



**VTT**

# Quality of AM Components

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Additive manufacturing in nuclear energy applications -webinar

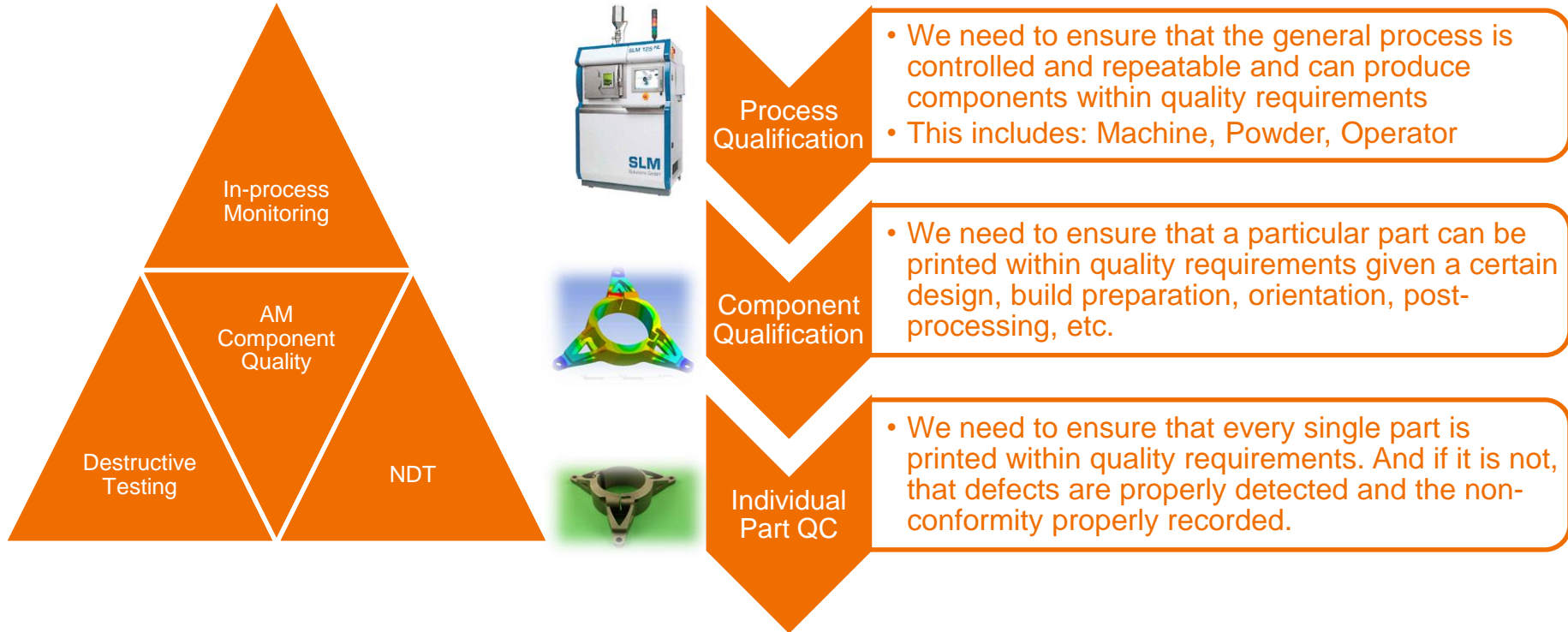
23.9.2020

VTT – beyond the obvious

# Why the need of quality?

- 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.

# Approach to QA/QC in AM



# Standards

# AM standardization overview

- Currently the AM standardization has many gaps that limit the adoption of the technologies. However, the SDOs are actively developing new standards to address many of the gaps.
- Application specific standards are being developed mainly for the demands of medical and aerospace industry and nuclear industry specific standards do not exist.

- Few examples of topics that are lacking in AM standardization:

- Material / application specific standards are needed that include manufacturing specifications and minimum requirements for corrosion, fatigue, fracture toughness of AM metals.
- AM specific heat treatment procedures and corresponding microstructures
- Post-processing specifications for complex structures
- Etc.

