framatome

Additive manufacturing of fuel components: from implementation of 316L components to heavily loaded applications with alloy 718

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3. Stress corrosion analysis on 718 alloy: towards highly loaded components

4. Conclusions

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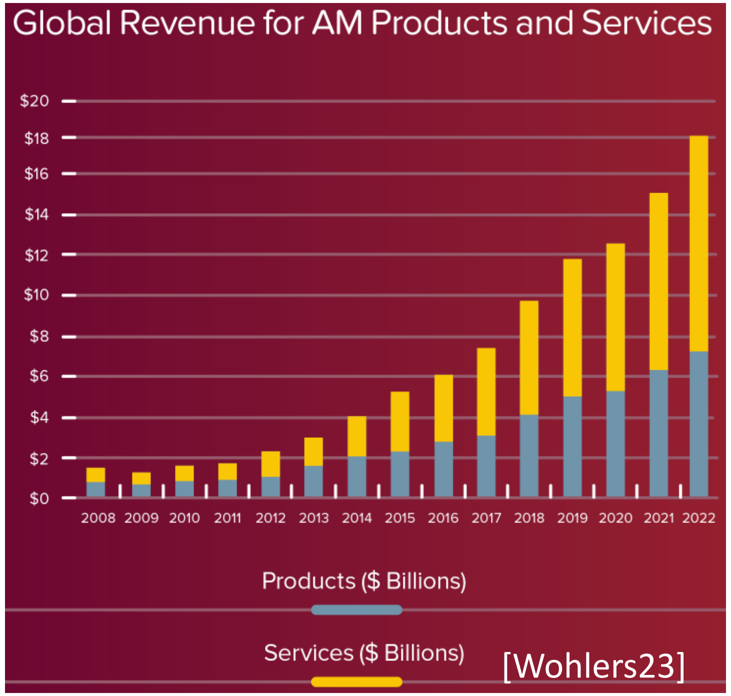
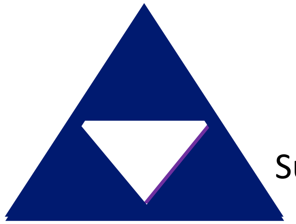
Introduction to AM @FRA and for Fuel products

Introduction to AM in industry & @FRA

- Growing interest in the past few years for AM, at Framatome and more generally in the industry due to the disruptive nature of this manufacturing technology



