DE LA RECHERCHE À L'INDUSTRIE

Challenges to the use of M&S to support the nuclear qualification of advanced manufacturing

A nuclear engineer's perspective

AMME Workshop on Advanced Manufacturing

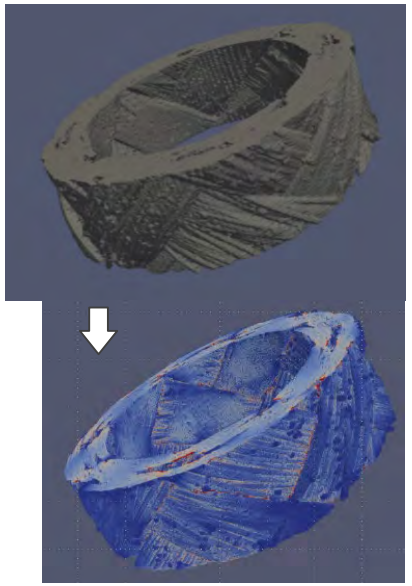
November 8, 2021, OECD, Paris, France

P.F. Giroux, O. Asserin, P. Aubry, Th. Cailloux, L. Dupuy, L. Gélébart, V. Jacquier, H. Maskrot, W. Pacquentin, S. Paillard

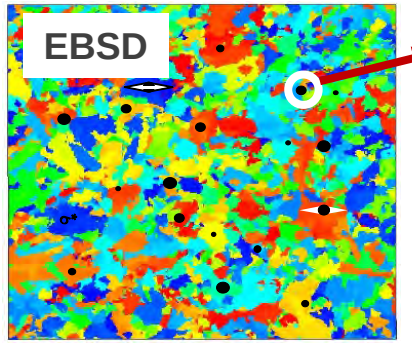
Development of multi-scale calculation methods

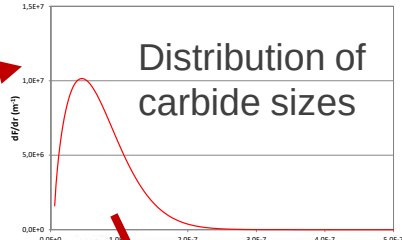
In situ mechanical tests

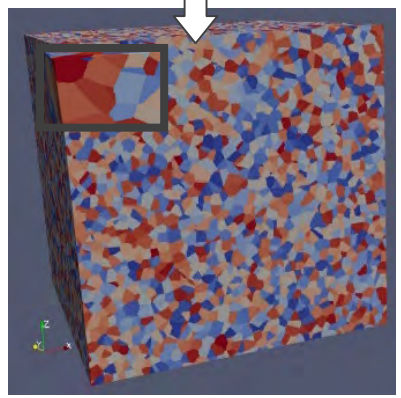
In situ tomography observations

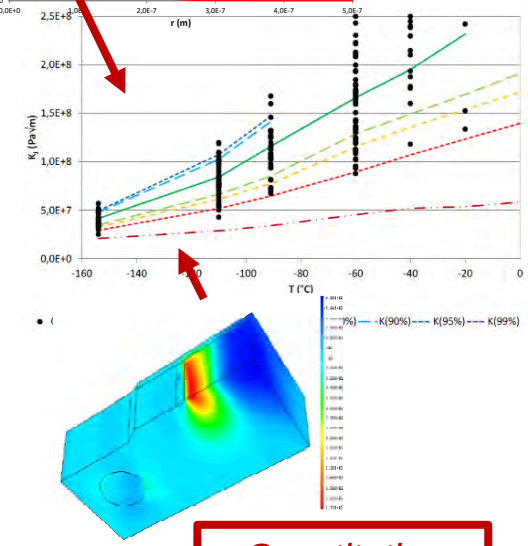


High resolution microstructural analysis



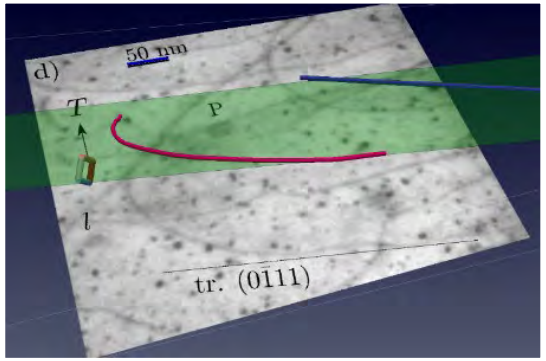






in situ TEM

Movement of dislocations



Distributions of clusters

CRESCENDO Code

Atoms

Electrons

NUMODIS Code
DDD calculation of dislocation behavior - taking into account interactions with irradiation induced defects

Crystal plasticity constitutive laws

Chainage

AMITEX_FFTP Code
Calculation of the polycrystalline mechanical behavior (RVE) by resolution in Fourier space

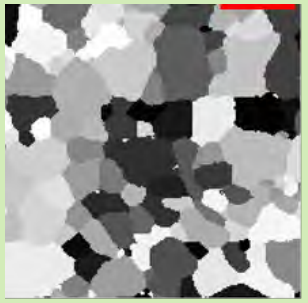
Constitutive equations

CAST3M Code

1 nm **1 µm** **1 mm** **Dimension**

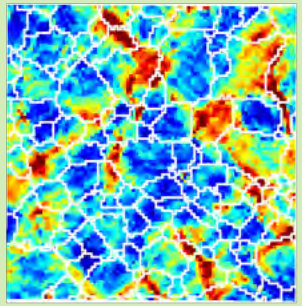
Position in the multi-scale approach of polycrystals (for nuclear application)

Polycrystal (EBSD map)

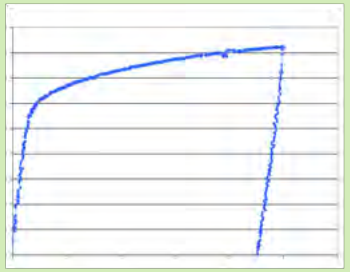


Tensile test

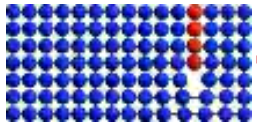
Local strain field



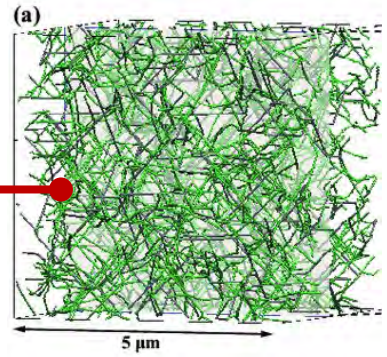
Macroscopic Stress-strain curve



(~nm)

