QA and QC Tools for Metal AM and implementing them in EU NUCOBAM project

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Rationale

- We need to ensure that Additively Manufactured components are build defect free and fit for purpose consistently and reliably.
- This is true for every industry, but specially for those in which components are safety critical as some applications of nuclear energy are.
- AM enables manufacturing of complex geometries and one-off components which brings added challenges to quality assurance.

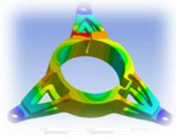
General approach for AM qualification

Process Qualification

- to ensure that the general process is controlled and repeatable and can produce components within quality requirements
- This includes: **Machine, Powder, Operator**

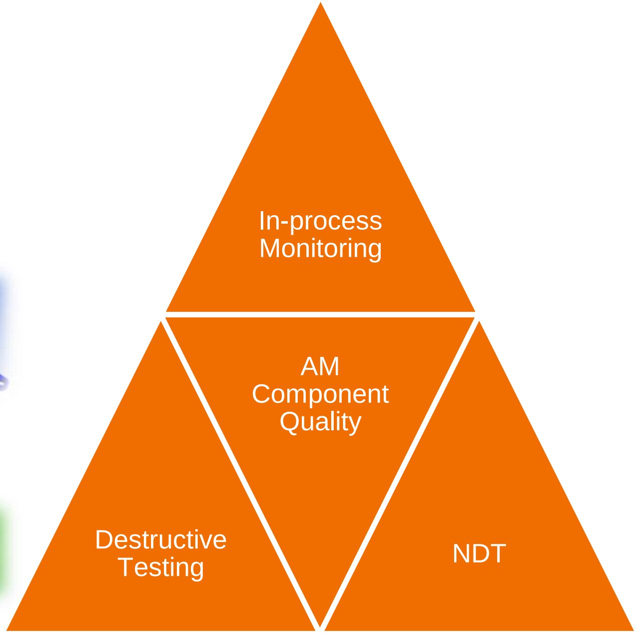
Component Qualification

- to ensure that a particular part can be printed within quality requirements given a certain design and use requirements

