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

Development of multi-scale calculation methods

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

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

**CRESCENDO Code**
- Distribution of clusters

**CAST3M Code**
- Crystal plasticity constitutive laws

**In situ mechanical tests**
- In situ tomography observations

**High resolution microstructural analysis**
- Distribution of carbide sizes

**Constitutive equations**

**Context**
Code/modeling development and instrumentation/observation development in support

**In situ TEM**
Movement of dislocations

**Distributions of clusters**
Atoms

**Electrons**

**1 nm**
**1 μm**
**1 mm**

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

Context
Code/modeling development and instrumentation/observation development in support

\[ \sigma = c : (\varepsilon - \varepsilon^P) \]

Polycrystal (EBSD map) → Local strain field → Macroscopic Stress-strain curve

Polycrystal (EBSD map)

Local strain field

Macroscopic Stress-strain curve

Atomic
Disloc. Dyn.
Crystal Plasticity Law
Polycrystal

MILADY
NUMODIS
AMITEX

CAST3M, MEFISTO, HELIX

Structures
MATIX platform multiphysics and multiscale

MATIX 2.7 (based on SALOME 8.5)
Development of Cast3M

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

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

**Mechanical simulation results**
Total or axial deformations, residual stresses, hardening model (isotropic, kinematic)

**Displacement field by interpass wait time**
Wall 3, isotropic hardening model

**Residual stress**
Experimental study on Laser Powder Bed Fusion

Experimental setup for studying laser metallic powder bed fusion process

- Fiber laser
- Scanner/Optical focusing head
- Provision of powder
- Manufacturing chamber - Diameter 100mm - Height 25mm

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 microphone/High speed camera
Prediction of grain structures - powder bed

Grain structure prediction of a 316L steel component made by laser fusion additive manufacturing on powder bed
**Objectives:**
- Understand the phenomena in the melt, the appearance of defects
- Estimate and optimize the characteristics (thicknesses, compositions, porosities)

**Means:** COMSOL Multiphysics simulation software:

Spray several types of powders for multi-materials:
- parts combining materials
- composition gradients
- in-situ creation of alloys

**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

Move 10mm/s

316L

%powder mass Cr

Speed (m/s)
Great importance of considering the fluid dynamics and taking into account the impurities on the mixture.

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

Cross sections of Cr deposit on 316L

Exp \([\text{Cr}]_m \sim 48\%\)

Theoretical \([\text{Cr}]_m \sim 52\%\)

With impurities (S and O)

Exp \([\text{Cr}]_m \sim 48\%\)

Theoretical \([\text{Cr}]_m \sim 67\%\)

Without impurities (S and O)
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

Scanning strategy

Process parameters:
- Laser power, feed speed, powder flow, ...

Form of the defect to be repaired

Thermal and mechanical properties of the material (stainless steel 316L)

Adaptation of tools to the LMD process

Obtaining the thermal history of the repaired part by LMD

Residual stress state in the part repaired by LMD

Tools developed by LTA for the WAAM process

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