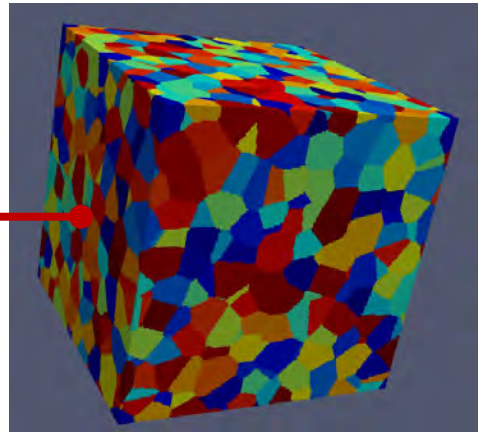


(~µm)

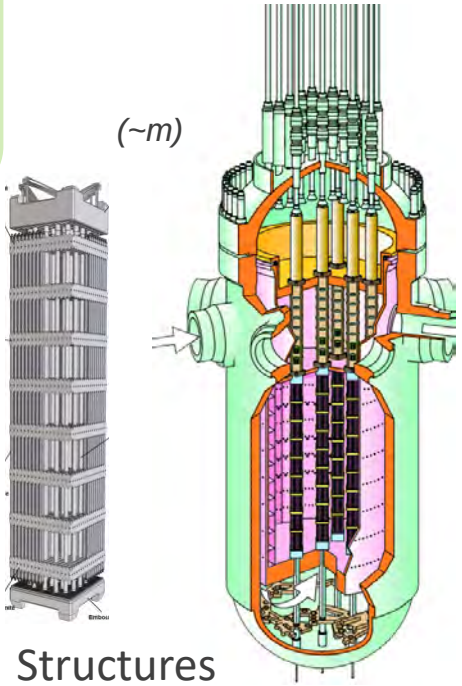


$\sigma = c : (\varepsilon - \varepsilon^P)$

(~mm)



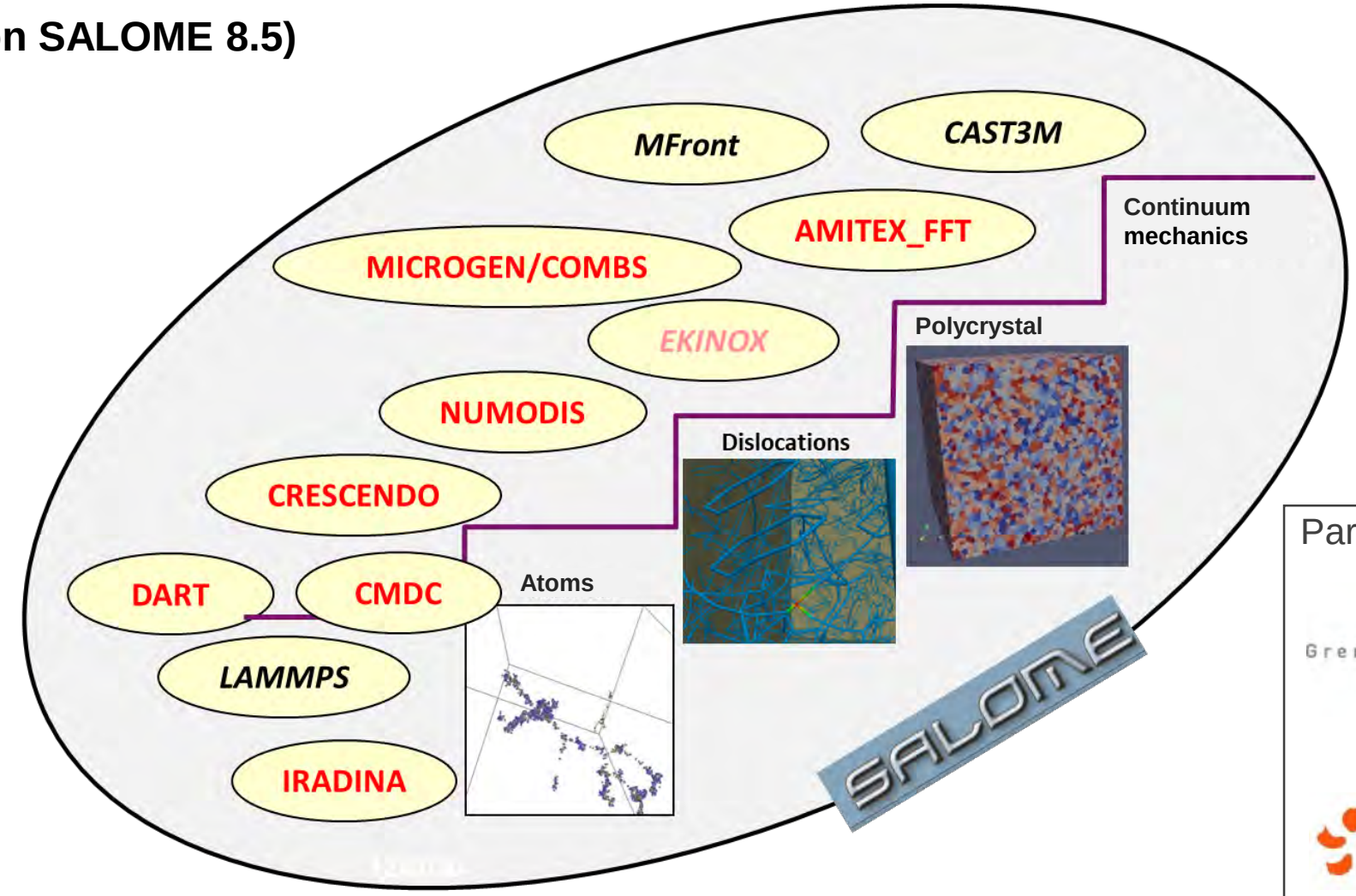
(~m)



