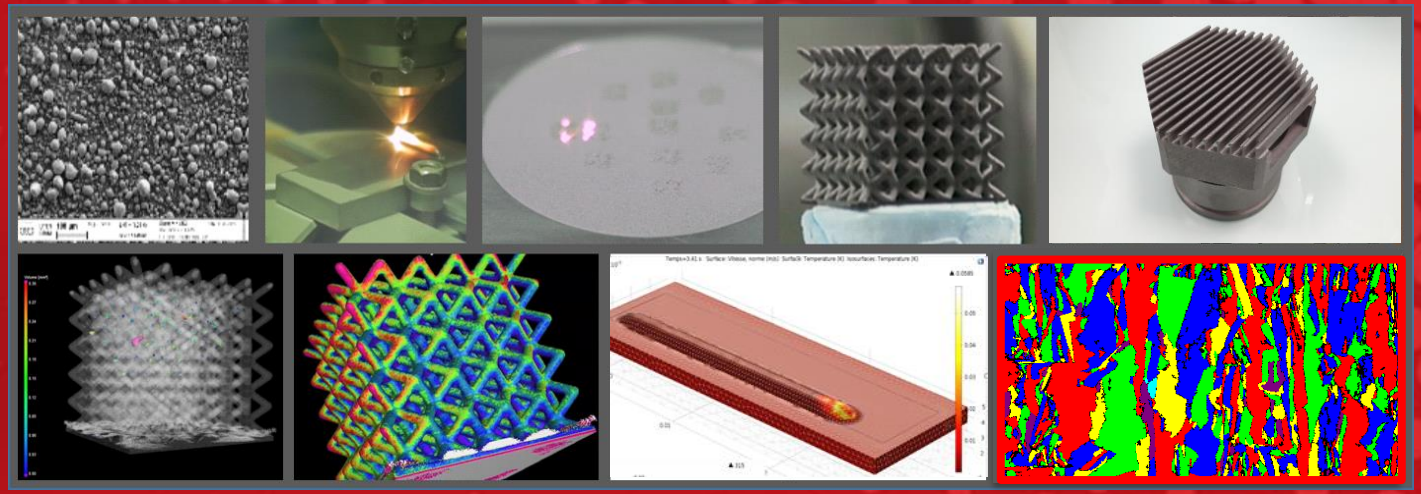


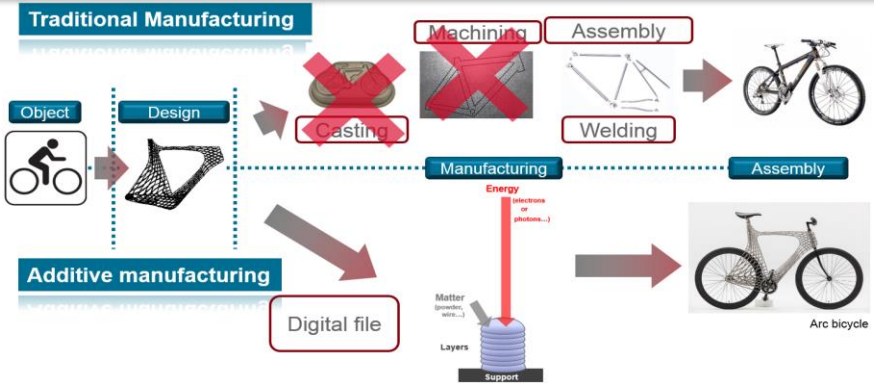
Additive Manufacturing for Nuclear Applications

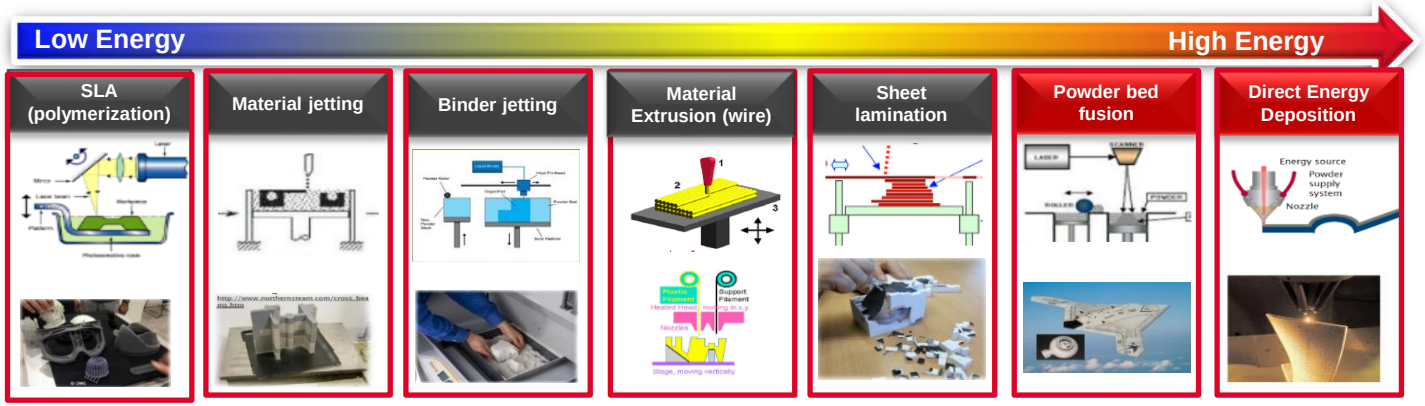
P. Aubry[1], F. Lomello[1], O. Hercher[1], W. Pacquentin[1], C. Blanc[1], P-F. Giroux[2], F. Villaret[2], Y. Decarlan[2], H. Maskrot[1]

