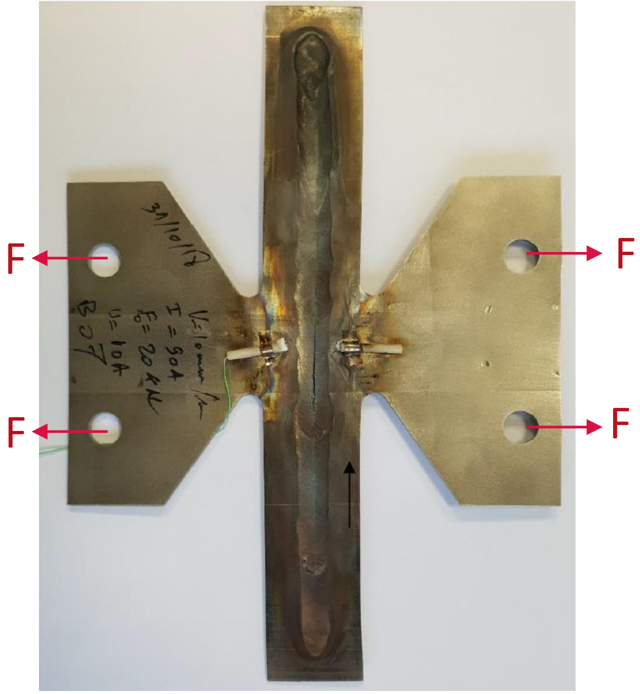
Criteria for SRC in 316L(N) steels



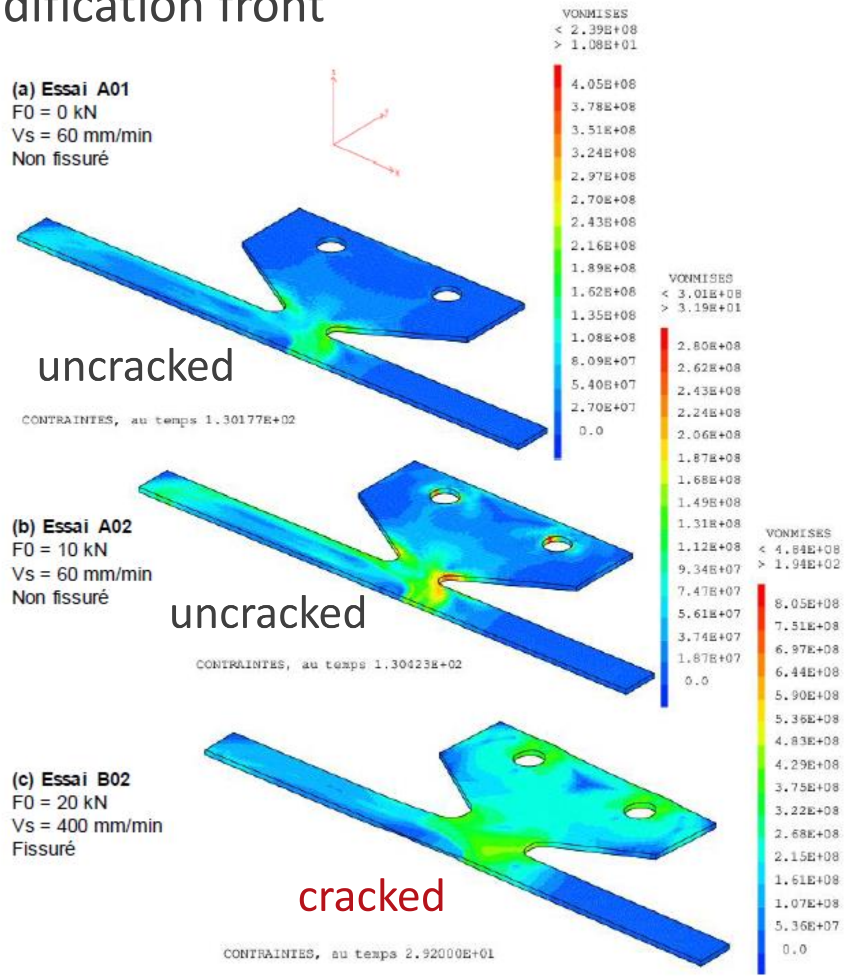
Comparison of stress relaxation damage fraction, predicted post-compression residual stresses and cumulated plastic strain. 316LN steel, 575°C, 1470h [Py-Renaudie, 2022]