Structures

Atomic	Disloc. Dyn.	Crystal Plasticity Law	Polycrystal	
MILADY	**NUMODIS**		**AMITEX**	**CAST3M, MEFISTO, HELIX**

MATIX 2.7 (based on SALOME 8.5)



Partners

MATIX SALOME MICROGEN

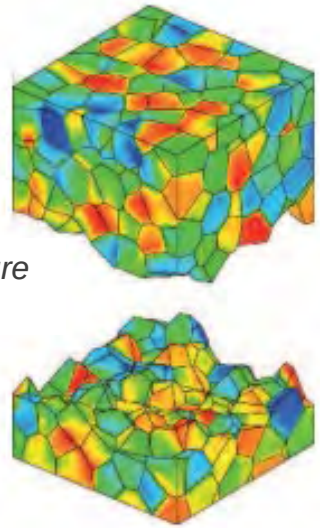
Cast3M is a finite element code for structural and fluid mechanics

System integrating:

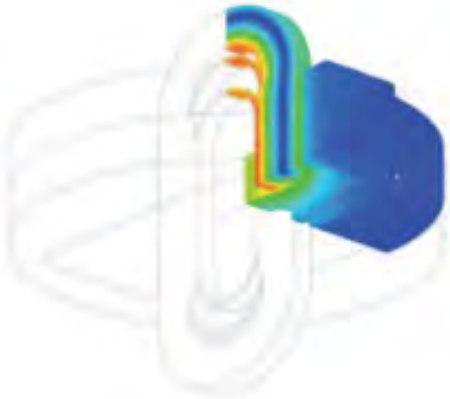
- Functions of calculation
- Construction of the model (pre-processor)
- Treatment of the results (post-processor)

Aim: defining a high-level instrument to support:

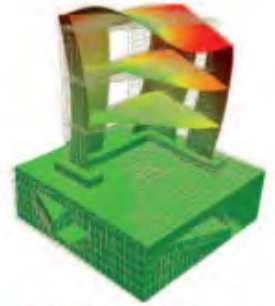
- Design
- Dimensioning
- Analysis of structures and components



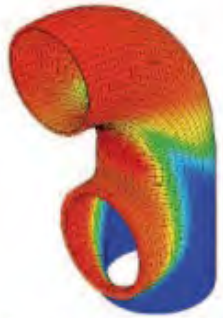
Microstructure modeling



Superconducting device: magnetic field strength



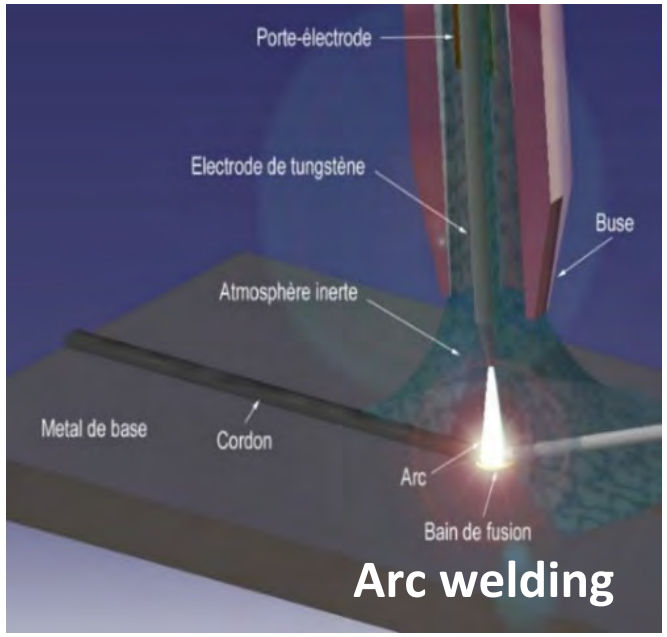
Deformation of a building model under seismic loading



Temperature in a mixing tee and pipe elbow

Cracking in a reinforced and prestressed concrete enclosure

Welding and Additive Manufacturing - powder bed & wire deposition processes



Bead

Microstructural prediction
(nucleation growth solidification)

Welding bath

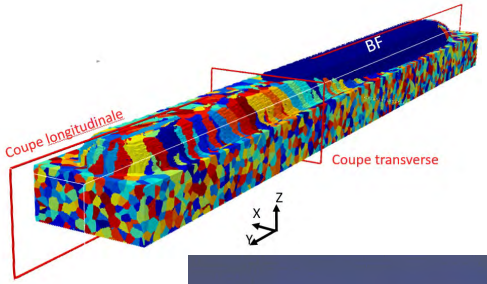
Thermohydraulic
(liquid metals)