[1]DES/ISAS/DPC/SEARS

[2]DES/ISAS/DMN/SRMA

Different processes that allow to manufacture a physical object by adding matter « layer by layer » following a digital file (AFNOR French standard E 67-001).

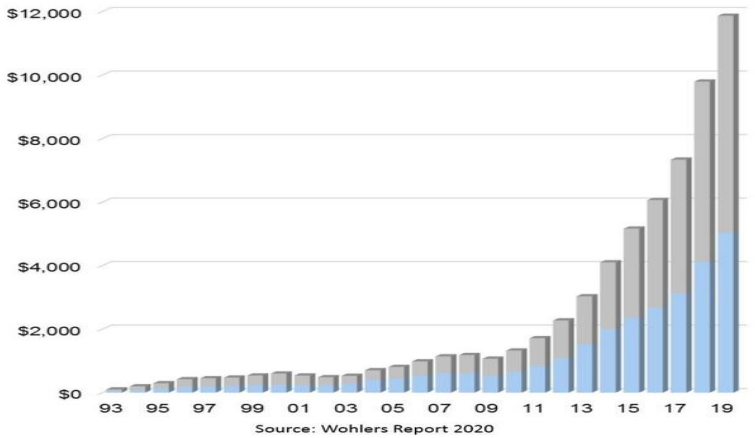




1. ADDITIVE MANUFACTURING : A DRAMATIC INCREASING MARKET

- ***The volume of the market's size increased up to 1.3 billions € in 2012: the highest market is conduced by the polymer 3D printers.***
- *Wohlers Report 2020 : Dramatic Rise in Metal Additive Manufacturing products and services (>20% 2019)*

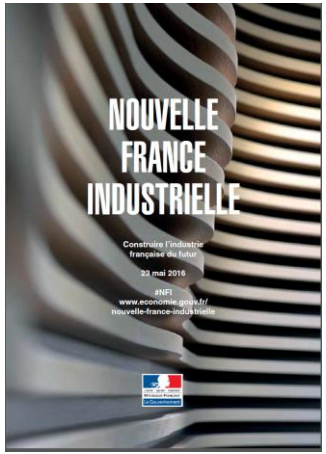
Worldwide



Revenues (in millions of dollars) for AM products and services worldwide. Blue segment : products. Gray segments : services.