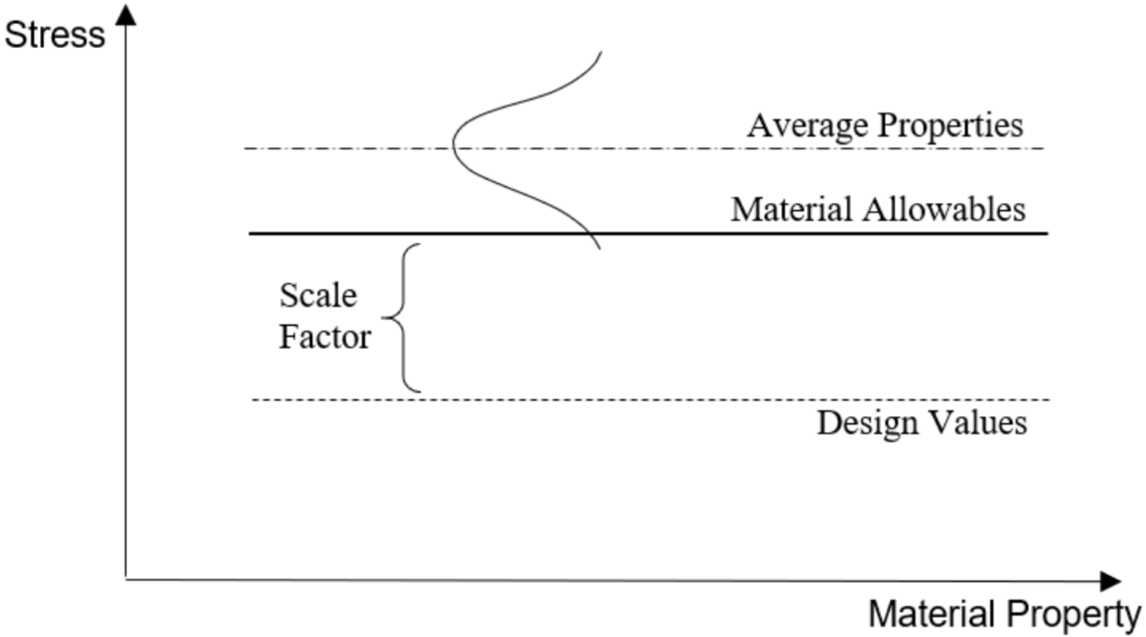


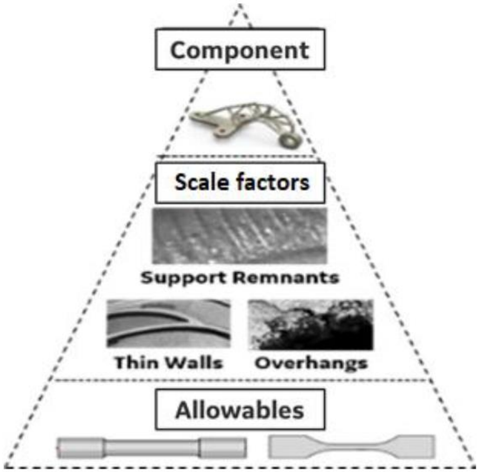
Individual Part QC

- to ensure that every single part is printed within quality requirements. And if it is not, that defects are properly detected and the non-conformity properly recorded.



Principle for Design values





Source: Recommended Guidance for Certification of AM Components - AIA Additive Manufacturing Working Group

EU NUCOBAM project

EU NUCOBAM Project

- Additive Manufacturing (AM) will allow nuclear industry:
  - to tackle component obsolescence challenges
  - to manufacture and operate new components with optimized design in order to increase reactor efficiency and safety
- NUclear COmponents Based on Additive Manufacturing aims at:
  - developing the qualification process
  - provide the evaluation of the in-service behavior allowing the use of additively manufactured components for nuclear installations

- Coordinator: CEA, Pierre-François GIROUX
- Partners: 12 from 6 countries + EU JRC
- Total Project Cost: ~4 M€
- Duration: 4 years (10/2020-9/2024)
- 7 Work Packages

Demonstrators (316L):

Valve block body

Workpackages:

- **WP1 “Methodology for AM qualification standardization” - CEA**
  - focus on establishment of a qualification methodology for AM components and on reviewing the existing standards and qualification processes
- **WP2 “AM process qualification” - VTT**
  - aim to create a general methodology for qualifying L-PBF process for nuclear energy industry applications so that components manufacture by L-PBF meet the quality expectations and design functions
- **WP3 “Qualification as processed: NDE & mechanical properties vs microstructure” – Naval Group**
  - focus on nondestructive tests and characterization as manufactured to ensure the capability to decide of the qualification as processed

Workpackages

- **WP4 “In-pile Behaviour of Additively Manufactured Samples (IBAMS)” - FRAMATOME**
  - deal with the description of the sample sets, irradiation conditions (fluence, temperature…), microstructure characterization, determination of the mechanical properties and documentation
- **WP5 “Performance assessment of ex-core user case: valve component” - ENGIE Tractebel**
  - assess the operational performance of ex-core valve component that will be produced by L-PBF process
- **WP6 “Dissemination and exploitation” - EDF**
  - ensure dissemination and then exploitation, by reaching out to industry, standardization and regulatory bodies
- **WP7 “Project Management” - CEA**
  - ensure effective coordination and management to monitor the progress of the project towards its planned objectives

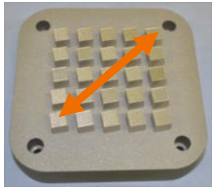
WP2 Objective

- To create a general methodology for qualifying L-PBF process for nuclear energy industry applications so that components manufacture by L-PBF meet the quality expectations and design functions. The study of machine-to-machine variations in properties will be studied.
- Advanced quality control methods will be evaluated with the objective of increasing safety by detecting defects during production and ensure batch consistency.
- Demonstration components and test coupons to be tested in other WPs will be manufactured.