- AM standards under development:

- Feedstock material characterization methods more suitable to AM
- Specifications for Gradient structures
- Surface characterization practices
- NDT methods for AM
- AM qualification (Industrial machines / machine operators)
- Safety guidelines
- Etc.

# AM standardization overview

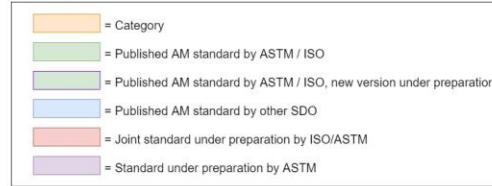
## ■ Metal AM standards (published/draft)

General
ISO/ASTM 52900:2015 Additive manufacturing — General principles — Terminology
ISO 17296-2:2015 Additive manufacturing — General principles — Part 2: Overview of process categories and feedback
ISO 17296-3:2014 Additive manufacturing — General principles — Part 3: Main characteristics and corresponding test methods
ISO 17296-4:2014 Additive manufacturing — General principles — Part 4: Overview of data processing
ISO/ASTM 52915:2016 Specification for additive manufacturing file format (AMF) Version 1.2
ISO/ASTM 52901:2017 Additive manufacturing — General principles — Requirements for purchasable AM parts
ISO/ASTM 52921:2013 Standard terminology for additive manufacturing — Coordinate systems and test methodologies
Y14.46 - 2017 Product Definition for Additive Manufacturing
ISO/ASTM CD TR 52618 Additive manufacturing — Data formats — File format support, ecosystem and evolutions
WK72172 Additive manufacturing — General principles — Overview of data pipeline

ISO/ASTM DIS 52900 Additive manufacturing — General principles — Fundamentals and vocabulary 40.99

ISO/ASTM DIS 52950 Additive manufacturing — General principles — Overview of data processing 40.99

ISO/ASTM DIS 52921 Additive manufacturing — General principles — Standard practice for part positioning, coordinates and orientation 40.99