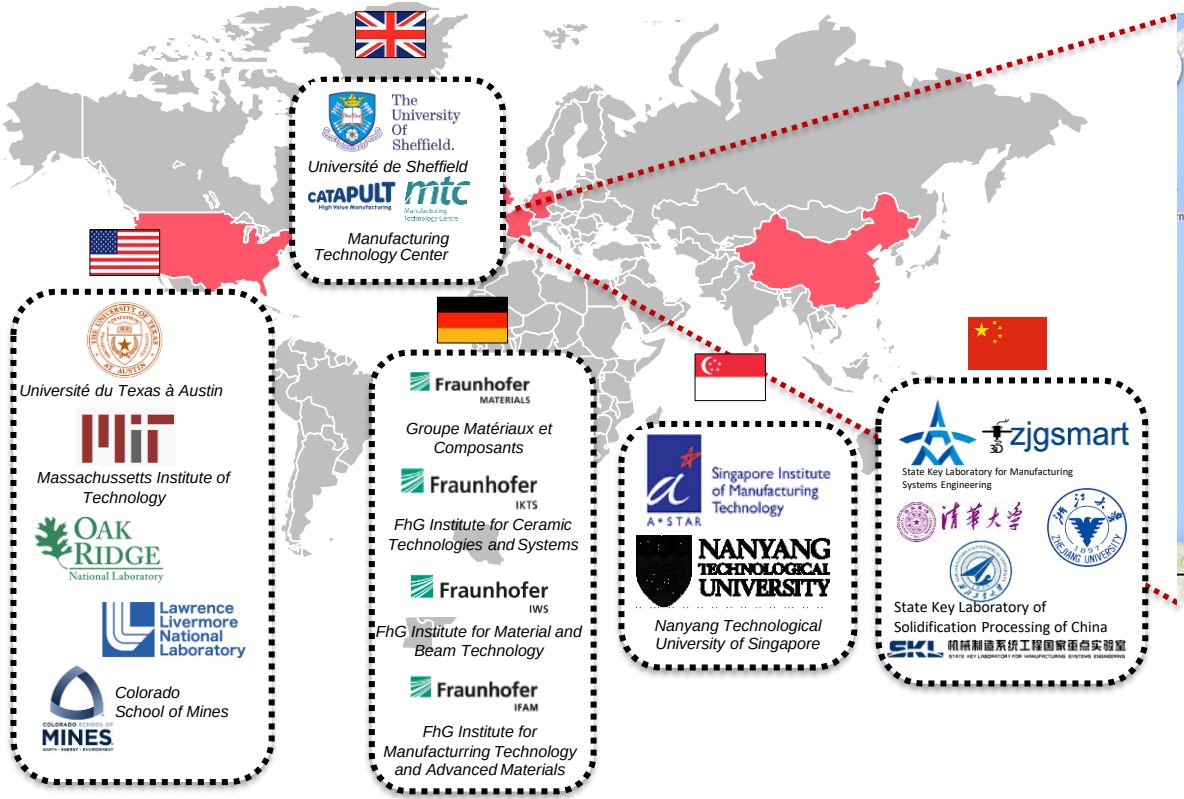
- **During the last 15 years, sales increased 15 times**
- **An important growing since 2004.**
- **Dramatic increase of Metal AM machine since 2012**
- **More than 40 % of the machines are located in the US, 28 % in Europe as well as in Asia.**

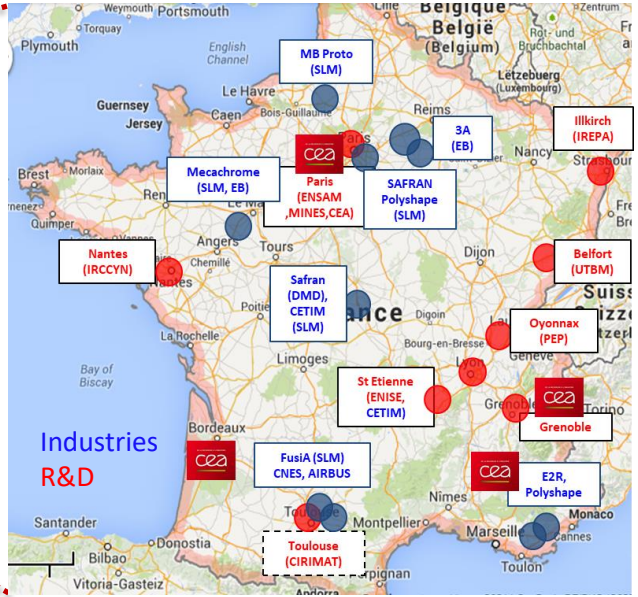
France



On 23rd May 2016, the "French Ministry of the Economy, the Industry and the Digital Sector" claimed that rapid manufacturing is one of the key technologies to be developed in the frame of the "French Future Industry Alliance".

2. ADDITIVE MANUFACTURING : INTERNATIONAL AND NATIONAL CONTEXT (R&T)





- Very Active R&T field at international level
- Very Active European R&T
- A large network of AM-related R&D Centers and Companies in France

Driving forces for Additive Manufacturing in nuclear industry

- Commonly, small amount of same parts
- Dimensions of parts compatible to exisiting machines
- Materials available yet (not for all!) for certain industrial applications
- Interest of AM for maintenance under operational conditions
- Lower dependence to subcontractors/providers

Requirements in nuclear field

- **Materials: Possible integration of AM materials in Nuclear Codification (towards a RCC-MRx reference)?**
  - Mechanical characteristics at high temperature (tensile, impact, creep)
  - Corrosion
  - Irradiation behavior

Huge work !

- **Robustness of AM: Manufacturing**
  - Inline monitoring and control

- **Other limits of AM capabilities**
  - Maximum dimensions
  - Manufacturing time
  - Finishing

3. THE PATHWAY OF COMPETENCES FOR AM

A lot of key Issues !