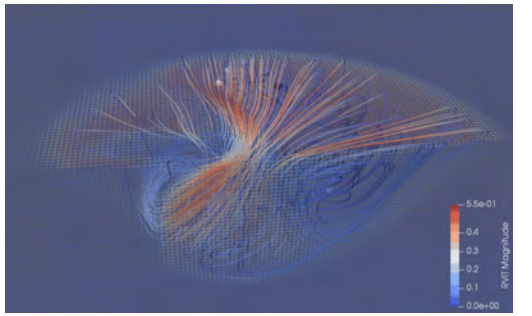
Arc

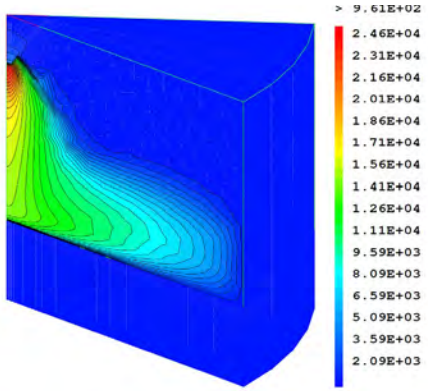
Plasma physics

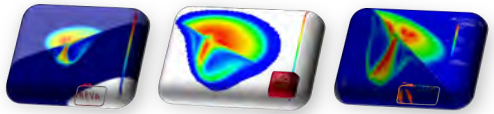
Base metal

Thermo-metallo-mechanical
evaluation





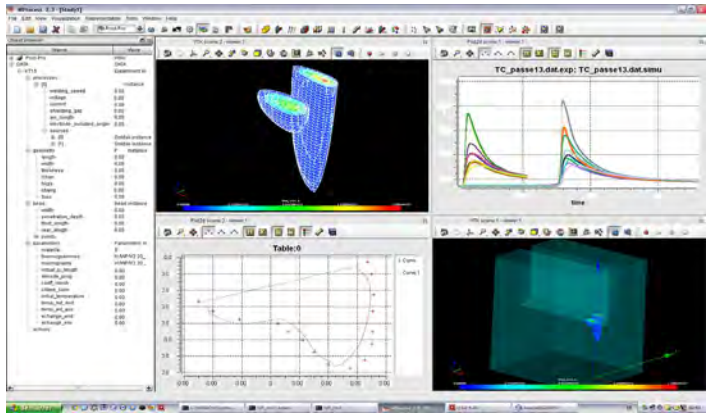




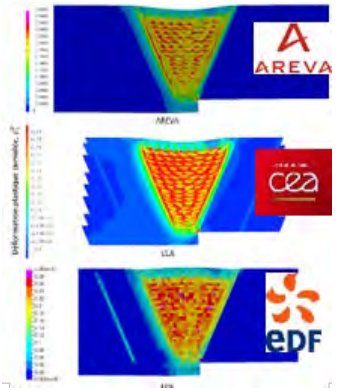
Flows in the welding bath

SALOME URANIE

WProcess Cast3M

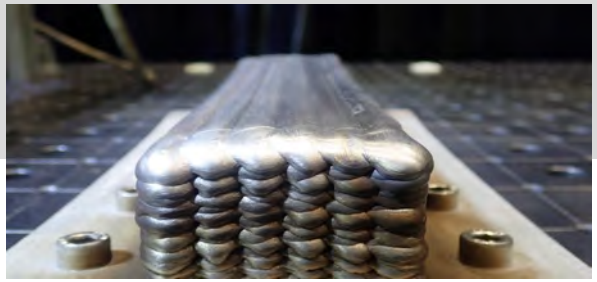


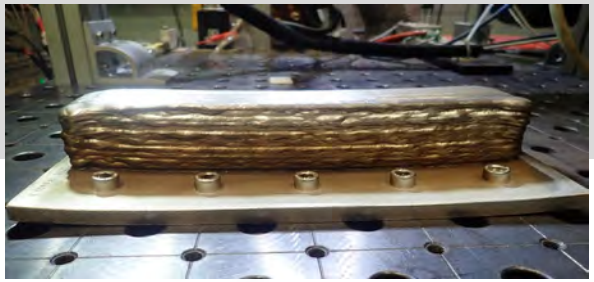
Capitalization



Residual stresses

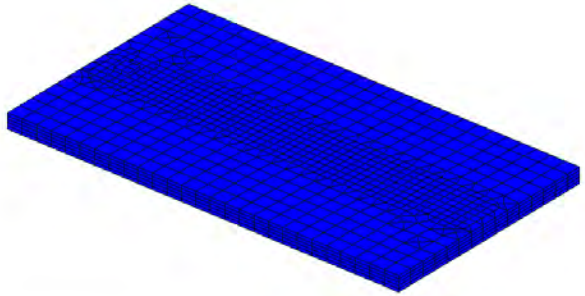
Simulation of the WAAM process under CAST3M

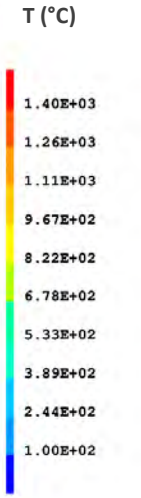




Thermal simulation results

Melted area, temperature at thermocouples, heat accumulation, time spent in a temperature range





Mur 3 Speed x 100

Champ de temperature (Â°C) au temps (s) :0

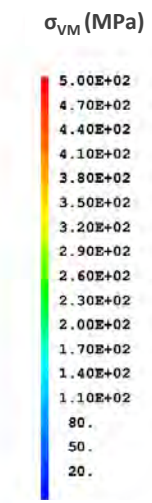
Mechanical simulation results

Total or axial deformations, residual stresses, hardening model (isotropic, kinematic)

Speed x 100

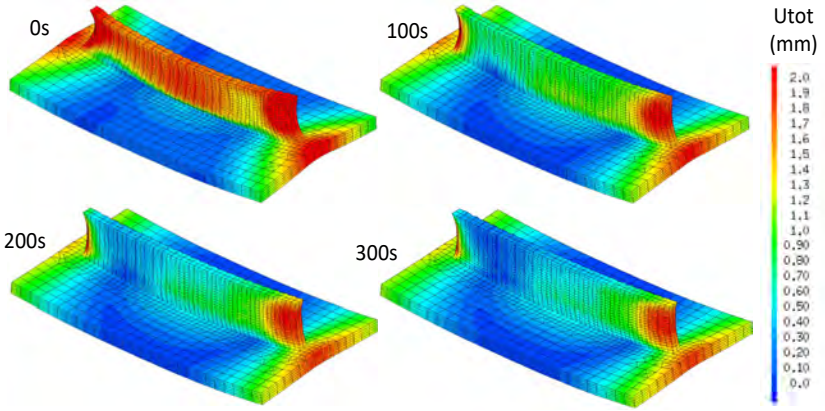
Champ de contraintes (MPa) au temps (s) :0