Study of the sensitivity of steels to hot cracking during welding

→ presence of residual liquid films and stresses in the solidification front



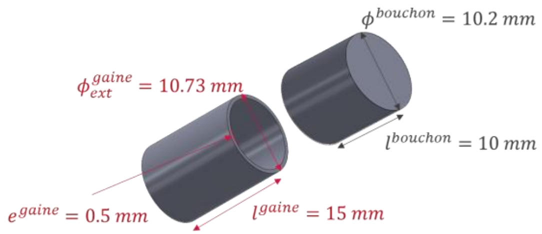
"Butterfly" type specimen, used for hot cracking study [Ayrault and Robidet, 2017-2021]



Definition of criteria for hot cracking of 316L(N) type steels, based on FEM predictions [Ayrault and Robidet, 2017-2021]

Study of the mechanical strength of plug-clad assemblies in ODS steels [Mabrouki, 2020-2023]

→ How does PRW affect the ODS steel properties ?



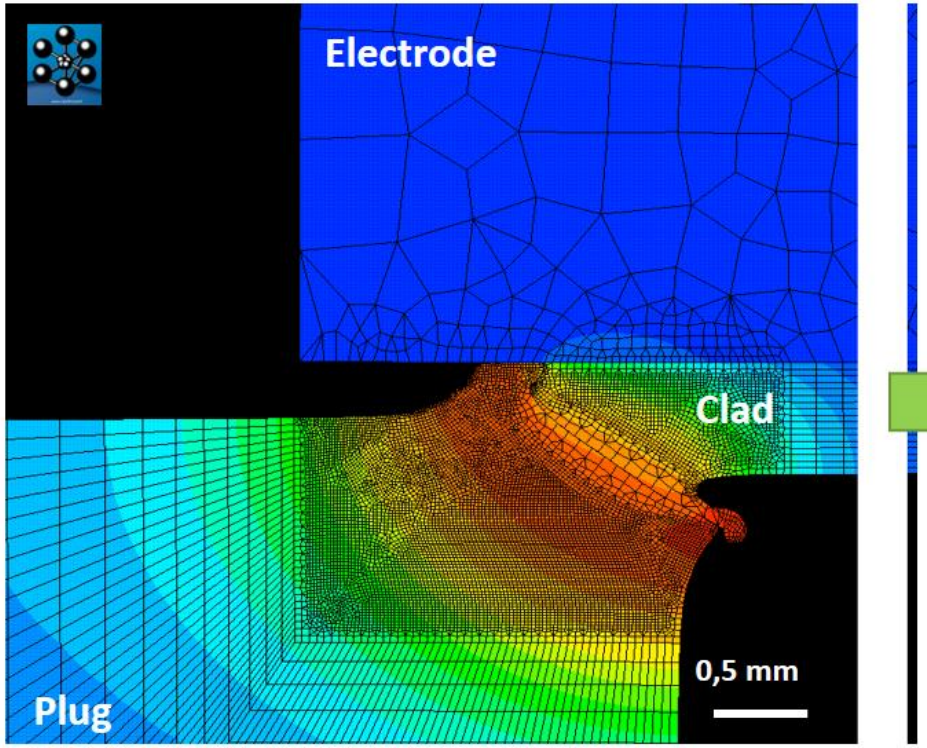
Welding parameters

Force - Fw

Current intensity - Iw

Welding time - tw

2D axisymmetric modeling
(ODS steel, elastic-plastic behavior)



Simulation of PRW process, in a plug-clad configuration [Mabrouki, 2022]