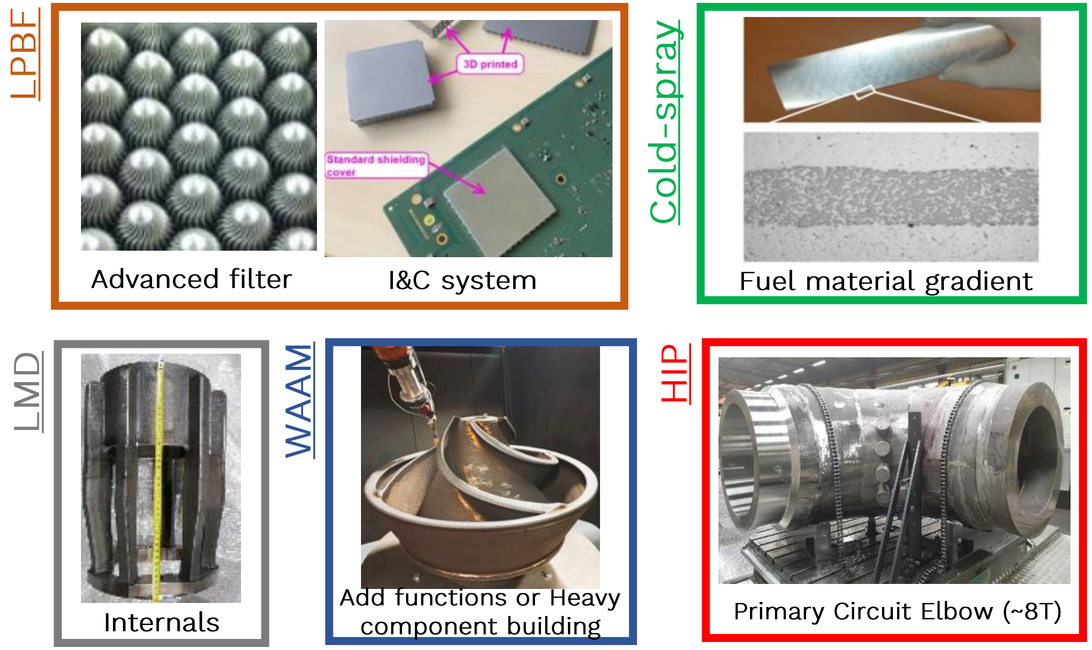
Product Performance



Product cost

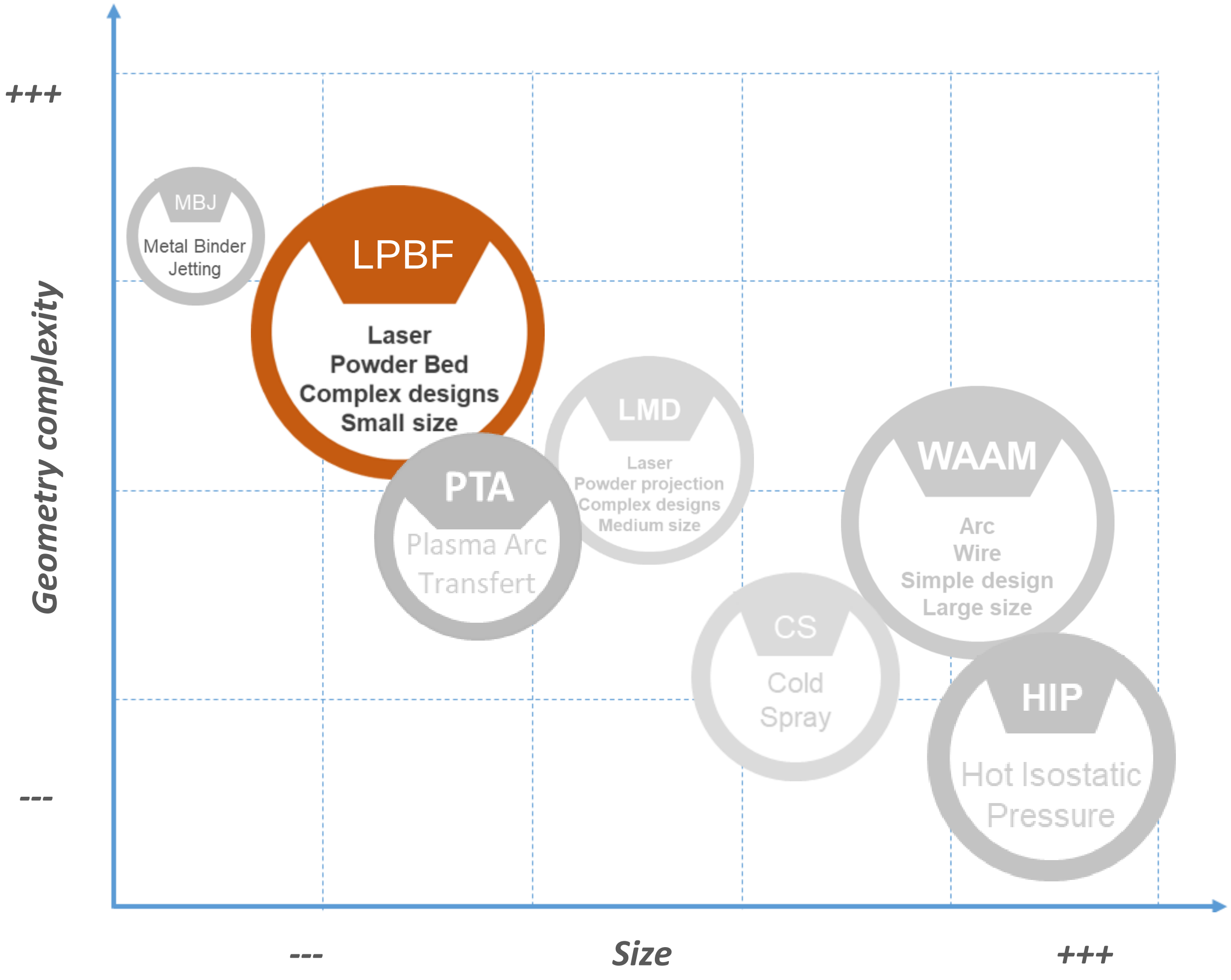
Supply chain Efficiency

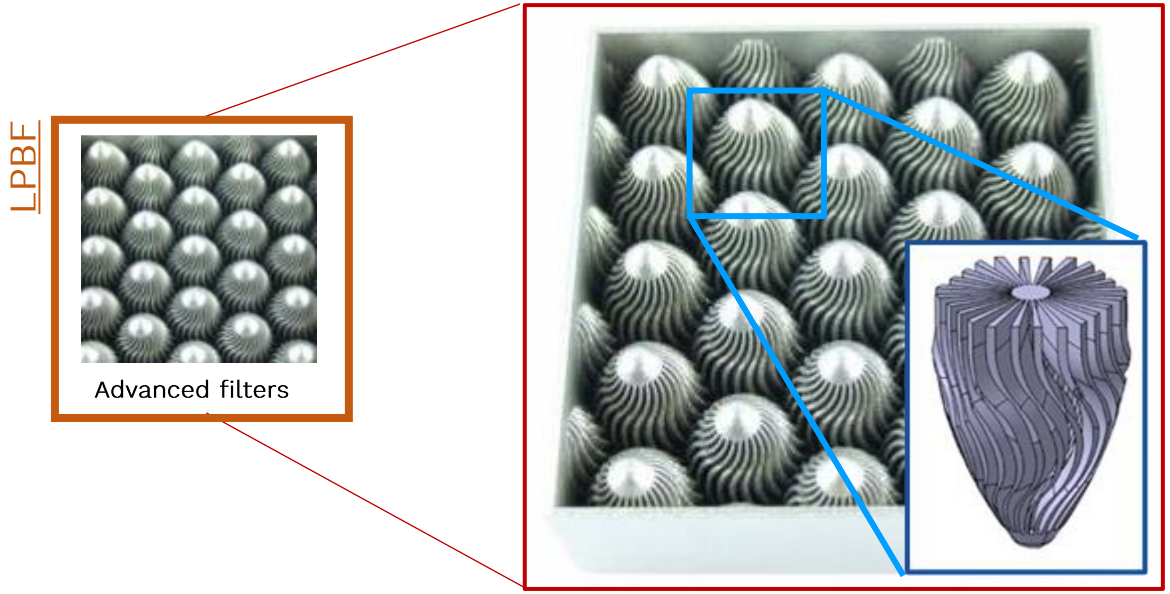
- At Framatome scale several technologies are deployed to cover all the component portfolio in Business Units



- The interest is such @FRA that a new plant, dedicated to AM, is being built (Romans, France, 2026) to operate several processes

Which technology for Fuel products developments ?





[Wiltz et al. (Framatome), AAMT Workshop2024]

Priority materials used for Fuel components:

- 316L
- Inconel 718

} Today's presentation

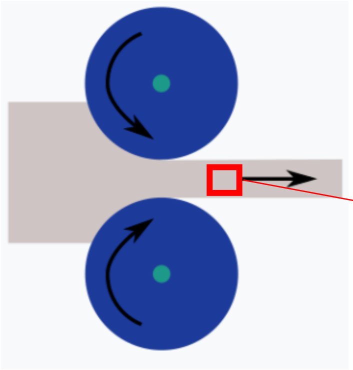
- Zr

} [Chauche et al. (Framatome), ASTM 2025]

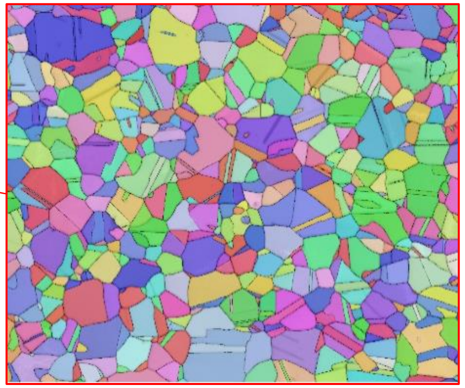
LPBF technology has a high potential to produce disruptive designs for Fuel applications while keeping « standard materials »