Wall 3, isotropic hardening model

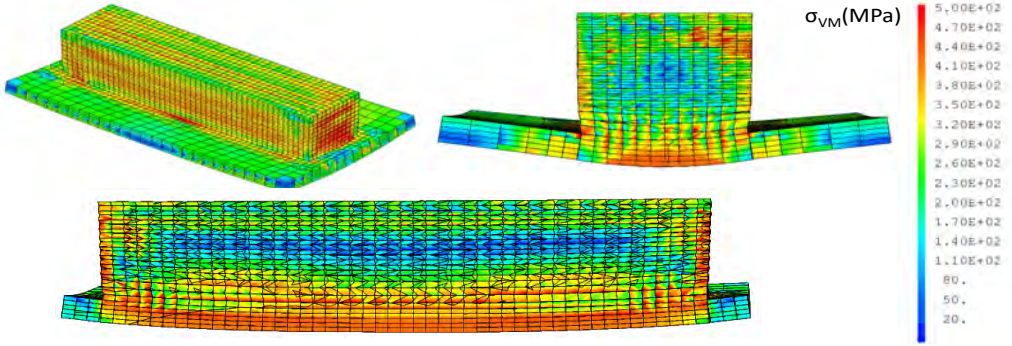


Amplitude déformée 5 X

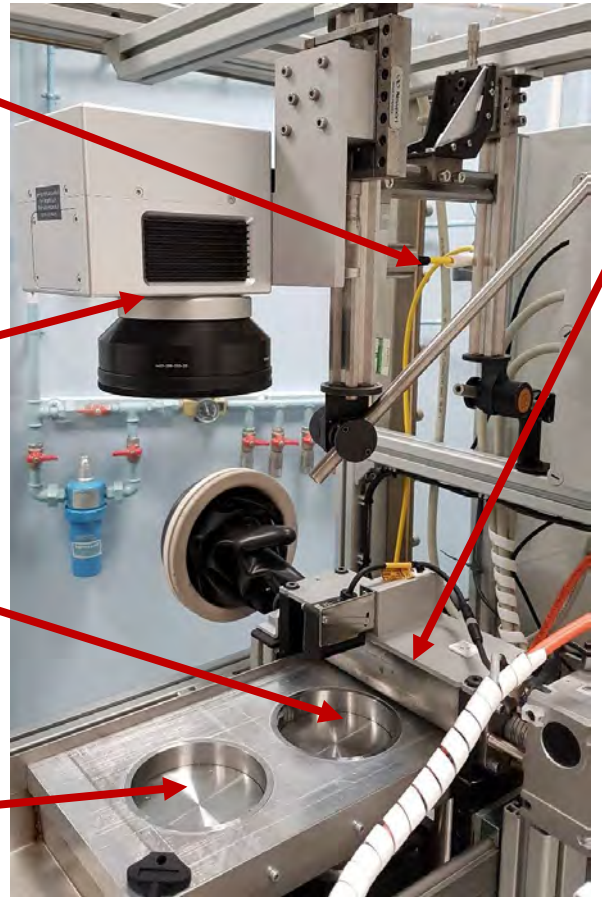
Displacement field by interpass wait time



Residual stress

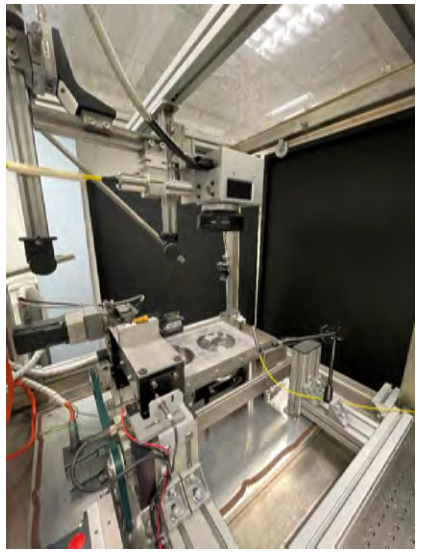


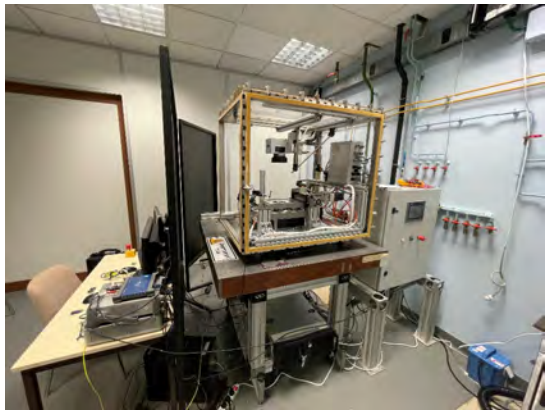
Experimental setup for studying laser metallic powder bed fusion process



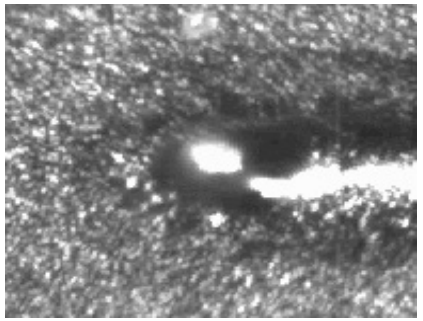
Open experimental setup representative of industrial LPBF machines

Layering device
- Cylinder
- Raclette

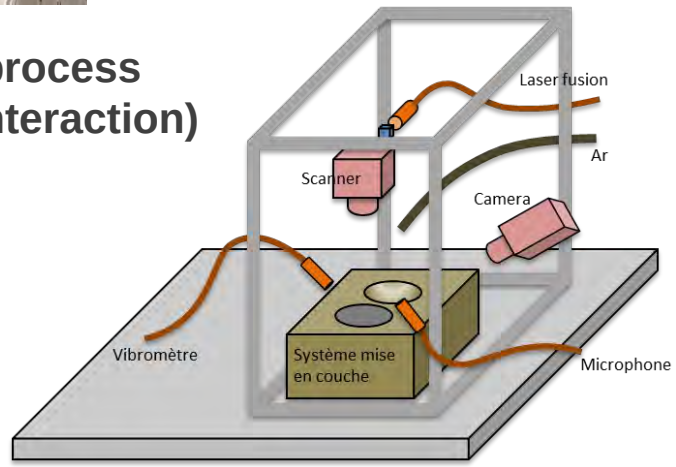




- **Open setup for close analyses of the process (fusion of the powder, laser-material interaction)**
- **On-line process control**