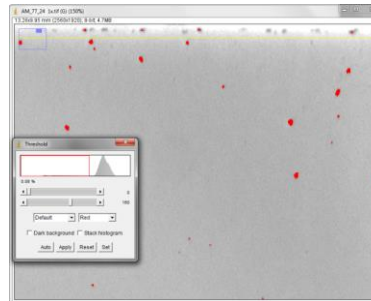
Feedstock material - Properties & Characterization	Design	Manufacturing	Post-processing	Test methods & Quality	Qualification	Safety / Other
AWS D20.1D20.1M:2019 - specification for fabrication of metal components using additive manufacturing for L-PBF and DED technologies						ISO/ASTM CD 52031 Additive manufacturing — Environmental health and safety — Standard guideline for use of metallic materials 30.20
F3184 - 16 Standard Specification for Additive Manufacturing Stainless Steel Alloy (UNS S31603) with Powder Bed Fusion						ISO/ASTM WD 52916 Additive manufacturing — Data formats — Standard specification for optimized medical image data 20.20
F3088 - 14 Standard Guide for Characterizing Properties of Metal Powders Used for Additive Manufacturing Processes	ISO/ASTM 52990:2019 Additive manufacturing — Design — Requirements, guidelines and recommendations	ISO/ASTM 52904:2019 Additive manufacturing — Process characteristics and performance — Practice for metal powder bed fusion process to meet critical applications	F3201 - 18a Standard for Additive Manufacturing — Post Processing Methods - Standard Specification for Thermal Post-Processing Metal Parts Made Via Powder Bed Fusion	ISO/ASTM 52902:2019 Additive manufacturing — Test artifacts — Geometric capability assessment of additive manufacturing systems 20.00	ISO/ASTM D2926-1 Additive manufacturing — Qualification principles — Part 1: Qualification of machine operators for metallic parts production 20.00	
ISO/ASTM 52987:2019 Additive manufacturing — Feedstock materials — Methods to characterize metal powders	ISO/ASTM 52919:1:2019 Additive manufacturing — Design — Part 1: Laser-based powder bed fusion of metals	AMS7003 Laser Powder Bed Fusion Process	ISO/ASTM AW 52908 Additive manufacturing — Post processing methods — Standard specification for quality assurance and post processing of powder bed fusion metallic parts 20.00	ISO/ASTM AWI 52902 Additive manufacturing — Test artifacts — Geometric capability assessment of additive manufacturing systems 10.99	ISO/ASTM WD 52920-2 Additive manufacturing — Qualification principles — Part 2: Requirements for industrial additive manufacturing sites 20.20	
AMS7002 Process Requirements for Production of Powder Feedstock for Use in Laser Powder Bed Additive Manufacturing of Aerospace Parts	ISO/ASTM PRF TR 52912 Additive manufacturing - Design - Functionally graded additive manufacturing 50.00	WK72317 Additive Manufacturing - Powder Bed Fusion - Multiple Energy Sources	WK69682 - Evaluating Post-processing and Characterization Techniques for AM Part Surfaces		ISO/ASTM WD 52926-2 Additive manufacturing — Qualification principles — Part 2: Qualification of machine operators for metallic parts production for PBF-LB 20.00	
WK65810 - Characterization of Powder Flow Properties for Additive Manufacturing Applications	WK64190 Additive Manufacturing Design - Decision Guide			F3122 - 14 Standard Guide for Evaluating Mechanical Properties of Metal Materials Made via Additive Manufacturing Processes 40.99	ISO/ASTM DIS 52942 Additive manufacturing — Qualification principles — Qualifying machine operators of laser metal powder bed fusion machines and equipment used in aerospace applications 40.99	
WK67454 Additive manufacturing — Feedstock materials - Methods to characterize metallic powders				ISO/ASTM WD 52917 Additive manufacturing — Round Robin Testing — Guidance for conducting Round Robin studies 20.00	WK7458 Additive Manufacturing — Qualification principles — Qualification of coordinators for metallic parts production	
WK62190 Additive manufacturing Feedstock materials Technical specifications on metal powder				ISO/ASTM DTR 52905 Additive manufacturing — General principles — Non-destructive testing of additive manufactured products 30.99	WK65640 - Additive manufacturing Guideline for Installation, Operation and Performance Qualification (IQ/OQ/PQ) of Laser Beam Powder Bed Fusion Equipment for Production Manufacturing	
WK67583 Additive Manufacturing — Feedstock Materials — Powder Reuse Schema in Powder Bed Fusion Processes for Medical Applications				ISO/ASTM CD TR 52906 Additive manufacturing — Non-destructive testing and evaluation — Standard guideline for intentionally seeding flaws in parts 30.00	WK70164 Additive Manufacturing - Finished Part Properties - Standard Practice for Assigning Part Classifications for Metallic Materials	
WK71303 Additive manufacturing — assessment of powder spreadability for powder bed fusion (PBF) processes				ISO/ASTM AWI 52909 Additive manufacturing — Finished part properties — Orientation and location dependence of mechanical properties for metal powder bed fusion 20.00		
				ISO/ASTM DIS 52941 Additive manufacturing — System performance and reliability — Standard test method for acceptance of powder bed fusion machines for metallic materials for aerospace application 40.60		
				WK66371 Standard practice for generating mechanical performance debits		
				WK71395 Additive manufacturing — accelerated quality inspection of build health for laser beam powder bed fusion process		