The challenge of material properties

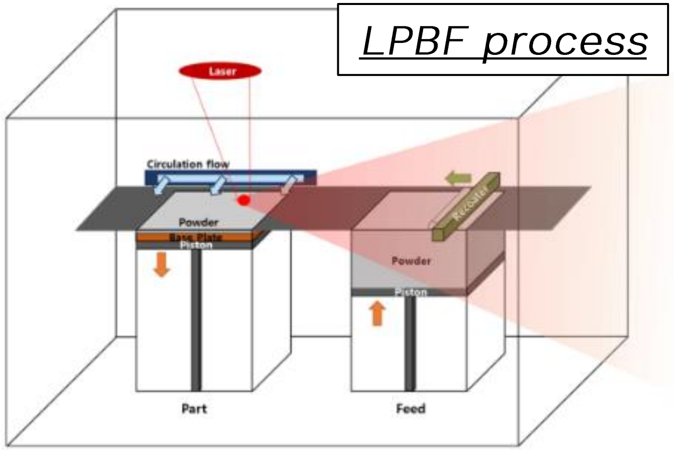
<u>*Conventional forged process*</u>

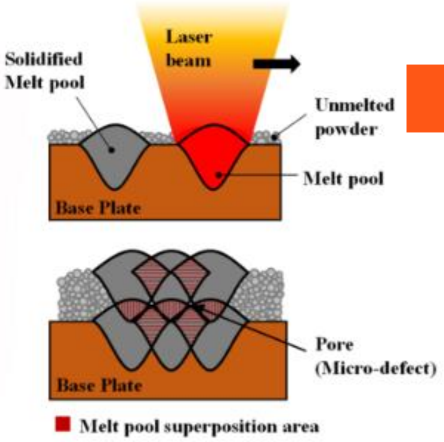


<u>718 alloy example</u>

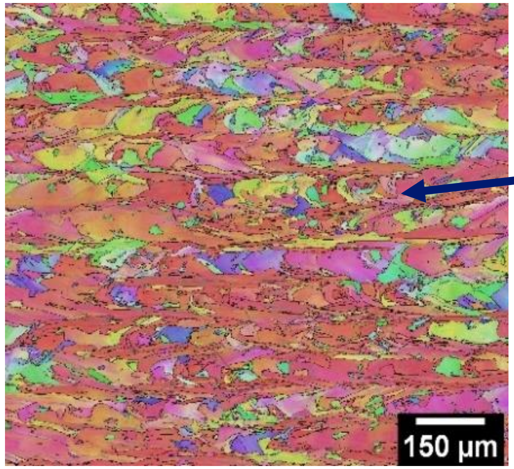


<u>*LPBF process*</u>

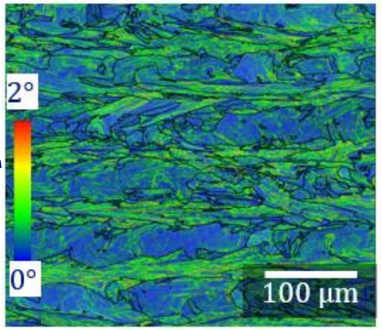




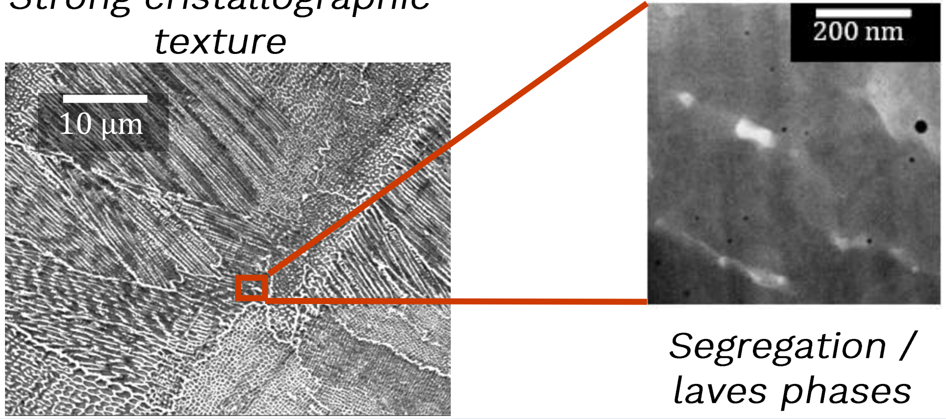
<u>718 LPBF alloy</u>



Strong cristallographic texture



High dislocation density
High misorientation



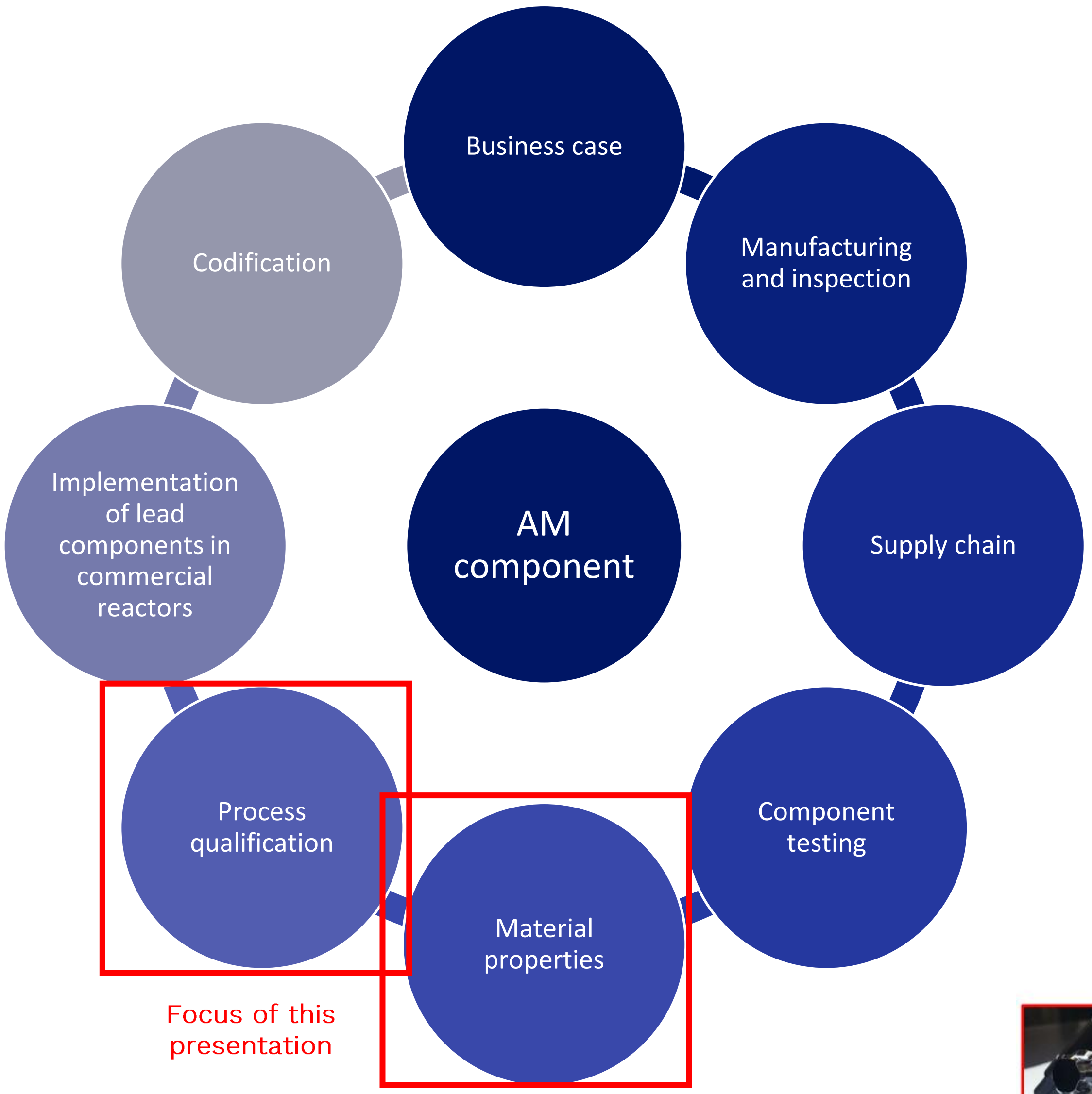
Segregation / laves phases

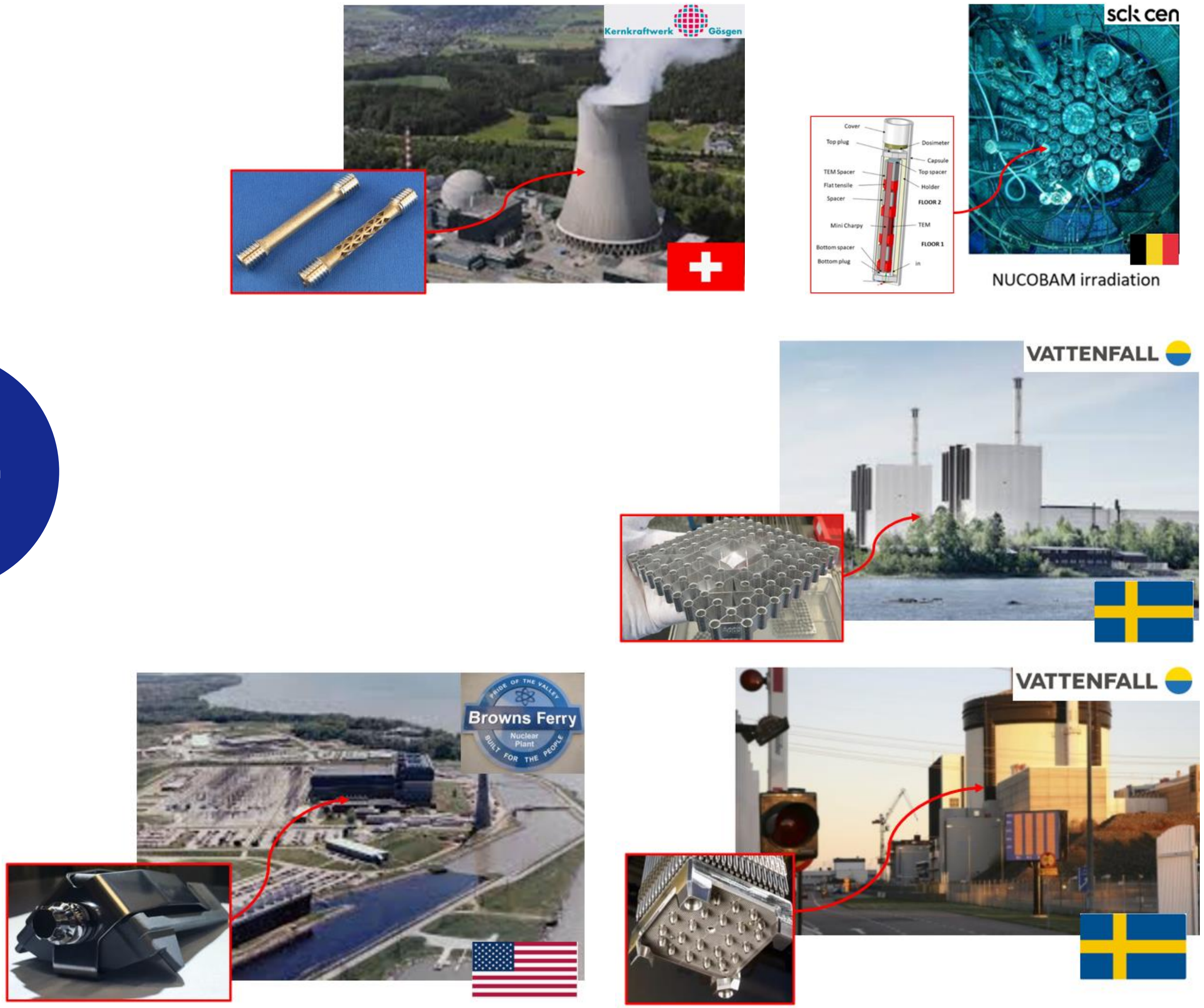
The access to this technology for nuclear component is limited by the capacity of justifying these new microstructures

2

Development path & achievements on 316L alloy

An integrated development approach with utilities' support





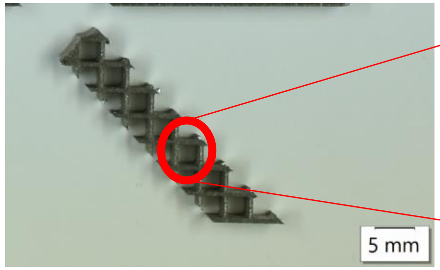
See also : [Badinier et al. (Framatome), TopFuel 2025]

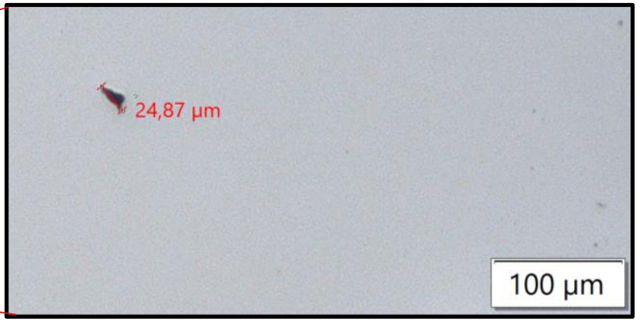
Machine/process qualification

- Machine qualification relies on a multi-step procedure, converged in European and National nuclear projets, to check **homogeneity + repeatability of the process**
- This robust approach is now **pushed by Framatome in nuclear codes & standards**
- Example of materials results :
  - Mechanical properties are homogeneous in the volume and repeatable
  - Absolute values are **well above 316L LPBF standard** (e.g. ASTM F3184)
  - **Porosity level is low** (<< 1% mentioned in standards)