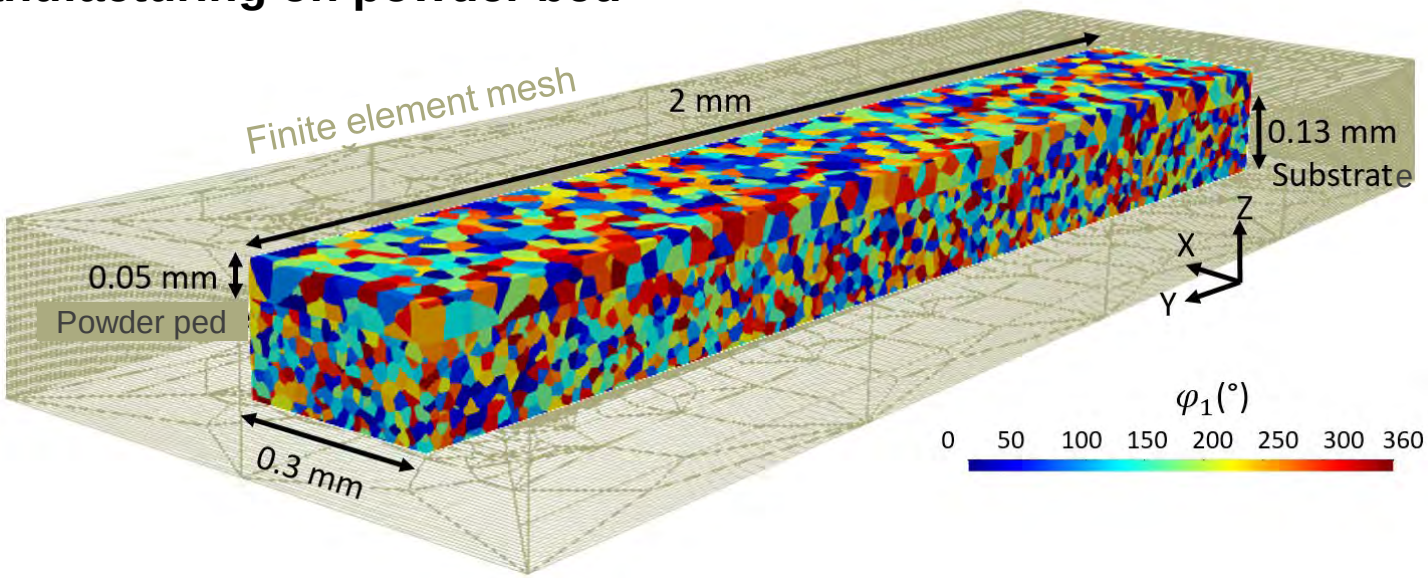


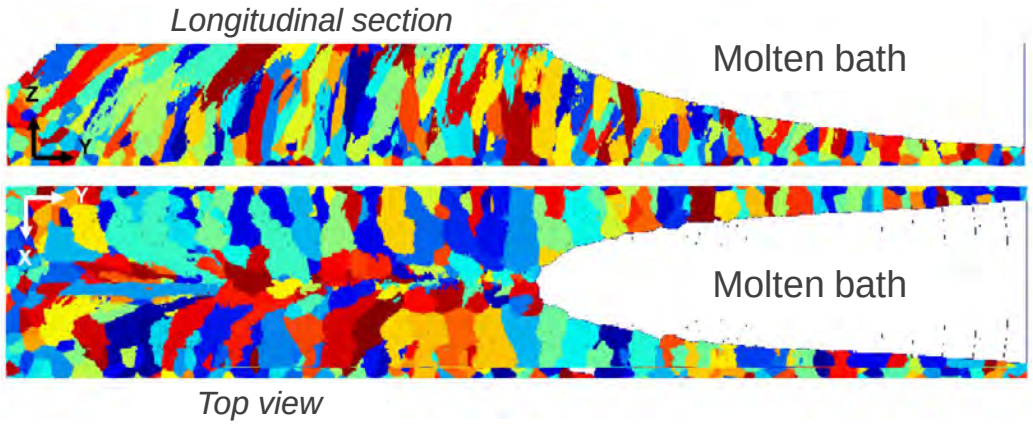
LPBF melt pool : vision with high speed camera

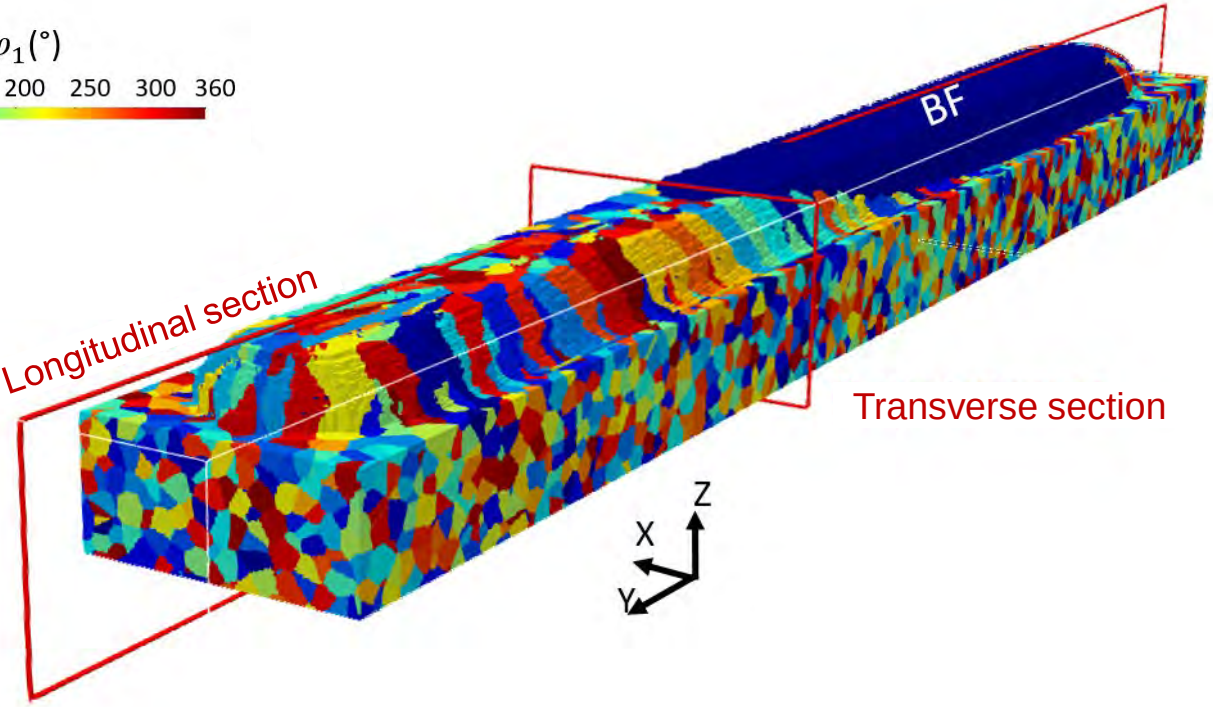


Experimental instrumentation of LPBF with US sensors/optical mictrophone/High speed camera