WP2 focuses on different variation sources

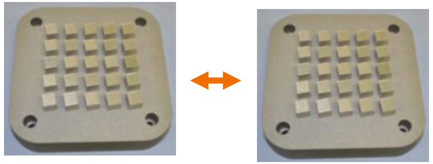
Improved Process Stability

- High process stability within same platform (same manufacturing batch).



Improved Process Repeatibility

- High process repeatability from build to build on same equipment (different batch).

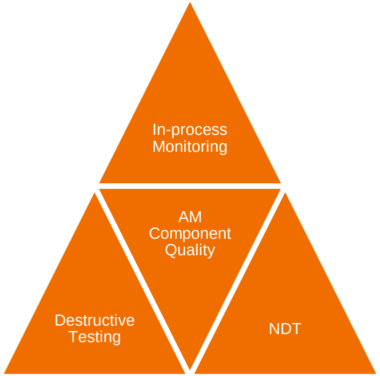


Improved Process Reproducibility

- High process reproducibility from build to build on different equipment

Some challenge related to LB-PBF QA & QC

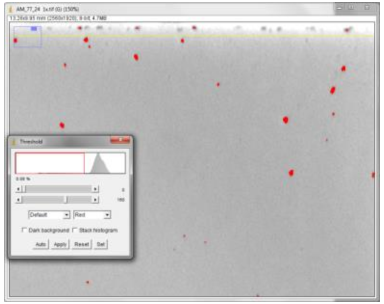
- Qualification procedures are laborous and require lot of experimental trials
- Due the differences between the machines – results are not directly transferable
- Complex geometrics poses challenges for utilizing conventional non-destcructive technologies (NDE)
- Destructive testing does not fit very well for single component testing
- Results of in-process monitoring are open to interpretations

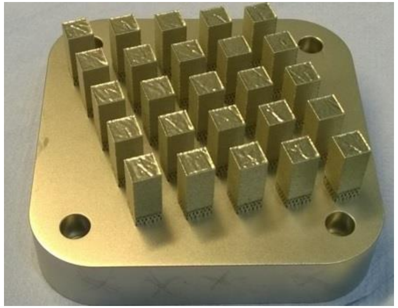


Destructive Testing

Witness samples and microstructural microscopy

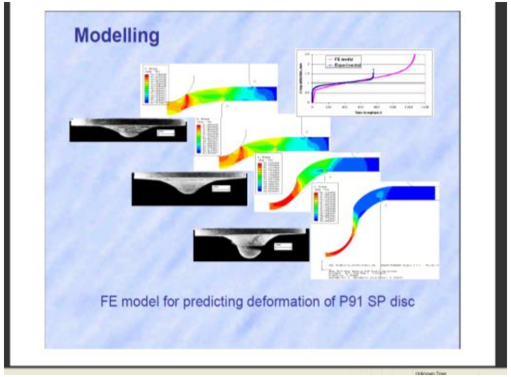
- Mechanical testing following recognized standards
- Specially useful for **process qualification**
- Usefulness reduced for component qualification and for single part quality control