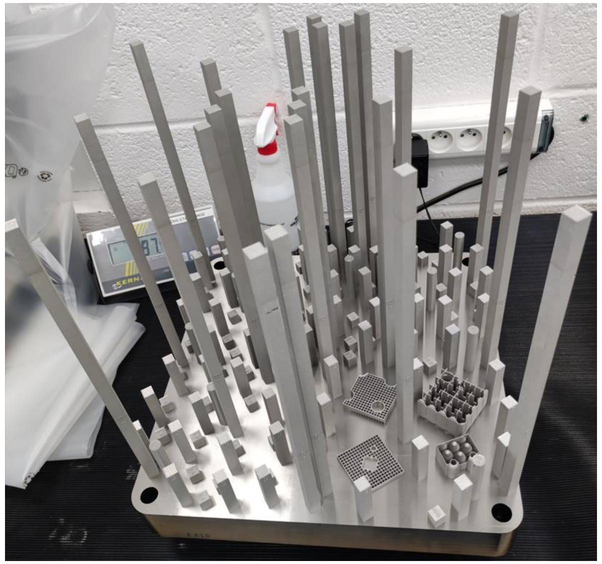
	Build platform 1				Build platform 2			
Parameter	YS (MPa)	UTS (MPa)	A (%)	KV (J)	YS (MPa)	UTS (MPa)	A (%)	KV (J)
Average	420,2	581,8	50,4	150,2	420,2	582,6	53,0	138,7
Standard deviation	1,8	0,4	3,4	26,0	1,3	0,5	2,4	25,0
Coefficient (ISO 16269-6)	4,21	4,21	4,21	2,07	4,21	4,21	4,21	2,07
Result	412,7	579,9	35,9	96,5	414,7	580,3	42,8	87,1
Criteria	≥ 205	≥ 515	≥ 30	≥ 50	≥ 205	≥ 515	≥ 30	≥ 50

- Local properties observed on products are consistent with machine qualification results





Codification on going in nuclear codes



Example of qualification built platform layout

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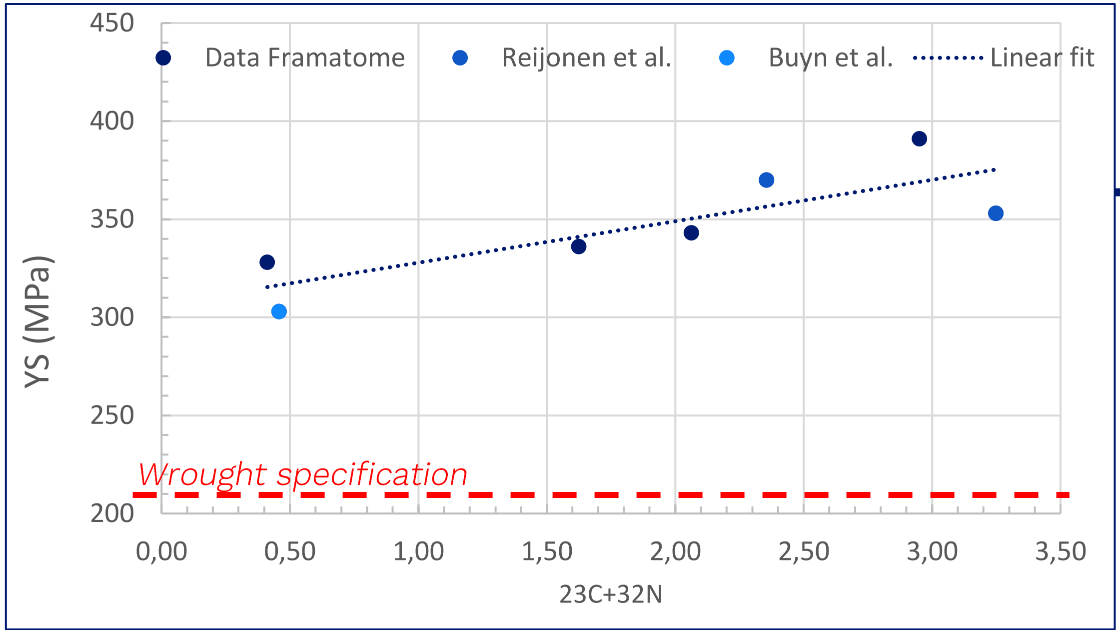
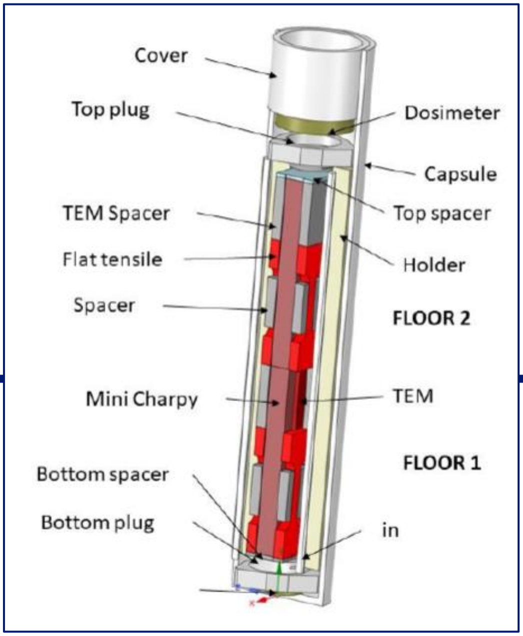
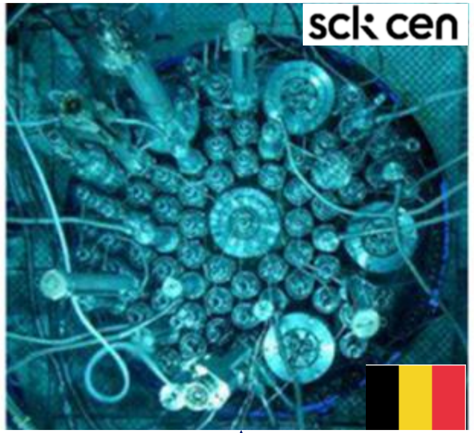
Material characterizations

- Material stability is studied in a wide range of configurations
- For example YS can be tuned over a 80 MPa range (roughly) through the interstitial content of the alloy, when C and N are bounded by the usual limits for 316L : N: [0-0.10] C: [0-0.03] wt%

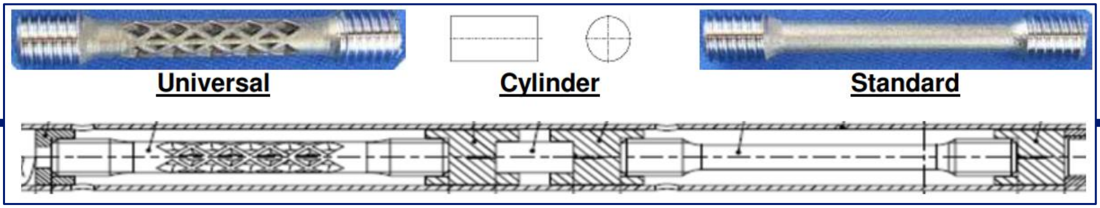






Irrad. & tests at 300°C

Careful selection of material batch for neutron irradiation in multiple programs



Commercial operation (1st world wide)

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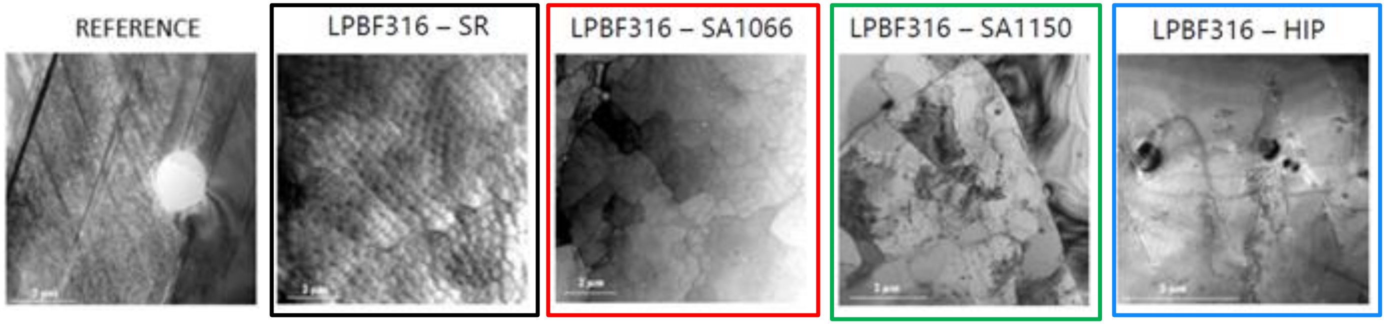
Material characterizations