Output

Final geometry of the welded joint

Temperature fields

Size of the HAZs

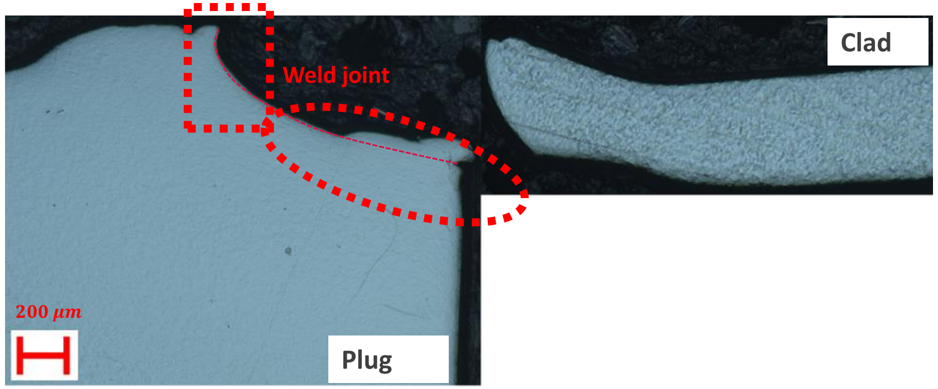
Strain rate

Plastic strain and residual stress fields

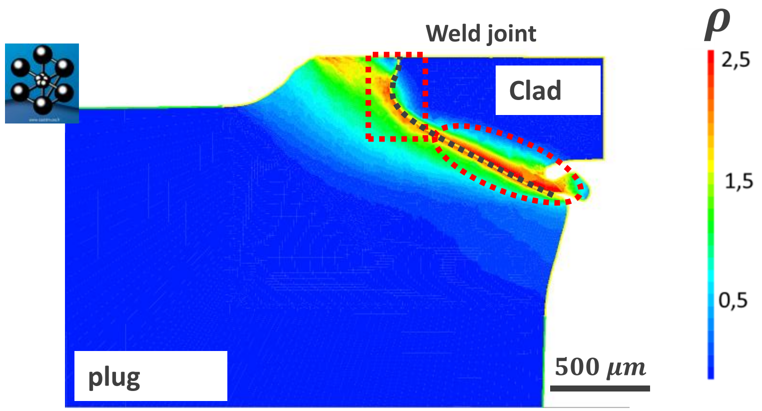
Proportion of metallurgical phases (not yet implemented)

Study of the mechanical strength of plug-clad assemblies in ODS steels [Mabrouki, 2020-2023]

→ How does PRW affect the ODS steel properties ?



View of the specimen after tensile test at 20°C: rupture at the level of the joint plane and the HAZ on the plug side [Mabrouki, 2022]

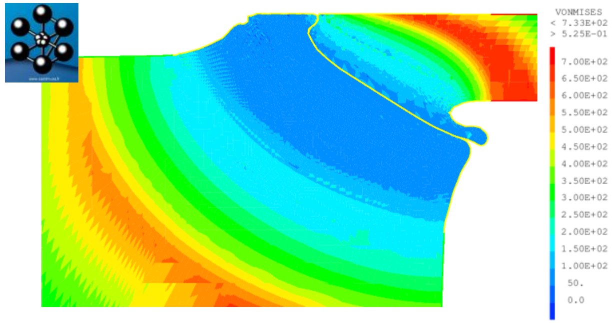


Predicted cumulated plastic strain [Mabrouki, 2022]

The mechanical strength of the welded joint can be associated with the area undergoing large plastic deformation and exhibiting the highest hardness values.

→ Effect of residual stresses and microstructure on the mechanical behavior ?

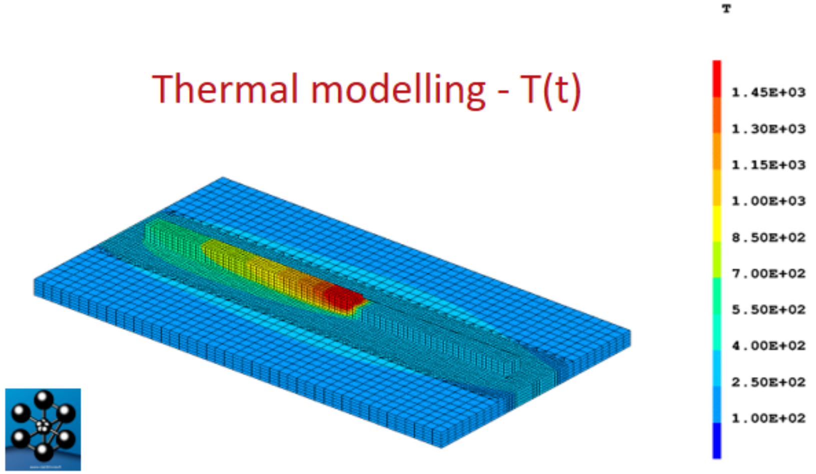
- Very heterogeneous distribution
- PWHT effect on mechanical strength