CAD/CAM
- Manufacturing optimization
- AM Design
- Reverse Engineering


Manufacturing
- SLM
- DEMD
- EBM of electrons
- CIC
- WAAM, TIG, MIG

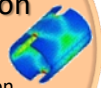
Control
- Process control
- Process monitoring
- NDT
  - Xray
  - US
  - Eddy current

Finishing
- Post-machining
- Surface finisihing
- Heat treatment

Characterization
- Microstructure
- Mechanical
- Corrosion
- Irradiation

Codification Standards
ISO/ASTM
52900 (Terminology), 52901 (Guide, Purchase), 52910 (Design), 52915 (Data Format), 52921 (Coordinate, Tests)
F3055-14a (Nickel alloys), F2924 (TA6V)

Modelling/ Simulation
- Processes
- Material (solidification, thermo-physial properties)



Material
- Powder
- Non conventional elaboration processes

POUDR'INNOV 2.0 (DRT/LITEN, CEA Grenoble)

Polymers and Ceramics (**Inkjet, SLS**)

Metals (**SLM**)

SAMANTA (DES/ISAS, CEA Saclay)

Polymers (**Filler, SLA**)

Metals (**SLM, EBM, DEMD, LWAAM**)

+ IRFU, CEA/DRF : Fondamental Research, Large Instruments
+ DAM, CEA Valduc and CEA Le Ripault : Defence applications

+ R&D cooperation

université PARIS-SACLAY

IRS FAPS

Additive Factory Hub

+ Established Industrial partnership

EDF

framatome

ENGIE

DEPHIS

orano

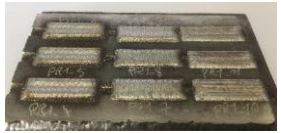
MECACHROME

Near-Shape Manufacturing

CEA-Gerailp, Inco718 neear shape casing

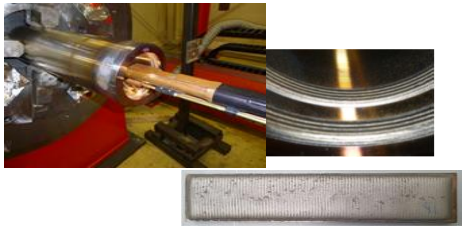
CEA-DEN, additive cylinder 316L

Repairing

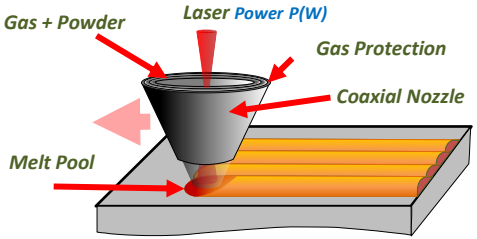


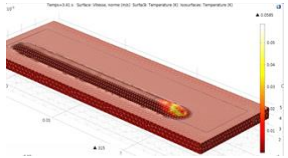
Stellite 6

Cladding/Coatings



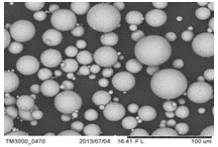
CEA-DEN/Nutech
Colmonoy52 Inner Cladding of Tubes





CEA-DEN

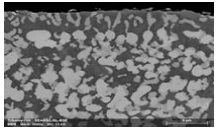
Modelling/Simulation



Plasma Spheroïdisation

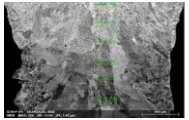
Advanced powder metallurgy

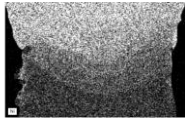
Powder/Wire



CEA-DEN, Tribaloy700

Cobalt free Harfacing Material





Ni to Fe base Graded material

Graded materials

Materials

OPTOMEC LENS MR-7

Machines **Nozzles**

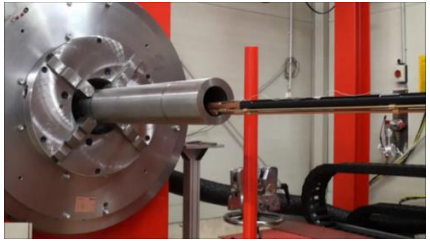
Systems

LASER CLADDING : COBALT FREE HARDFACING MATERIALS

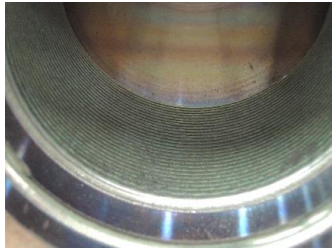
GEN IV Reactor ASTRID: Inner cladding of diagrid tubes with hardfacing material

- Diagrid demonstrator
- Deep deposition head (Nutech)

- Material: COLMONOY 52 (NiCrFeSiCB)
- Search of parameters on plates
- Trial on tubes
  - Avoiding cracks by heating
  - Geometry OK