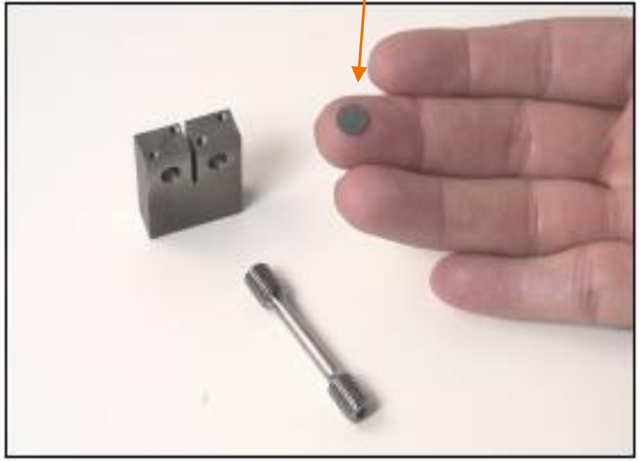




Small Punch Testing

- Allows scooping small samples from critical areas
- Can complement standard methods for process and component qualification
- Can be used as a more cost alternative for batch QC
- **EN 10371** Small Punch Test Method for Metallic Materials to be voted in October 2020.





Non-Destructive Examination

NDI Technology applied to AM: gaps

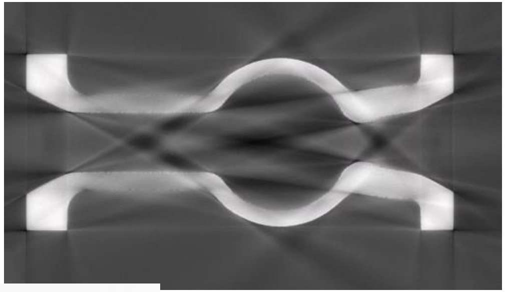
- Geometrical complexity
  - AM has practically no geometry-related limitations
- New defect types
  - Porosity: no reliable, cheap and easy-to-use method exists.
- New materials
  - Elastic anisotropy: Several ultrasound related problems
- New reference standards are required
  - NDI devices must be calibrated using known defects
- No POD data
  - Without POD methodology, the actual reliability of inspection cannot be determined

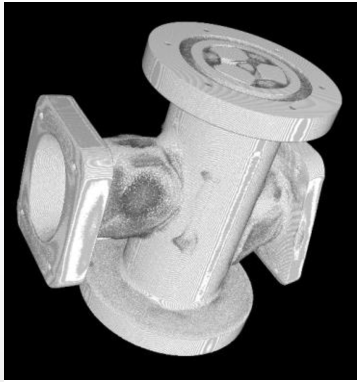
Applicability of NDI to AM

NDI Technique	Geometry Complexity Group					Comments
	1	2	3	4	5	
Visual Testing	Y	Y	P(c)	NA	NA	
Liquid Penetrant Testing	Y	Y	P(a)	NA	NA	
Magnetic Particle Testing	Y	Y	P(a)	NA	NA	Only for ferromagnetic materials
Leak Testing	P	P	P	P	P	Screening for containers, valves etc.
Eddie Current Testing	Y	Y	P(c)	NA	NA	
Ultrasonic Testing / Phased Array Ultrasonic Testing	Y	Y	P(b)	NA	NA	Quantitative methods are possible for GCG 1
Alternate & Direct Current Potential Drop	Y	Y	P(c)	NA	NA	
Process Compensated Resonance Testing	Y	Y	Y	Y	Y	Screening, size restrictions
Radiographic Testing	Y	Y	P(d)	NA	NA	
Computed Tomography	Y	Y	Y	Y	Y	Restrictions how small defects are detectable
μ-focus Computer Tomography	Y	Y	Y	Y	Y	Size restrictions for sample

So, what NDE method to use?

- CT/uCT is the method of choice currently as is the only method capable of handling complex geometries. But it is not a perfect solution:
  - Trade-off between resolution / sample size / equipment performance
  - For quality control quite expensive and time consuming technology
- For GCG1-2 parts, other methods can still have a major role:
  - Advantages in cost
  - Possibilities for in-service inspection.