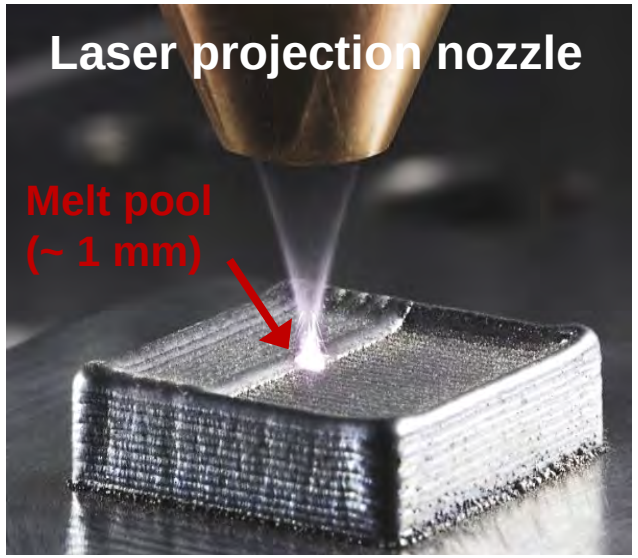
Grain structure prediction of a 316L steel component made by laser fusion additive manufacturing on powder bed







Multi-material simulation of the bath in laser projection, Comsol



Spray **several types of powders** for **multi-materials**:

- parts combining materials
- composition gradients
- in-situ creation of alloys

Objectives:
- Understand the phenomena in the melt, the appearance of defects
- Estimate and optimize the characteristics (thicknesses, compositions, porosities)

Means: COMSOL Multiphysics simulation software:

Physics of the model

Thermal conductivity	Free surface of the bath
Fluid dynamics	Diffusion of the elements

Numerical simulation

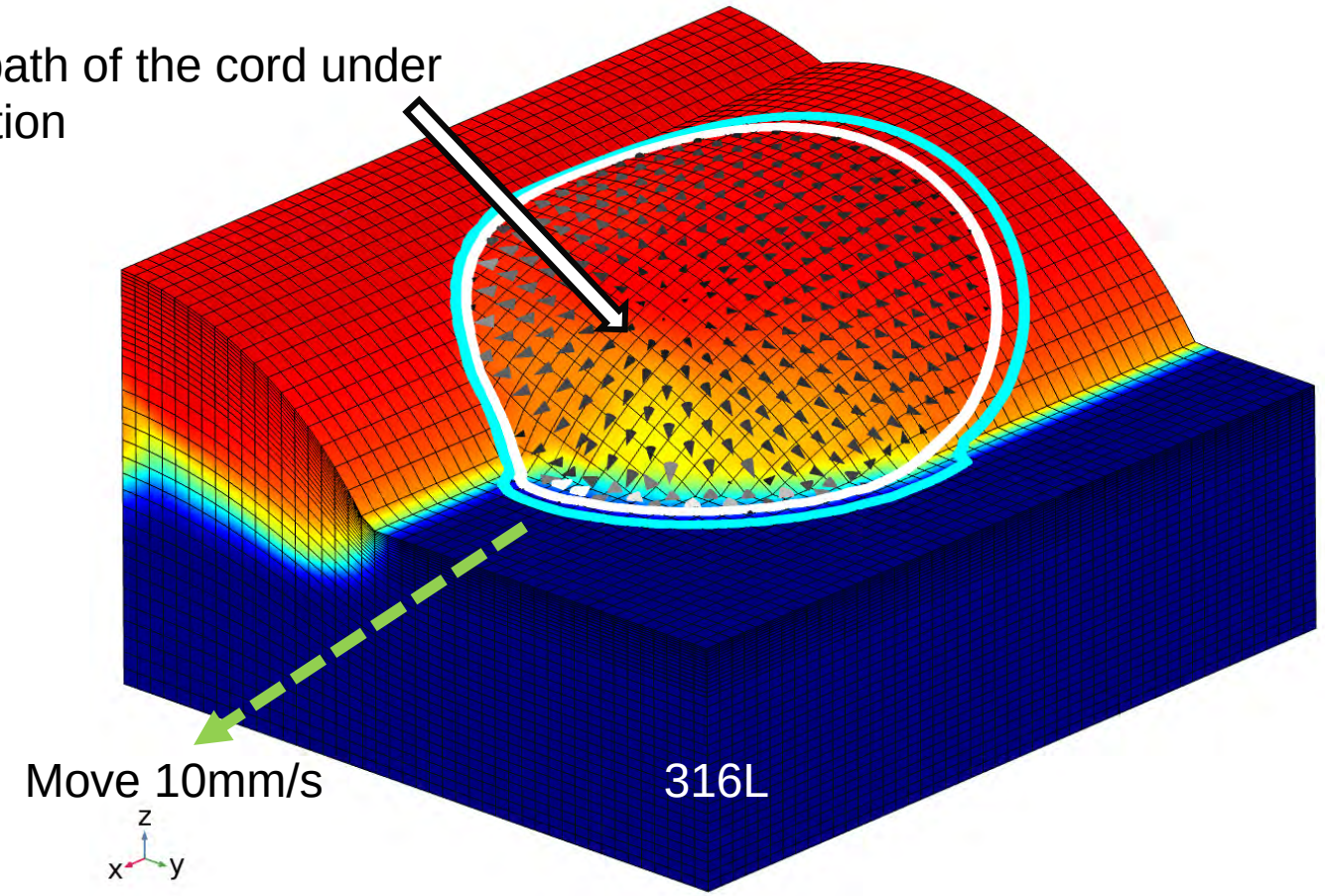
Quick solution (**30 min**) :