# Destructive Testing

# Witness samples and microstructural microscopy



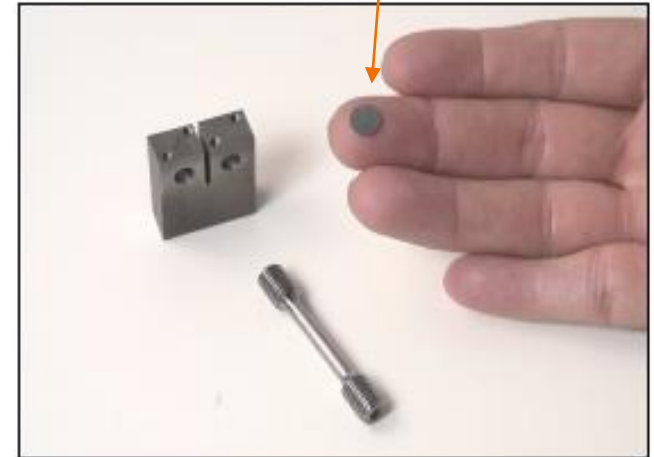
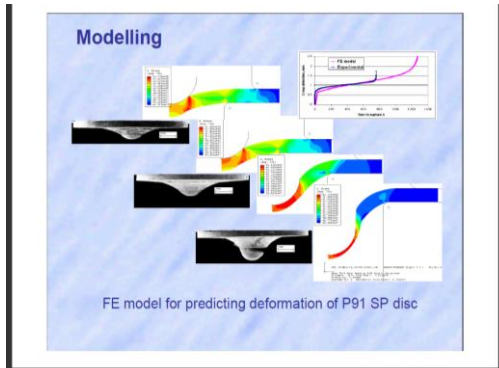
- Mechanical testing following recognized standards
- Specially useful for process qualification
- Usefulness reduced for component qualification and for single part quality control





# 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.



# In-Process Monitoring

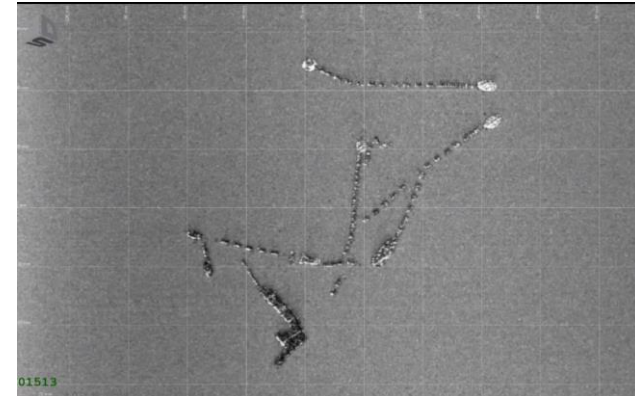
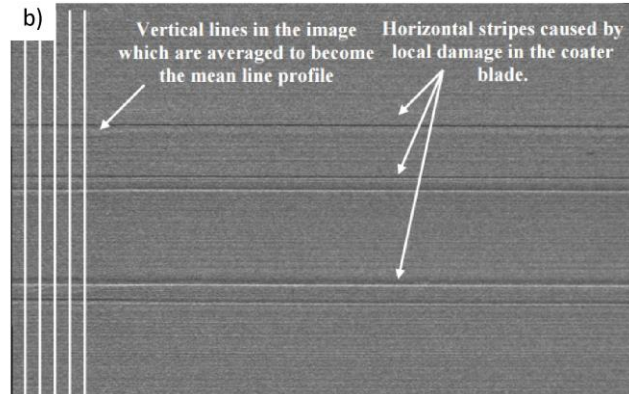
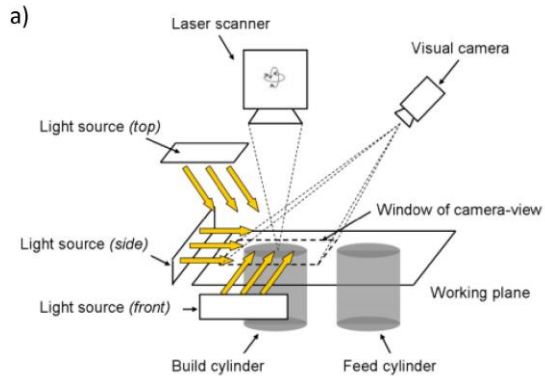
# AM Process Monitoring

- Detects 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. Most machine manufacturers have their own solutions. Some third party offerings available as well.
- These process can be real-time, but currently no closed-loop control available.