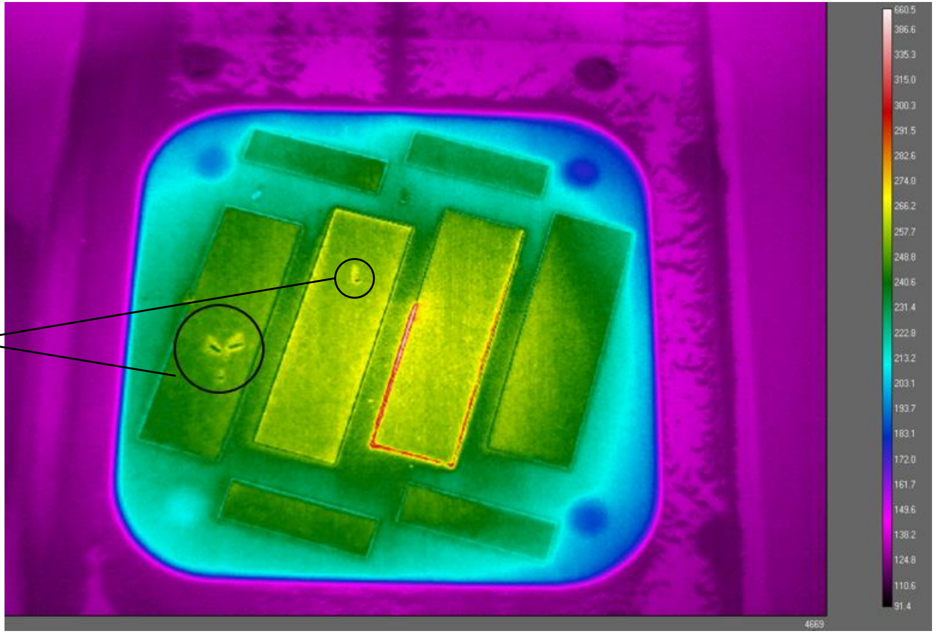
In-Process Monitoring

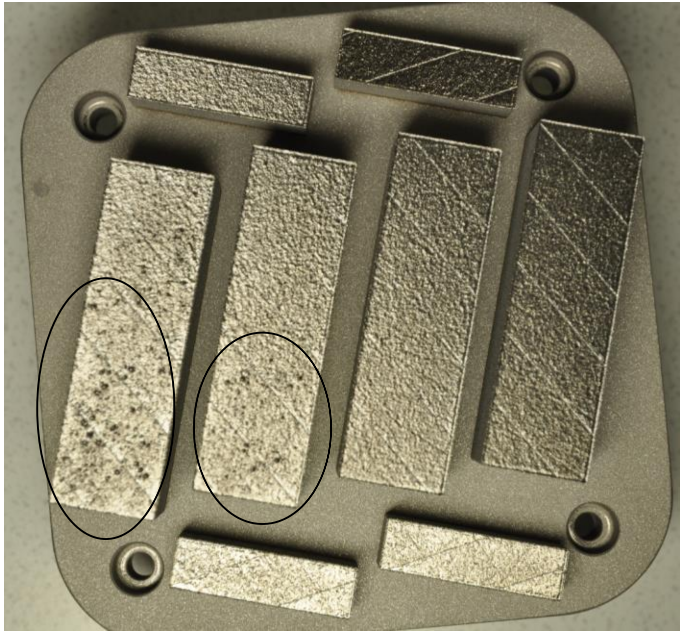
AM Process Monitoring

- Detected process variations not necessarily linked to a specific defect. Can be used for AM process qualification leading to reduced NDT requirements
- As it is done simultaneously while manufacturing: it might reduce system downtime.
- There are several process monitoring types commercially available:
  - Basic process and environmental sensors (oxygen level, gas flow rate..)
  - Powder bed monitoring
  - Thermal signatures monitoring
    - Off-axis, platform scale field-of-view (usually with IR/near-IR-cameras)
    - On-axis, high spatial and temporal resolution (usually with photodiodes)
- Currently no closed-loop control available.