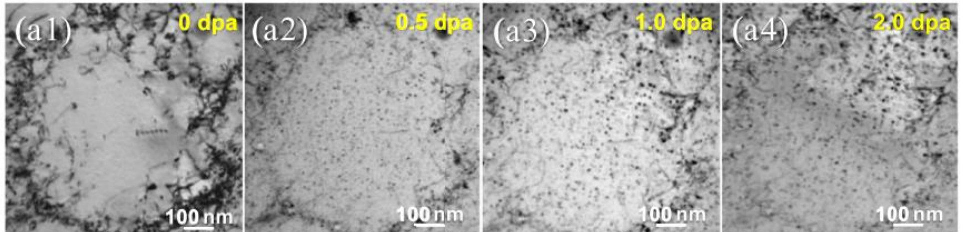


Structural tests showed :

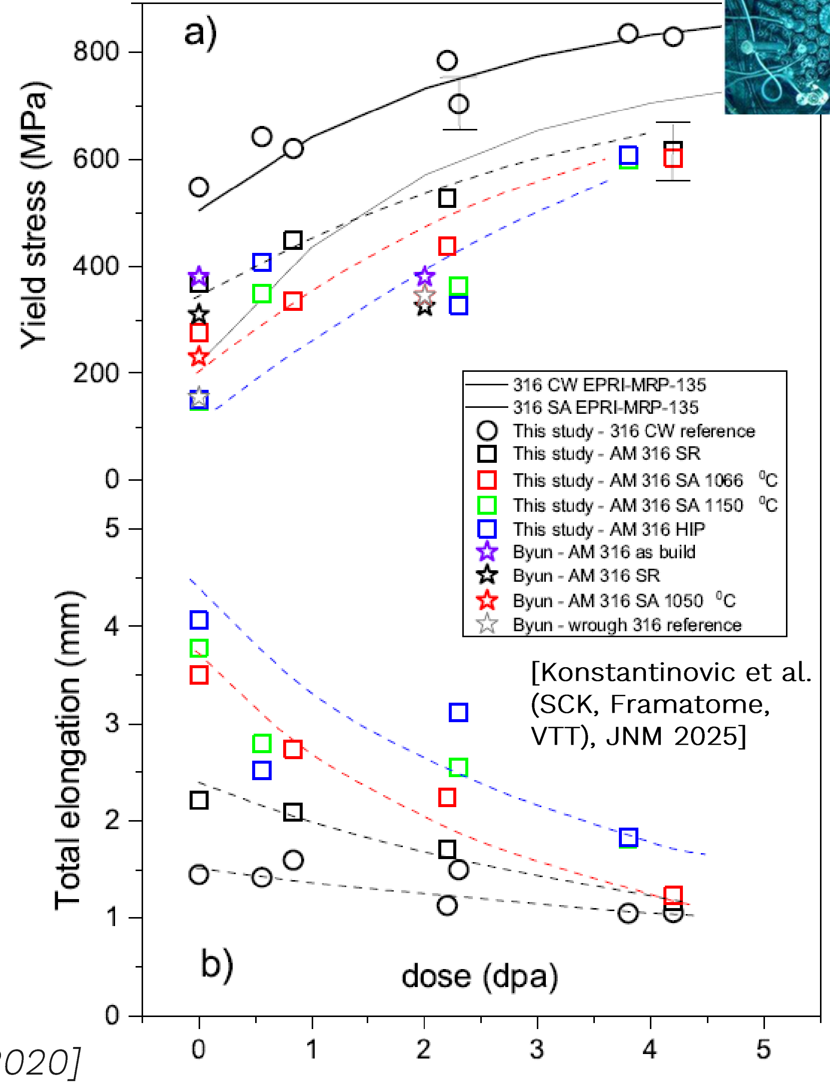
- Tests performed on reference sample (316L CW) confirm good irradiation setup
- No embrittlement (i.e. fracture in elastic domain) were observed, even for the most exotic microstructures from LPBF process
- Hardening behavior is similar to an annealed 316L (MRP EPRI curves)
- Elongation is better or similar to conventional 316L CW material
- Despite strong differences before neutron irradiation, the materials behave similarly after ~4 Dpa in tensile

Possible

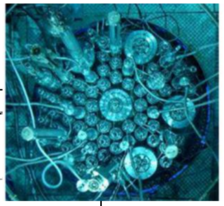
microstructural link



LPBF Dislocation cells suppressed with irradiation? [Li2020]



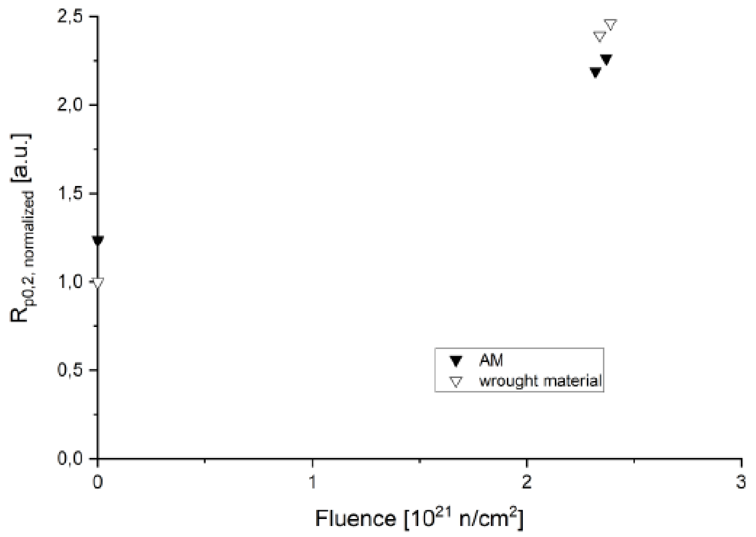
[Konstantinovic et al. (SCK, Framatome, VTT), JNM 2025]



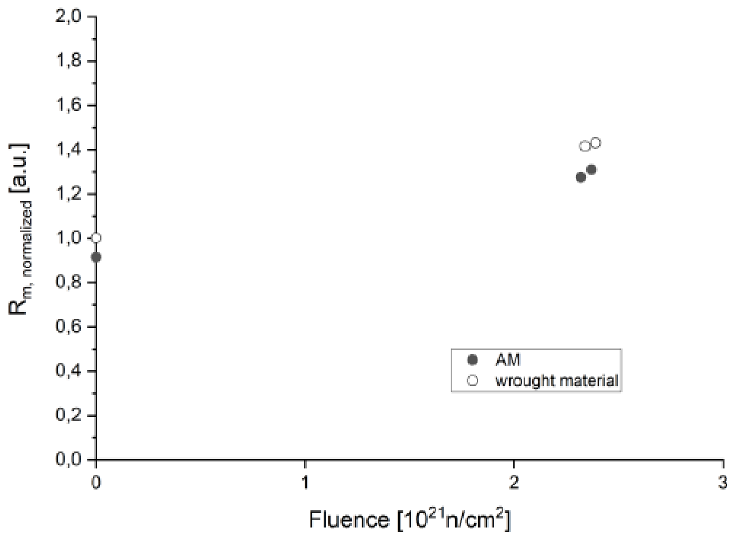
No embrittlement after irradiation / Hardening behavior similar to annealed 316L / Similar behavior at 4Dpa for all HT

Material characterizations

- Mechanical behavior in representative environment at Goesgen NPP* follows expected trends

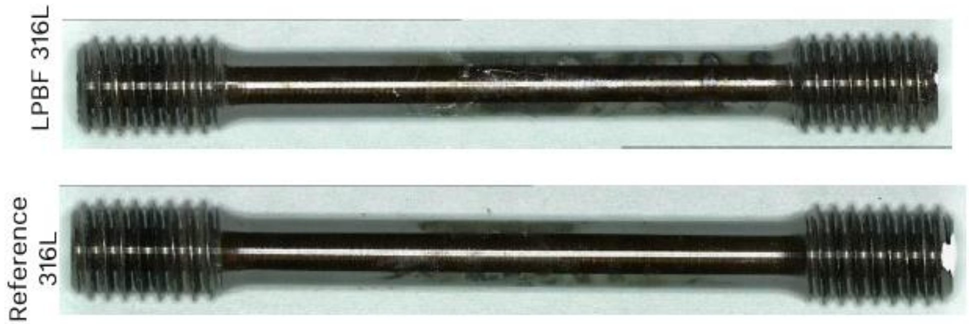


Effect of neutron irradiation on Yield Strength



Effect of neutron irradiation on Ultimate Tensile Strength

- No material degradation (corrosion) after irradiation



Visual examination of conventional (reference) and AM 316L samples after 1st irradiation cycle in the AddMagic program