Clading of internal surface of tube with adapted deep cladding head



Claded internal surface of tube diam.100mmx500mm

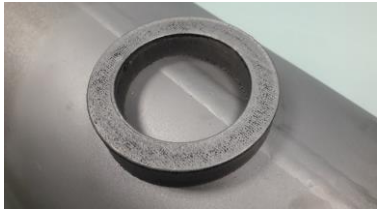
Clading of internal surface of tube diam.100mmx500mm

LASER CLADDING : Manufacturing and repairing

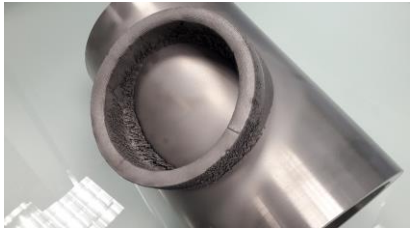
GEN IV Reactor ASTRID: Other possibilites for Laser CLadding

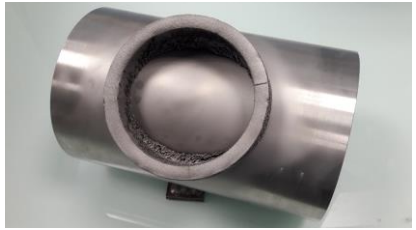
- Addition of structure on simple geometries
- Laser Cladding
- Material: 316L

- Combination with repairing issues
- Cost and time reduction for manufacturing



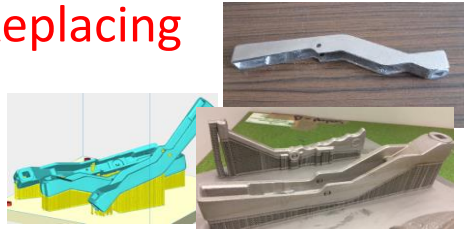
Addition of cylindrical shape 316L, OPTOMEC LENS system





Addition of cylindrical shape 316L, BeAM system

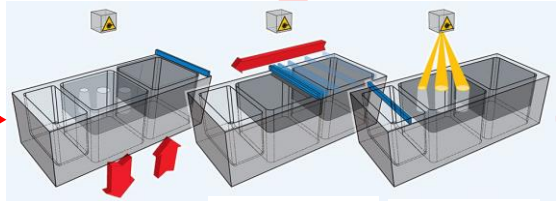
Replacing

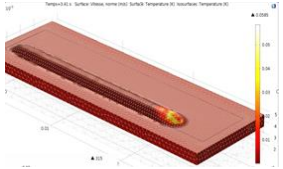


CEA-EDF LAM part

Complex geometry/ topogical optimization

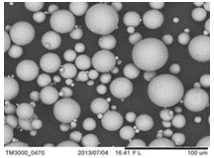
Integration of functions/ Structure Lattice





CEA-DEN

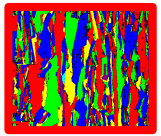
Modelling/Simulation



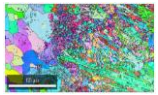
Plasma Spheroïdisation

Advanced powder metallurgy

Powder

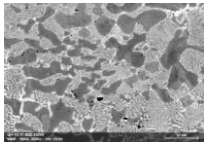


316L



Ferritic Steels

ODS Steels



Ni based alloys

HEA/CCA

Materials

SLM machines

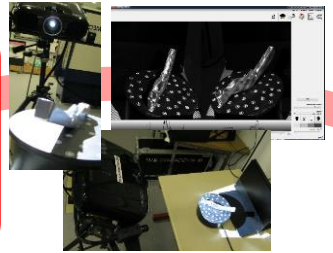
Process control

Systems

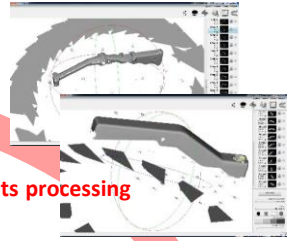
Powder Bed Fusion for Replacement of Existing Valve Handle

Maintenance in Operating Condition

Original Parts



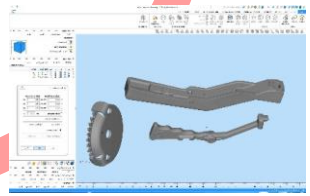
Digitalization



3D points processing

Data fusion

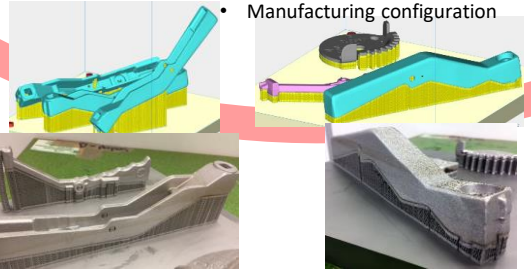
- 3D points fusion
- STL file generation

