Non-Destructive Testing for Additive Manufacturing

JOINING
INNOVATION
AND EXPERTISE

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NDT in AM

- Importance of NDT in AM:
  - Ensures the integrity and quality of complex AM parts.
  - Essential for industries such as defence, aerospace, where reliability is critical.

- Challenges in NDT for AM:
  - AM processes introduce unique challenges for NDT:
    - Complex geometries
    - Internal defects
    - Material variations
    - Uneven surface
  - Need for specialised standards
  - Post processing or in-situ pose different challenges to NDT

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Examples of Direct Energy Deposition (DED) Arc Wire defects

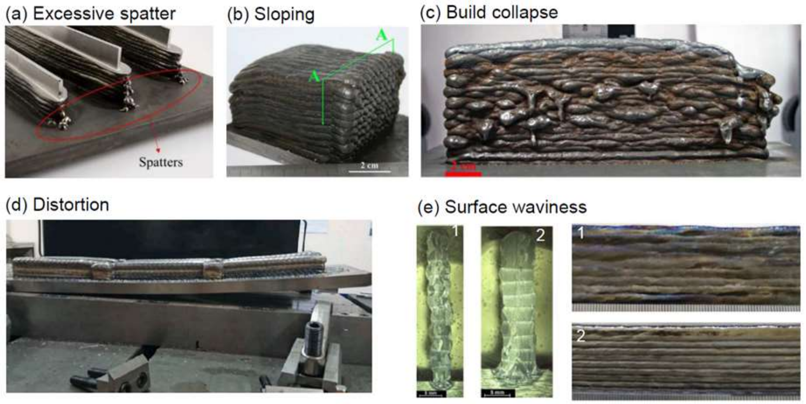


Fig 1. Examples of macro-scale defects geometric accuracy.

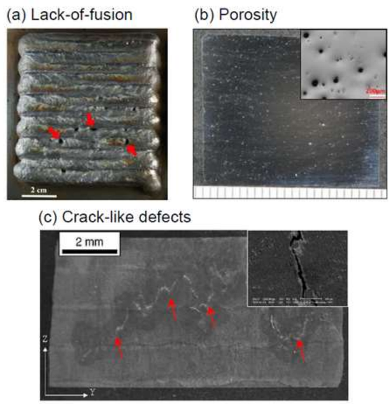
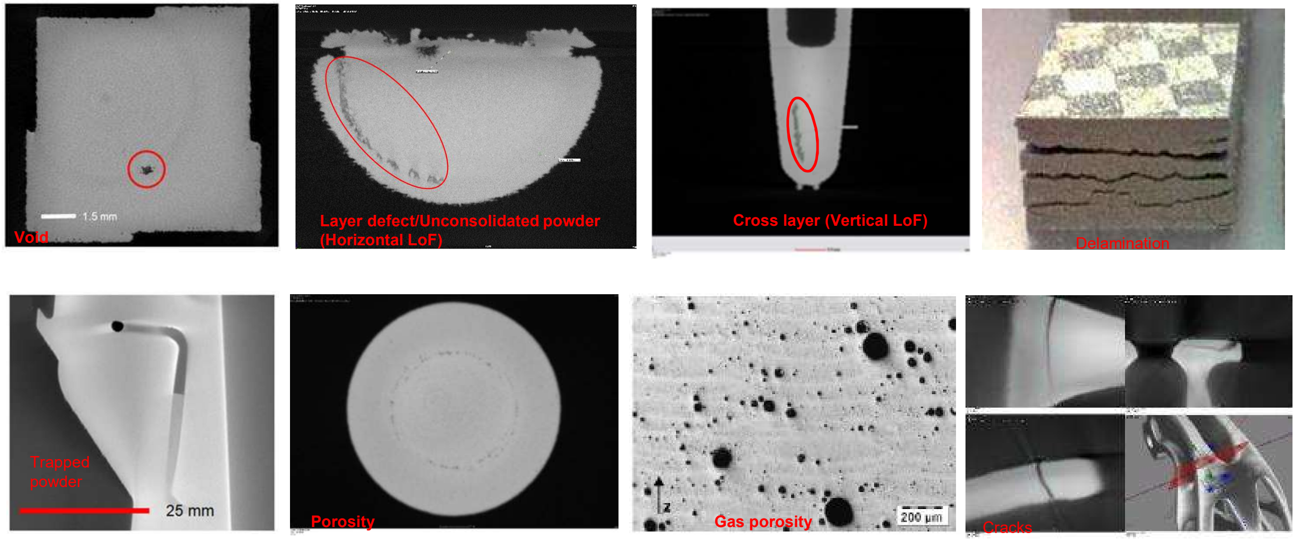