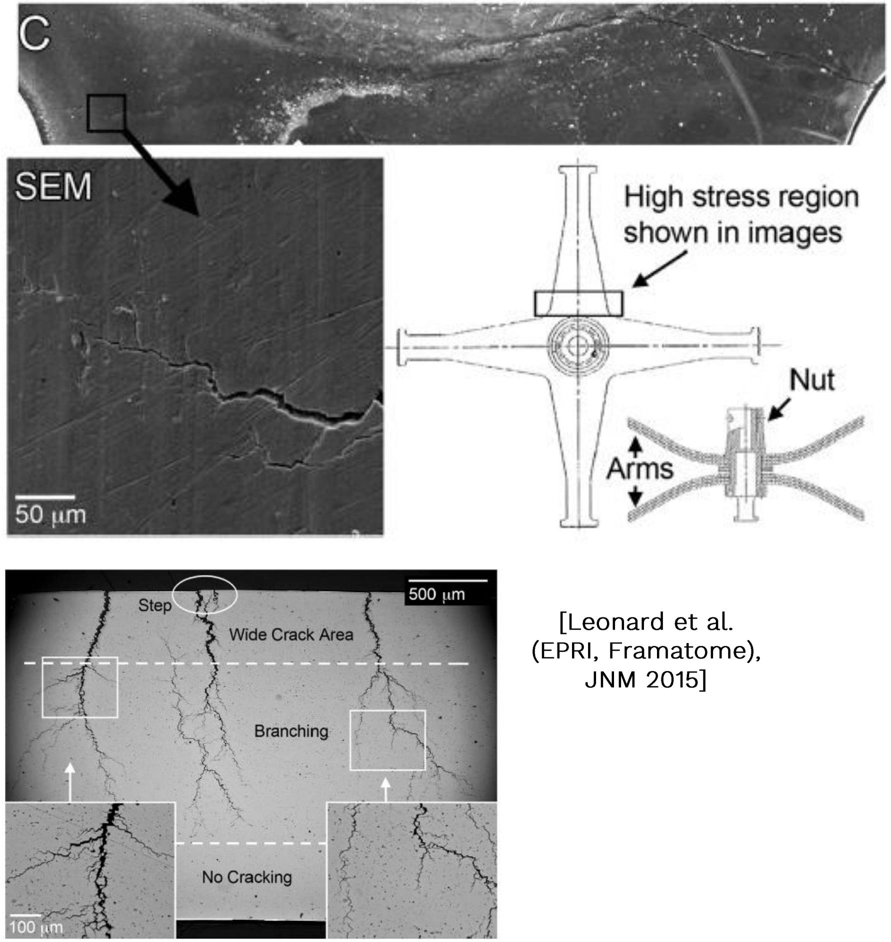
Commercial operation (1st world wide)

3

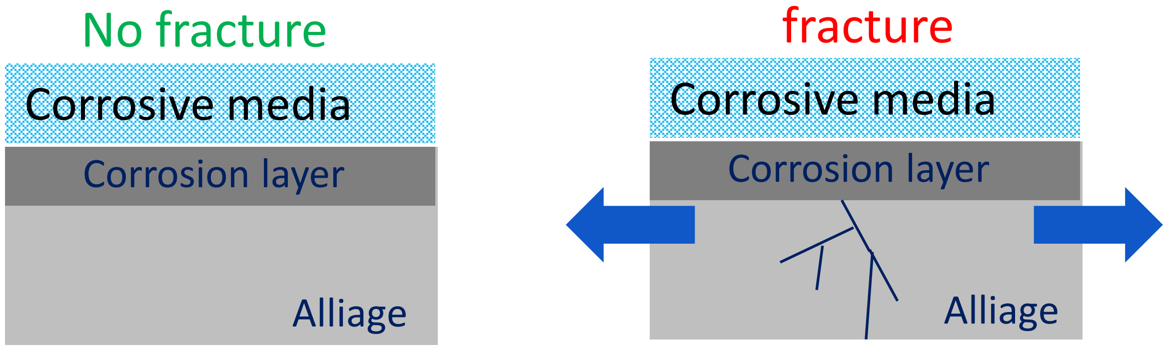
Stress corrosion analysis on 718 alloy: towards highly loaded components

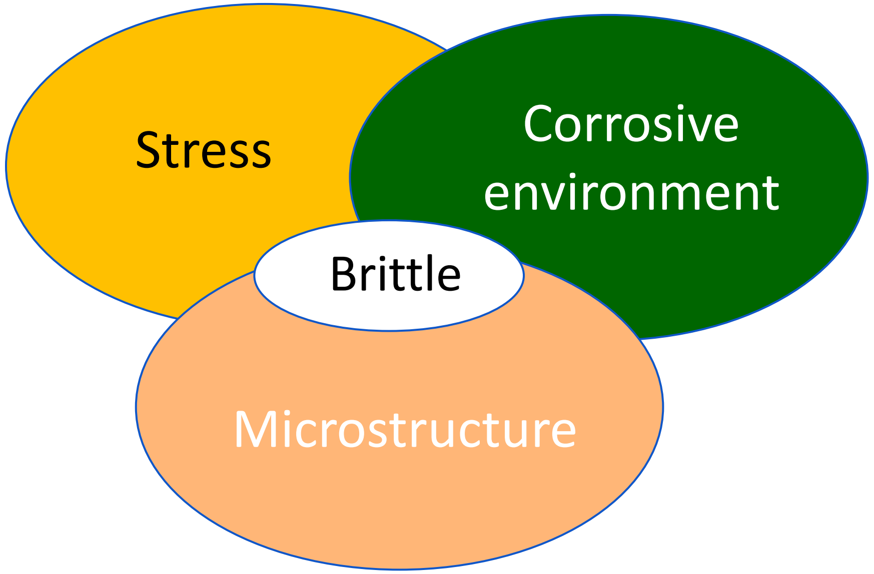
Is AM able to resist to SCC loadings ?

- HDS: an example of stringent application in Nuclear
  - One of the most challenging damaging process



[Leonard et al. (EPRI, Framatome), JNM 2015]





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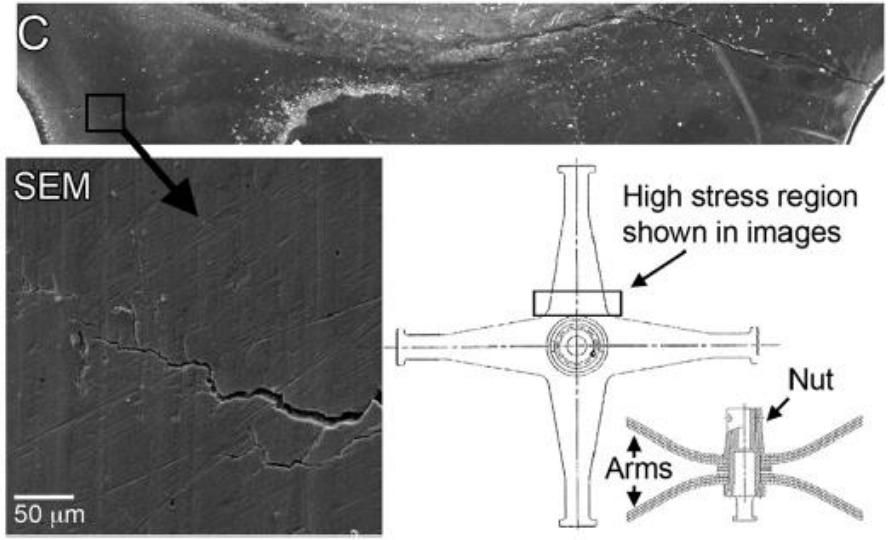
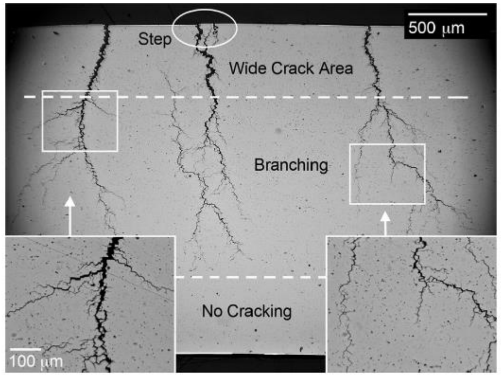
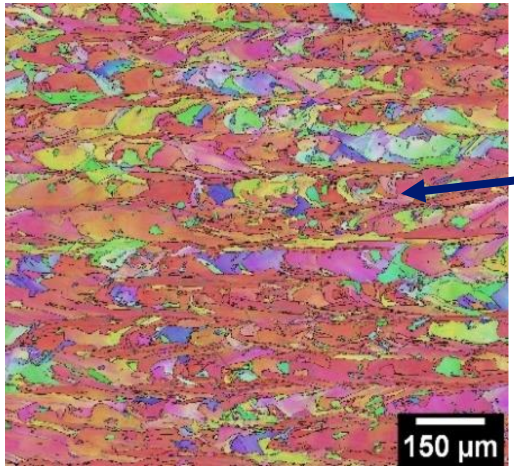