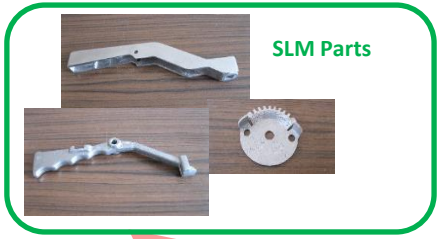


CAD/ Analysis of 3D model

CAM / SLM

- Preparation of file
- Support generation
- Manufacturing configuration





SLM Parts

R&D Study for **Sodium Gas Heat Exchanger**

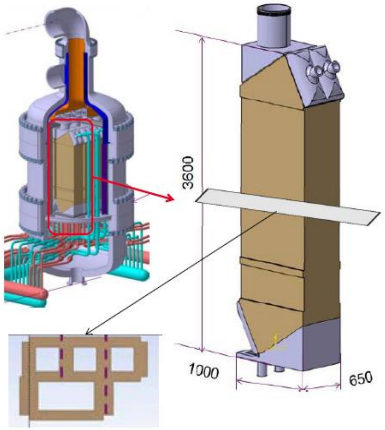
Started in 2015

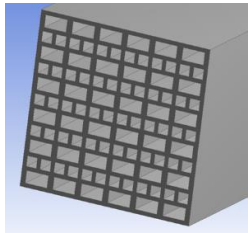
2 different processes tested:

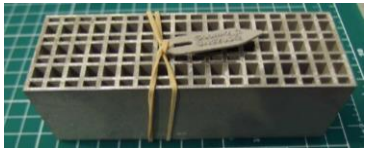
- **DMD :** Direct Metal Deposition, by IREPA
- **L-PBF :** Powder Bed Fusion, by POLYSHAPE

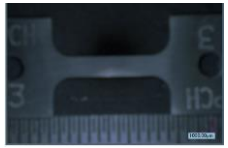
Different mock-ups realised:

- Metal specimen produced by additive manufacturing and some with future thermal treatment
- Post HIP treatments lower the stresses and improve elongation



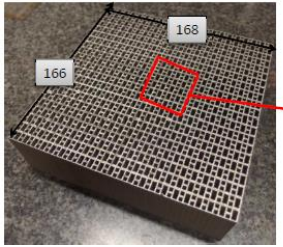


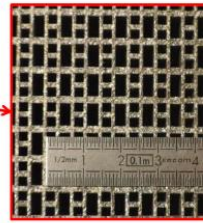


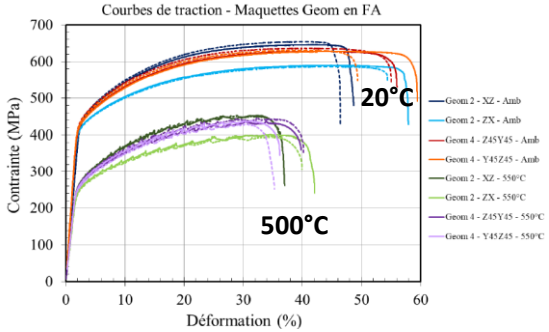


Alexandre type specimen for tensile test

Normalized tensile specimens







Powder Bed Fusion of Fuel assembly components

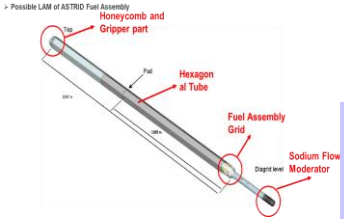
GEN IV Reactor ASTRID: Fuel Assembly Grid

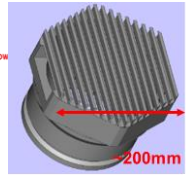
- Initial design: 1 main component + 17 welded "rails"
- Material: 316L(N)

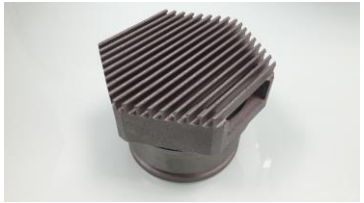
- SLM process: 1 part (316L)
- Critical issues: Dimension+ Surface roughness

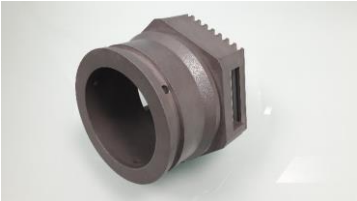
Objectives:

- ✓ Feasibility demonstration of complex parts.
- ✓ New manufacturing opportunities.
- ✓ New designs.