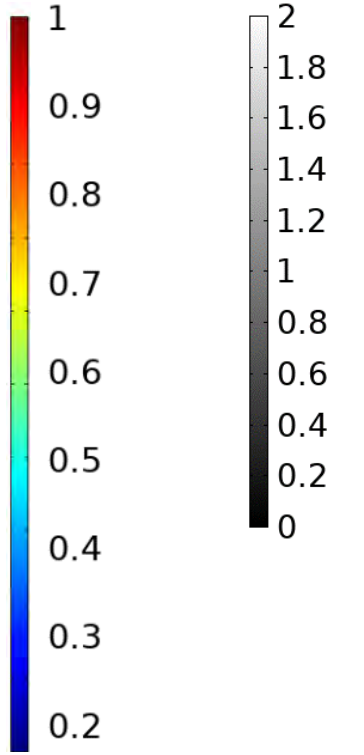
- starting from a **1st approximation**
- **stationary** solution (multi-cordon)
- **viscosity** increased by turbulence

Cr powder deposition on 316L: concentration field, velocity vectors

Perspective view:

Melting bath of the cord under construction



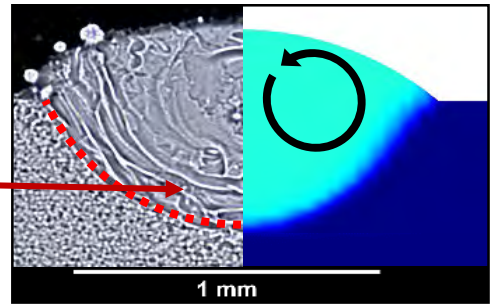


Influence of surface-active impurities (S and O) on the mixture

Cross sections of Cr deposit on 316L

Exp $[Cr]_m$ ~ **48%**

melted zone

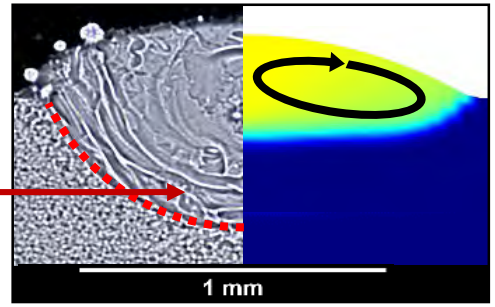


Theoretical $[Cr]_m$ ~ **52%**

With impurities (S and O)

Exp $[Cr]_m$ ~ **48%**

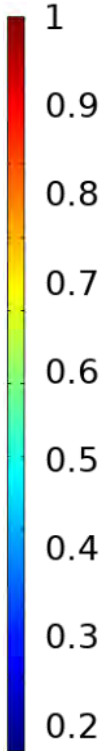
melted zone



Theoretical $[Cr]_m$ ~ **67%**

Without impurities (S and O)

%powder mass Cr



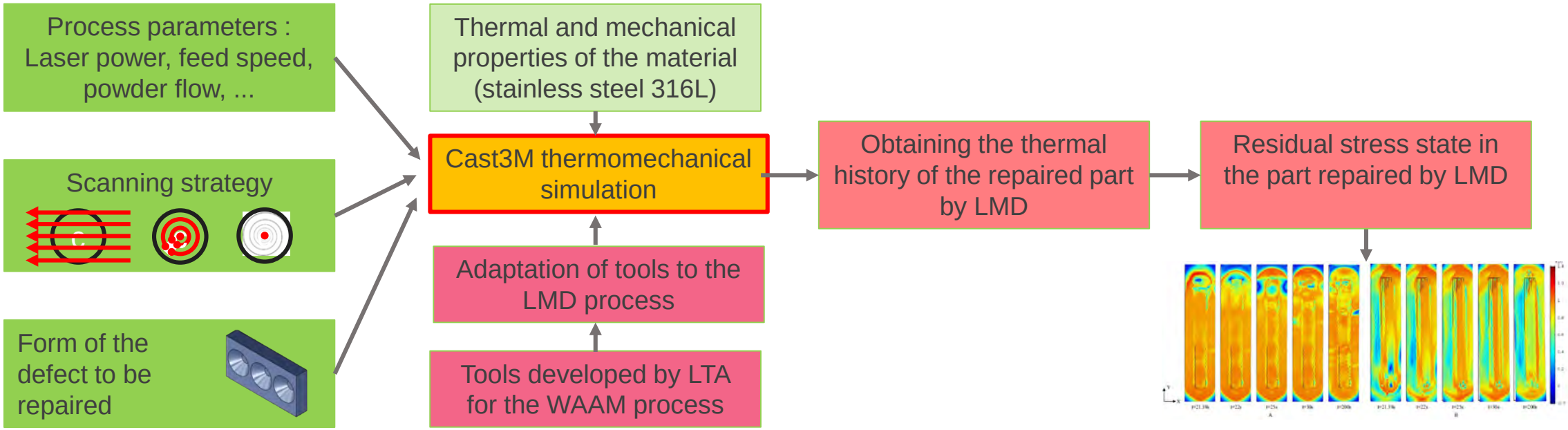
Great importance of considering the **fluid dynamics** and taking into account the **impurities**

Objective

Simulate the introduction of residual stresses in the part according to different scanning strategies during the Laser Metal Deposition (LMD) repair process

Means

- Cast3M simulation software developed by CEA
- Use of tools developed for welding at the Advanced Techniques Laboratory and transposition to the repair process by LMD



Ren et al. – Thermo-mechanical analyses for optimized path planning in laser aided additive manufacturing processes - 2019

International and national collaborations on qualification actions for AM

Qualification and coding actions conducted in the framework of collaborative projects (process control and simulation, creation of defect library, behavior under irradiation...)

- EURATOM « **NUCOBAM** » Project (NUclear COmponents Based on Additive Manufacturing) coordinated by the CEA

- France Relance « **ARQANE** » Project (Actions de Réalisation et de Qualification en Additif pour le NucléairE)

- **EURATOM** and **Horizon Europe** (new materials & processes & simulation) projects proposals

Conclusion, challenges and perspectives

- Prediction of the properties of low-carbon energies materials and their evolution upon aging is key to **accelerate** the development and deployment of these technologies
- Multi-scale description is crucial to understand and predict these properties, leading to the **development of simulation tools at different scales**
- Development of **dedicated experiments** at these different scales is key to both develop and validate these tools
- Development of simulation platforms allows to **capitalize** developments and to force both **top-down** and **bottom-up** multi-scale simulation strategies
- Development and valorization of this work in the framework of **national and international academic and industrial collaborations**

Thank you for your attention