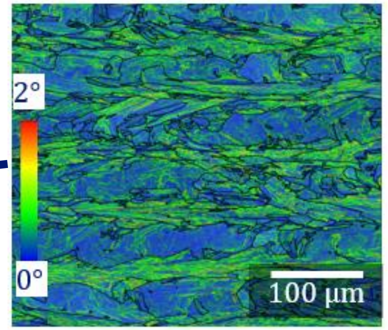


[Leonard et al. (EPRI, Framatome), JNM 2015]

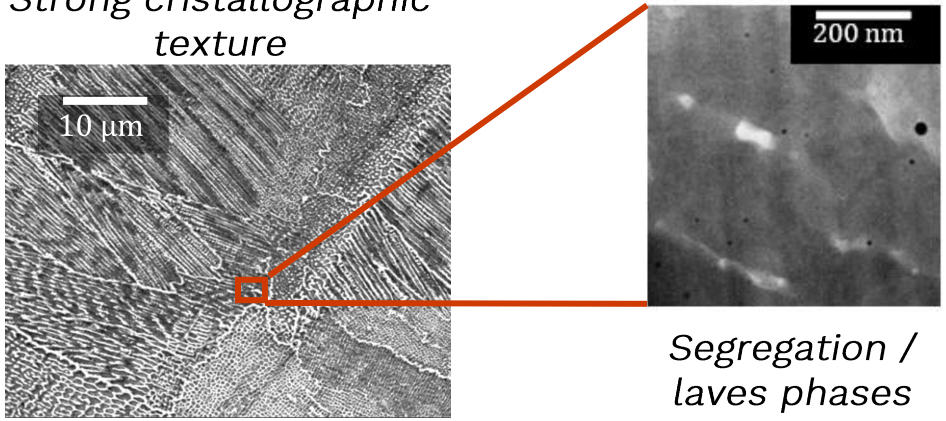
718 LPBF alloy



Strong cristallographic texture



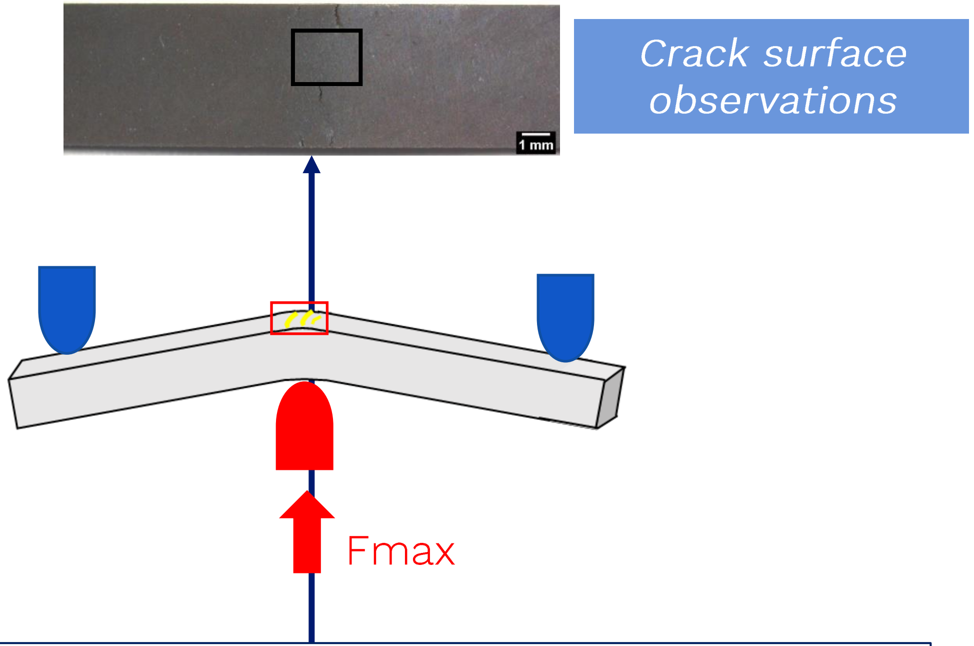
High dislocation density
High misorientation



Segregation / laves phases

Dynamic SCC tests on 718 LPBF

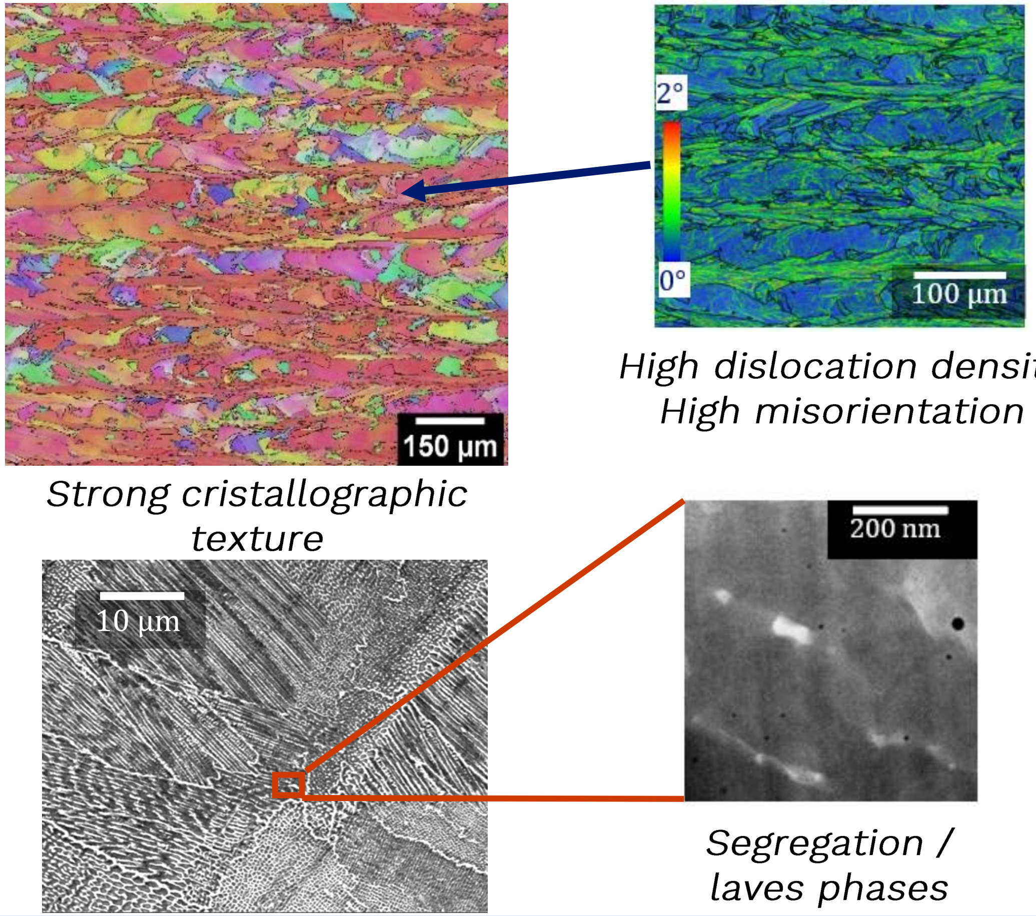
[V. Pelouard et al. (Framatome), Env. Deg. TMS, 2023]



SCC tests performed:

- 3 points interrupted bending tests on LPBF and Std 718
- Thousands of hours at ~4% total strain
- PWR simulated environment in autoclave (de-aerated aqueous solution at 350°C with H_3BO_3 and LiOH; pH= 6.8-7.4)

718 LPBF alloy



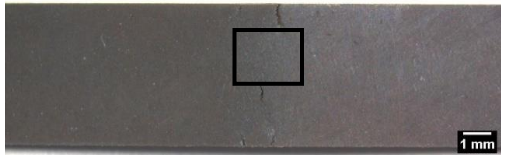
Strong cristallographic texture

High dislocation density
High misorientation

Segregation / laves phases

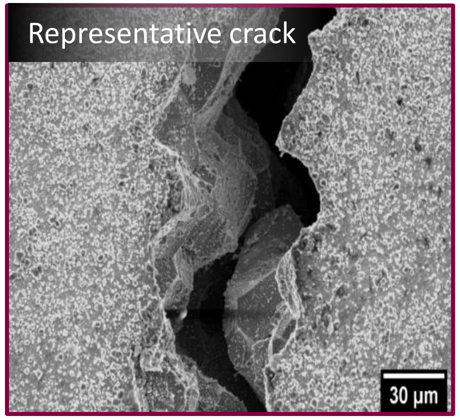
Are these exotic microstructures relevant for structural materials in the nuclear sector ?