GEN II-III-IV Reactor Flow Moderator/ Filters

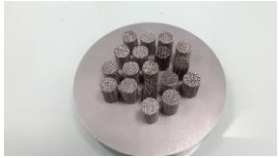
- Initial design: Plates with holes, Sintered porous elements, metallic sponge, metallic fibers
- Material: 316L(N)
- Critical issue: Control of pores

- SLM manufacturing of differents samples

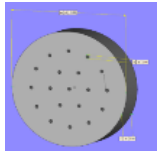
Objectives:

Nuclear-fuel pins possess a calibrated pore filter with the aim of controlling their reactivity.

The new design contains 37 holes with a diameter of 400 µm inside a cylindrical disc.



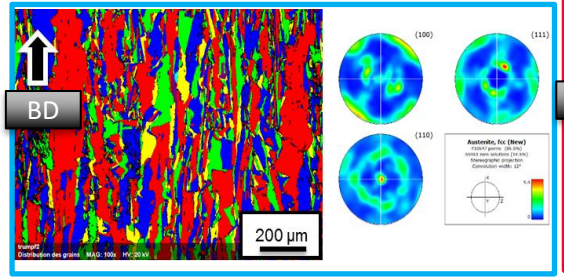
- Opportunity for new design of structured materials
- Material Design from Function (simulation)

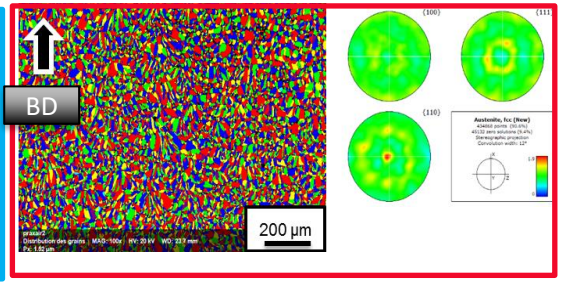


Calibrated Pore Filter

Example: Powder Bed Fusion of AISI 316L Metallurgy & Material properties

Influence of the process parameters

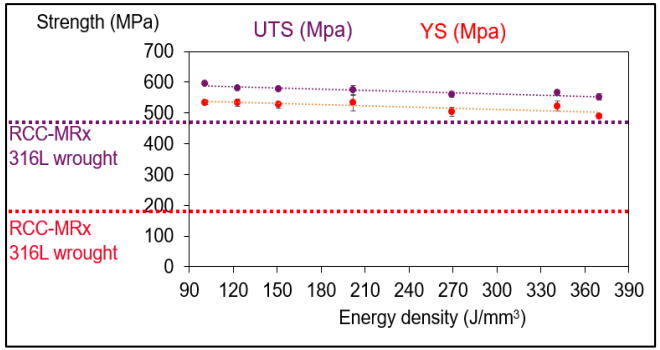


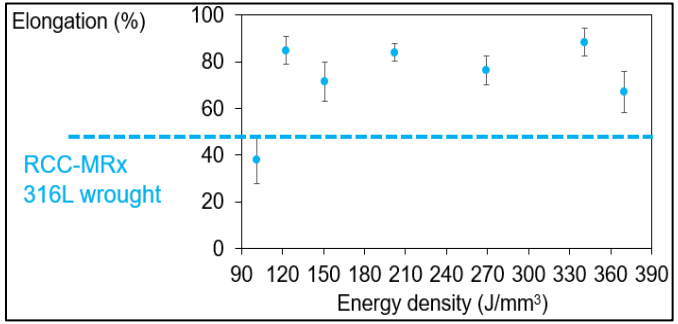


Powder 1 ➢ Columnar grains

Powder 2 ➢ Equiaxed grains

Mechanical properties: **High UTS/YS and El values** (> RCC-MRx requirement)





- **Variable micrsotructures available (Columnar vs. Equiaxed)**
- **Mechanical properties demonstrated (tensile, resilience)**
- **Other tests ongoing**
  - **Irradiation**
  - **Test on compoments**

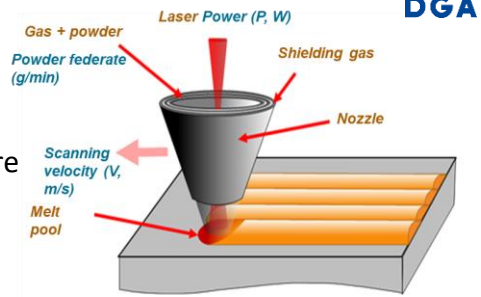
A. Chniouel PhD. DEN/DANS/DPC/SEARS/LISL