Study of the wire additive manufacturing (WAM) [Artières, 2021-2024]

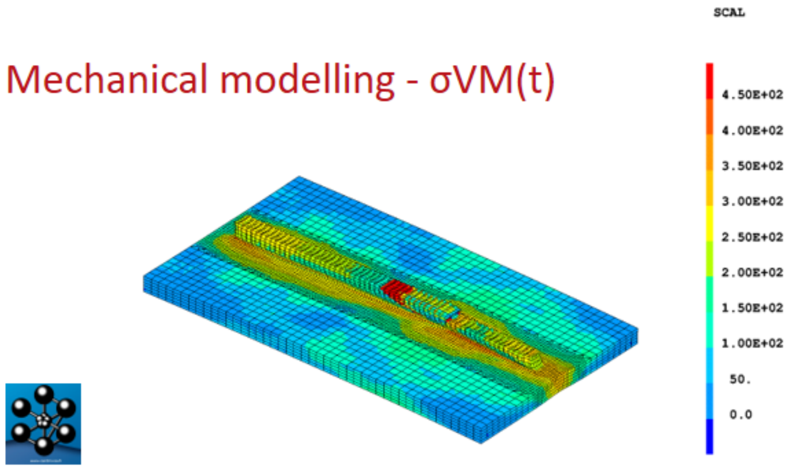
→ Interest of nuclear industry by additive manufacturing → FEM in order for mastering these processes

Thermal modelling - T(t)

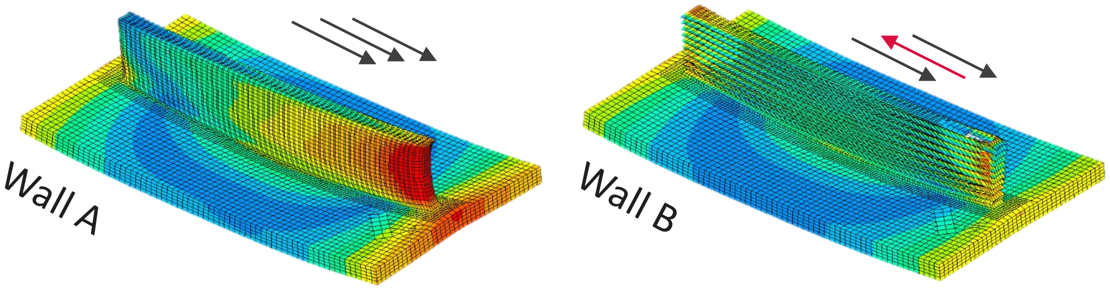


Wall A - 20 passes, speed x 100

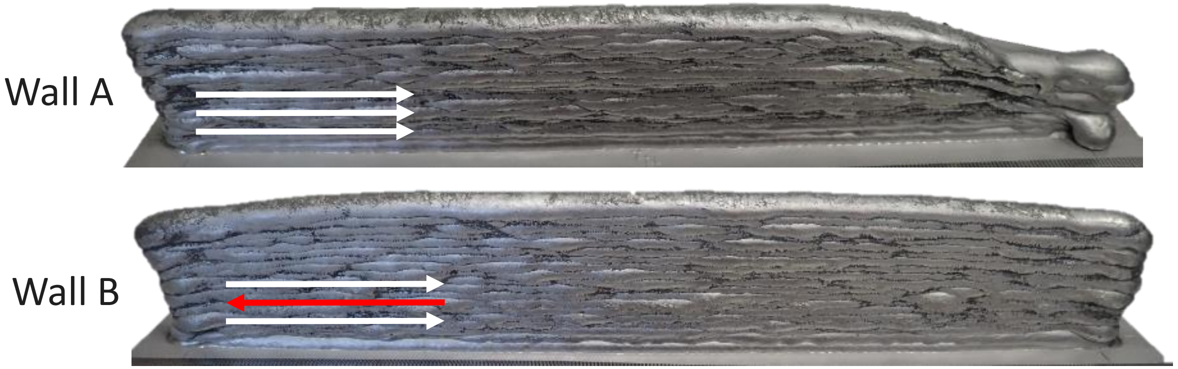
Mechanical modelling - σVM(t)



Wall A - 20 passes, deformation x 5, speed x 100



Displacement field prediction on deformed mesh (x5)



[Artieres, 2021]

Thank you for your attention!

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