# Examples of existing (commercial) monitoring solutions

- Basic process and environmental sensors:
  - Laser power, oxygen level, gas flow rate, platform temperature
  
- Powder bed monitoring
  - Images of the powder bed before and/or after re-coating & exposure (usually with CMOS/CCD machine vision cameras)
  
- 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)

# Powder bed monitoring

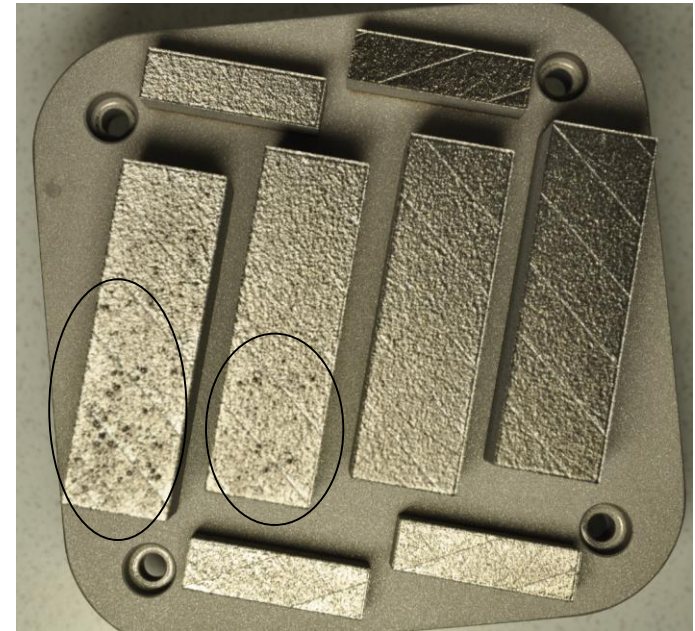
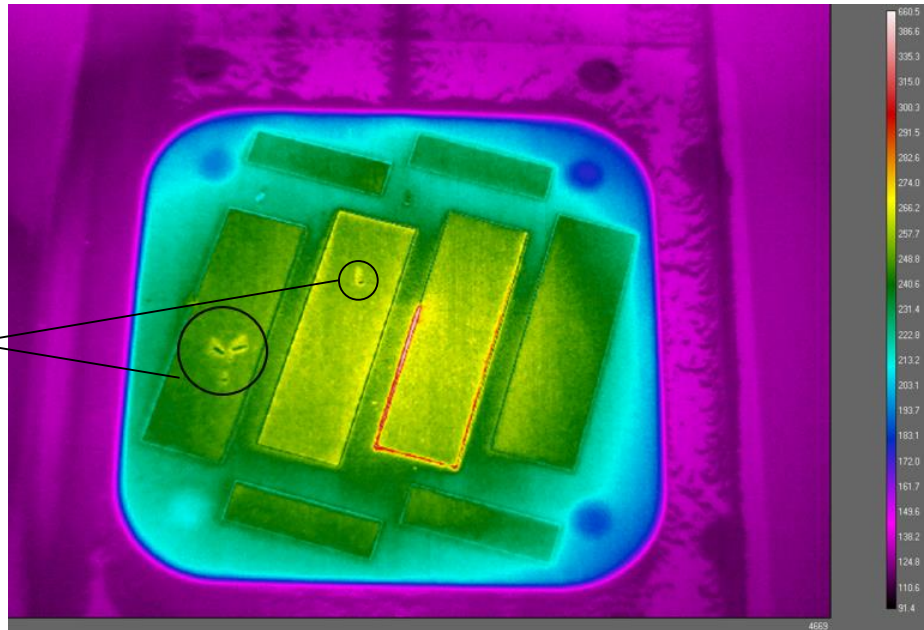