Objective : To elaborate innovative materials with tailored properties

- **Corrosion, Wear, Thermal resistance**

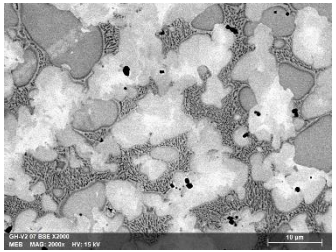
Proposal : High Entropy Alloys/Complex Composition Alloys

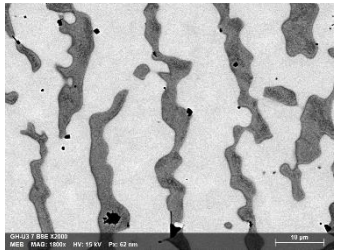
- At least five principle elements between 5 and 35 %at
- Access to a combination of good properties
- Use of CALPHAD (CALculation of PHAse Diagram) to dertermine the compostions that present intere



Direct laser deposition

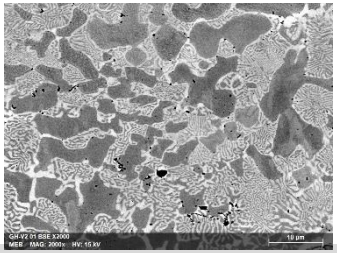
- Additive manufacturing process use to deposit thick coatings (several milimeters)
- Combinatory metallurgy : composition gradient, different compositions on the same sample





Tribological test

- Pin on disk test
- Access to the friction coefficient, the specific wear rate and the wear loss
- Analysis of the wear tracks to determine the type of wear
- Correlate the wear comportement with the microstructure



$(NiFeCr)_xMo_yTi_z$

G.Huser PhD. Student DEN/DANS/DPC/SEARS/LISL

Objective : To tackle difficult junctions of dissimilar materials

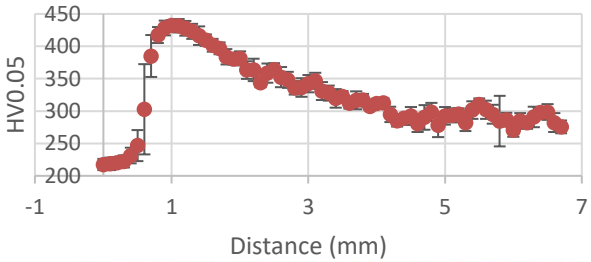
- Metallurgical icompatibility
- Stress cracking

Proposal : Graded transitions

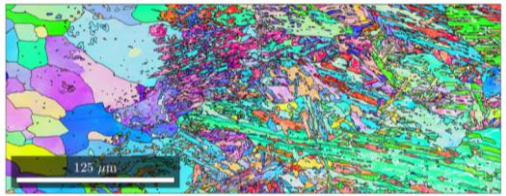
Example : 316L/ Fe-9Cr-1Mo junction

Laser Cladding

H V

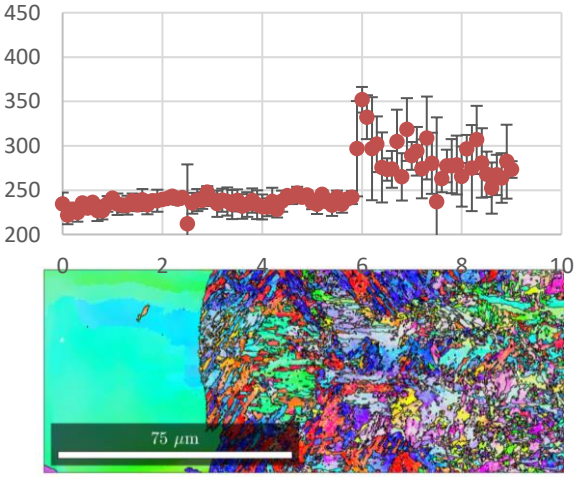


E B S D



IPFZ, 1px = 0.1 µm

Selective Laser Melting



F. Villaret PhD. Student DES/ISAS/DMN/SRMA/LA2M

- **Additive Manufacturing in nuclear industry (France)**
  - Ongoing and Increasing activities
  - First AMed parts for nuclear applications
  - Opportunities of new design, part optimization, tailored material

- **Main issues for penetration**
  - Validation of materials (Irradiation resistance) : ongoing studies
  - Robustness of the process
  - **Introduction of the process into nuclear codification/regulation**
  - **Teaching/Training (process, design, materials,…)**

  →
  - Process understanding
  - **Process control**
  - Material engineering
  - **Need work on nuclear codification/regulation of AM process**

- **Other issues**
  - Maximum dimensions to be considered : Increase of machine capacities (Powder Bed Fusion)
  - Accuracy
  - Material issues : development of other materials
  - Post-treatment/Finishing
  - Validation of the continuity of the manufacturing chain