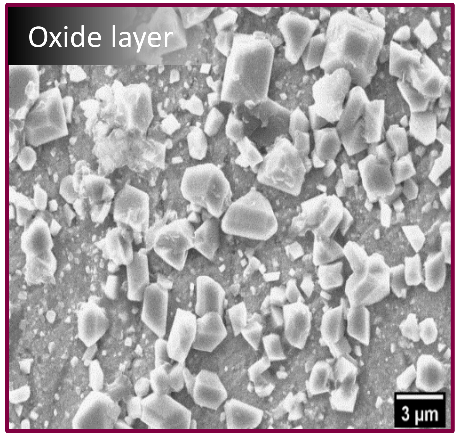
SCC results

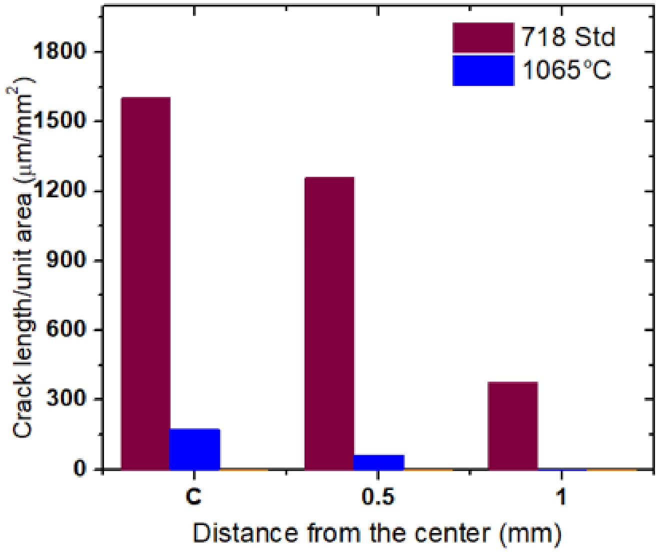


Crack surface observations

Conventional (annealed + aged)

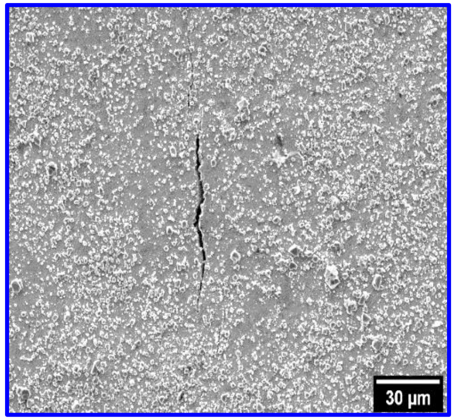


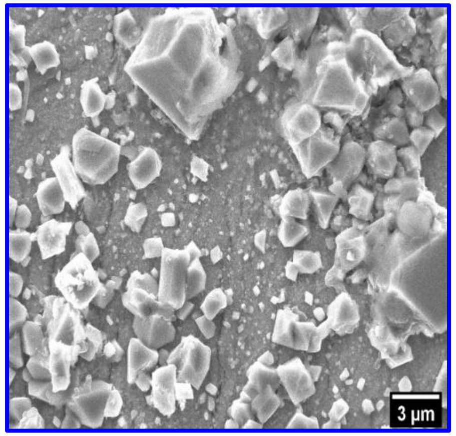




- Brittle intergranular behavior of 718 conventional alloy
- Better SCC resistance of LPBF (less cracks & lower size)

LPBF (annealed + aged)

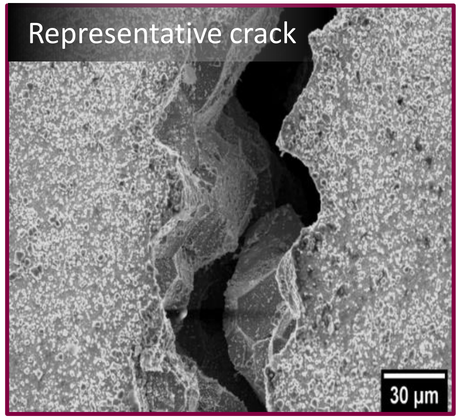


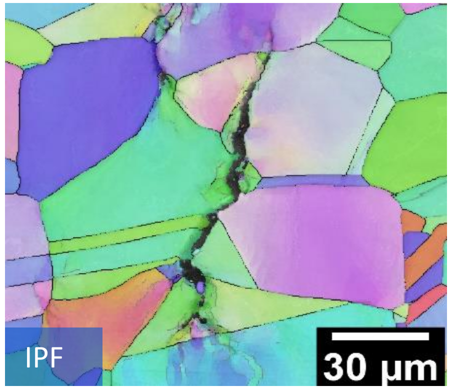


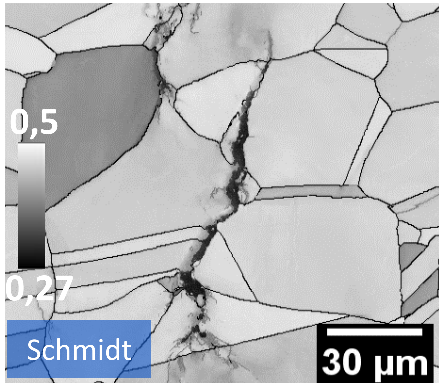
Different SCC behaviours between conventional and LPBF 718 / Better properties for LPBF 718

Link with microstructure

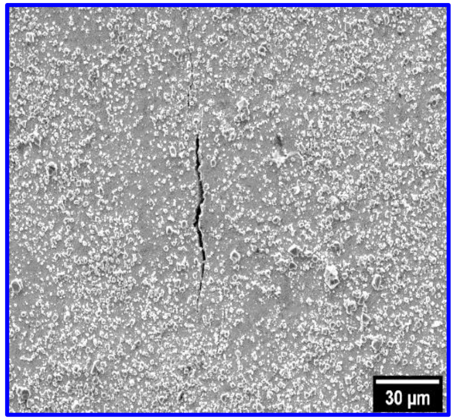
Conventional
(annealed + aged)

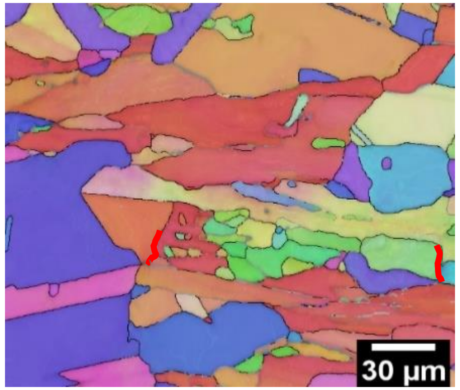


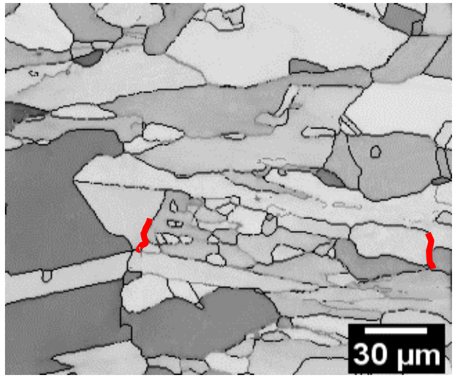




LPBF
(annealed + aged)







Crack pattern :

- Both: No link with potential precipitates *(even remaining Laves phases)*
- Both: Intergranular, on high angle boundaries
- LPBF: on straight boundaries and not on serrated ones produced by the LPBF process

Despite small segregations and not recristallized state, better SCC performances were observed for LPBF 718

4 Conclusions

Conclusions

Framatome / nuclear context

- A wide roadmap is on-going at Framatome to deploy disruptive AM products, with investment in a new plant dedicated to AM
- Interesting grades for Fuel components : Stainless steels (e.g. 316L) & Ni-base alloys (e.g. 718)

LPBF applications

- LPBF process is an interesting process to design Fuel components with advanced performances
- But this process produces very exotic / complex microstructures that have to be studied carefully
- Machines were successfully qualified for 316L following standard procedures, demonstrating the stability and the repeatability of the L-PBF process. Also, qualification results were proved to be representative of component manufacturing, which shows that the L-PBF qualification procedure is well defined and reliable

➔Qualification procedures are now stabilized and pushed by Framatome in nuclear code and applications.

Overview of some material results on 316L

- Following several successful out-of-pile results an irradiation program were conducted by SCK and Framatome
  - Irradiation tests highlights that mechanical properties differences vanishes at ~4 Dpa
  - The program shows that LPBF have comparable in-pile properties comparing to conventional reference

➔These results are confirmed by Framatome / Goesgen* program and extended to higher irradiation level and commercial conditions

Extension to stress corrosion cracking on 718 alloy

- Mechanical tests performed in PWR autoclave were performed on standard and LPBF samples
- Despite the exotic microstructures (not fully recrystalized / texture / remaining segregations) the LPBF samples performed better than the wrought reference
- Serrated boundaries could explain the better performance of LPBF microstructure on SCC

➔ 316L & 718 LPBF materials used @FRA were validated in harsh conditions (irradiation, SCC).
It is paving the way to introduce more and more Additive Manufacturing technology for fuel product applications

(*) The support of NPP Gösgen-Däniken, Switzerland, in carrying out the AddMAGIC irradiation program is gratefully acknowledged.

Thank you