<http://sffsymposium.engr.utexas.edu/Manuscripts/2011/2011-17-Craeghs.pdf>

<https://www.3dsystems.com/dmp-monitoring-solution>

# Off-axis thermal monitoring

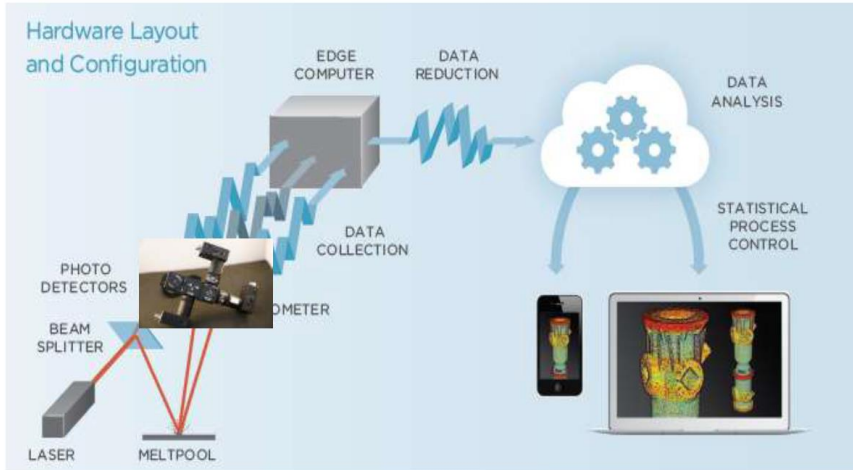
Spatter landing at the left hand side parts



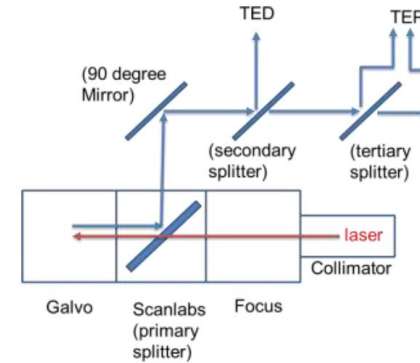
- Thermal camera FLIR A655sc at VTT
- Experimental material, non-optimal powder size & parameters caused excessive spattering

# On-axis thermal monitoring: Melt Pool Monitoring

How Does PrintRite3D® Collect Sensor Data Today?



On-Axis 3 Sensor Array



Sensor	Monitoring	Quality Metric	Measures	Usage
PD1	Melt Pool	TED™ Metric (Thermal Energy Density)	Melt Pool Emissivity	Process Input System Monitor
PD2	Melt Pool	Relative Temperature TEP™ Metric (Thermal Energy Planck)	Visible Wavelengths	<ul style="list-style-type: none"> <li>Measure of melt pool quality by characterizing and analyzing spectral data</li> <li>Looks at specific spectral regions of interest</li> <li>Ratio of two wavelengths to calculate relative melt pool temperature</li> <li>TEP™ metric used for analysis and process control</li> </ul>
PD3	Melt Pool		Infrared Wavelengths	

# Example of Melt Pool Monitoring

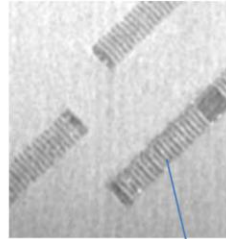
Inconel 625 : Evaluation of Thermal Signatures using Part-Layer SPC (Statistical Process Control) to detect powder disturbance



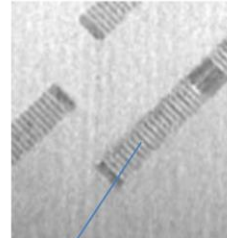
Qualitative versus Quantitative Approach