Off-axis thermal monitoring

Spatter landing at the left hand side parts





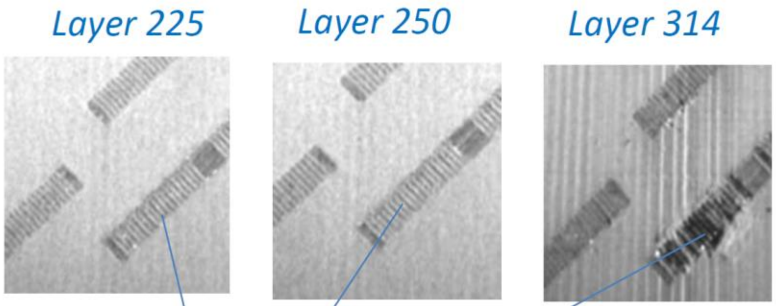
- Thermal camera FLIR A655sc at VTT
- Experimental material, non-optimal powder size & parameters caused excessive spattering

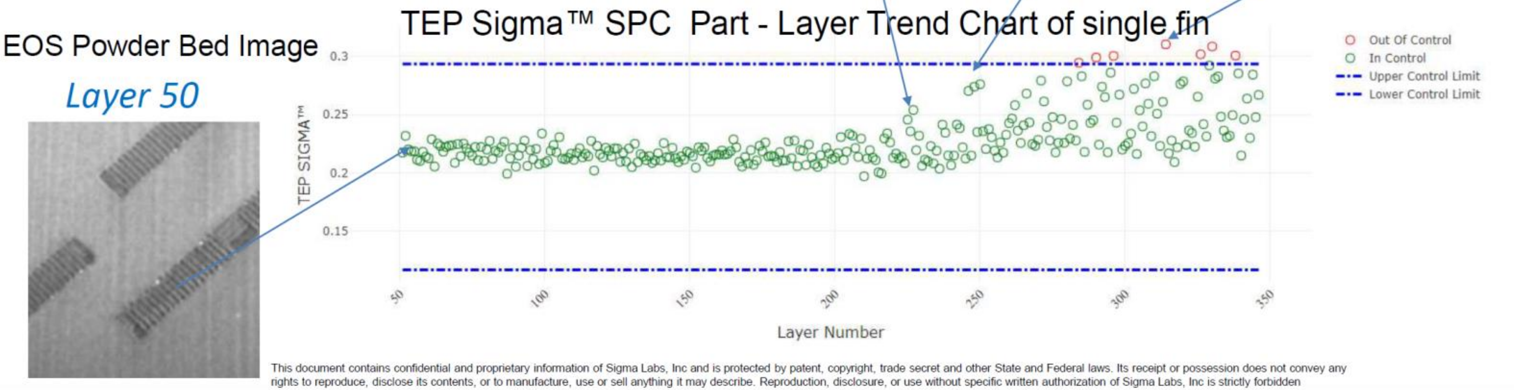
Example of Melt Pool Monitoring

Inconel 625 : Evaluation of Thermal Signatures using Part-Layer SPC (Statistical Process Control) to detect powder disturbance

Qualitative versus Quantitative Approach

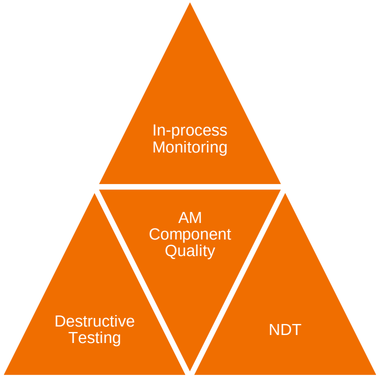
Method :- each fin categorized as separate part





Summary

- General models for AM qualification procedures exist – the challenge is to implementing them on different industrial domains and different requirements
- EU NUCOBAM project aims to develop and implement qualification procedures for Nuclear Industry
- There is no single magic bullet to ensure quality on a component
  - Combination of in-process monitoring, NDT and destructive testing can support our efforts.



beyond

the obvious

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