Method :- each fin categorized as separate part

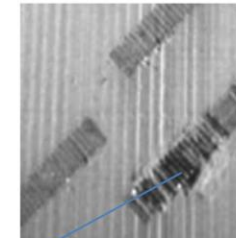
Layer 225



Layer 250

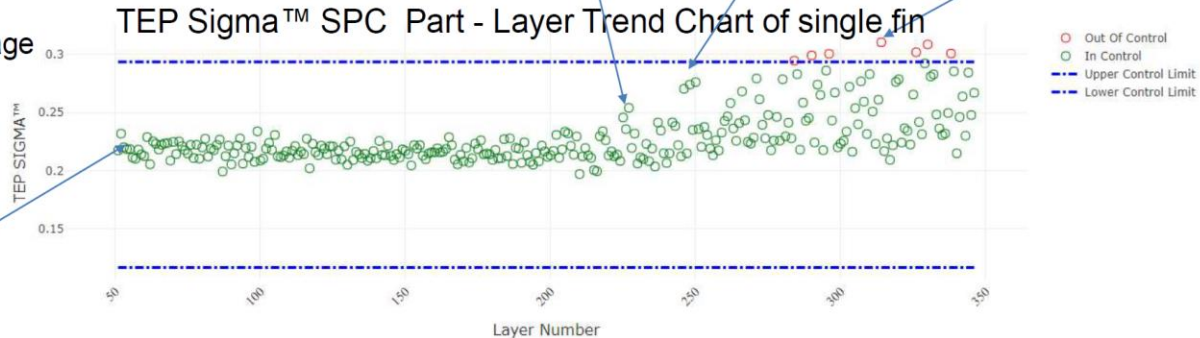
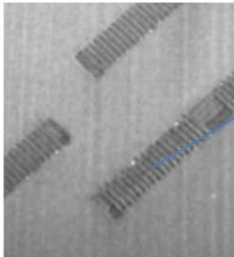


Layer 314



EOS Powder Bed Image

Layer 50



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# 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

# Geometrical complexity

## USAF Classification of complexity

GCG	Description	Example
1	Line-of-sight to almost every surface Only few details	Typical CNC manufactured component
2	Line-of-sight to most surfaces	Weight optimized components
3	Line-of-sight to some surfaces Embedded features	Turbine plates with internal cooling channel
4	Full of details Line-of-sight to only few surfaces High total surface area	Thermodynamically optimized heat exchanger.
5	Full of tiny details No line-of-sight to the surfaces Extremely high total surface area	Lattice structures Metal foams

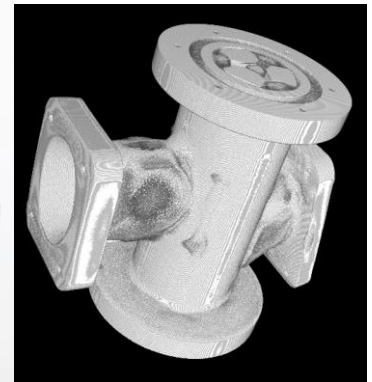
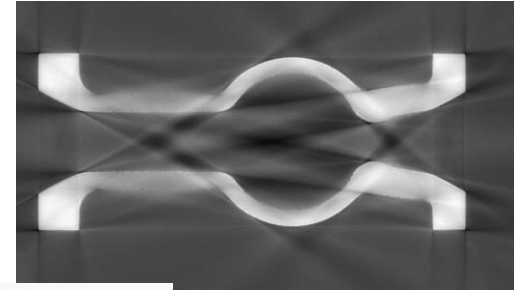


# Applicability of NDI to AM

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

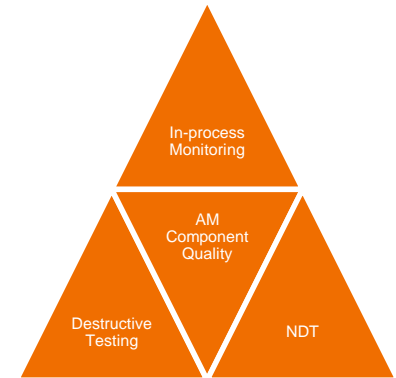
## So, what NDE method to use?.

- CT/uCT is the method of choice currently as is the only method capable of handling complex geometries. But is not completely hassle free.
- For GCG1-2 parts, other methods can still have a major role:
  - Advantages in cost
  - Possibilities for in-service inspection.



# Summary

- There is no single magic bullet to ensure quality on a component
  - But a combination of in-process monitoring, NDT and destructive testing can support our efforts.
- AM standards are still lacking, but developing steadily.
- QC methods applied to AM are actively being researched



# bey<sup>0</sup>nd

## the obvious

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