Fig 2. Examples of micro/meso-scale defects inside build (internal).

Image references:
Fig 1. (a) L. Ji et al., "Research on mechanisms and controlling methods of macro defects in TC4 alloy fabricated by wire additive manufacturing," Materials (Basel)., vol. 11, no. 7, p. 1104, Jun. 2018.
Fig 1. (b), Fig 2(a) X. Xu, J. Ding, S. Ganguly, C. Diao, and S. Williams, "Preliminary Investigation of Building Strategies of Maraging Steel Bulk Material Using Wire + Arc Additive Manufacture," J. Mater. Eng. Perform., vol. 28, no. 2, pp. 594–600, Feb. 2019.
Fig 1. (c) X. Xu, J. Ding, S. Ganguly, C. Diao, and S. Williams, "Oxide accumulation effects on wire + arc layer-by-layer additive manufacture process," J. Mater. Process. Technol., vol. 252, pp. 739–750, Feb. 2018.
Fig 1. (d) F. Xu et al., "Realisation of a multi-sensor framework for process monitoring of the wire arc additive manufacturing in producing Ti-6Al-4V parts," Int. J. Comput. Integr. Manuf., vol. 31, no. 8, pp. 785–798, 2018.
Fig 1. (e) G. Pardal, F. Martina, and S. Williams, "Laser stabilization of GMAW additive manufacturing of Ti-6Al-4V components," J. Mater. Process. Technol., vol. 272, pp. 1–8, Oct. 2019.
Fig 2. (b) K. Derekar, J. Lawrence, G. Melton, A. Addison, X. Zhang, and L. Xu, "Influence of Interpass Temperature on Wire Arc Additive Manufacturing (WAAM) of Aluminium Alloy Components," MATEC Web Conf., vol. 269, p. 05001, 2019.
Fig 2. (c) D. Clark, M. R. Bache, and M. T. Whittaker, "Shaped metal deposition of a nickel alloy for aero engine applications," J. Mater. Process. Technol., vol. 203, no. 1–3, pp. 439–448, 2008.

Examples of Laser Powder Bed Fusion (LPBF) Defects



Dutton, B., Vesga, W., Waller, J., James, S. and Seifi, M., “Metal Additive Manufacturing Defect Formation and Nondestructive Evaluation Detectability,” in Structural Integrity of Additive Manufactured Parts, ed. N. Shamsaei, S. Daniewicz, N. Hrabe, S. Beretta, J. Waller, and M. Seifi (West Conshohocken, PA: ASTM International, 2020), 1–50. http://doi.org/10.1520/STP162020180136.

NDT for AM

- X-ray computed tomography (XCT)
  - XCT powerful NDT technique capable of producing volumetric three-dimensional density data of a scanned part
  - Insitu loading of components during XCT process

- Digital radiography (DR)
  - Produces a two-dimensional rendering of the density and material thickness of uniformly shaped regions of interest

- Other techniques
  - We are researching various in-situ inspection techniques based on optics, Eddy current, advanced ultrasound and laser ultrasound to identify material defects of AM metallic parts during and post the build process.

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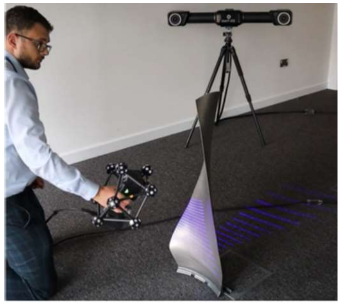
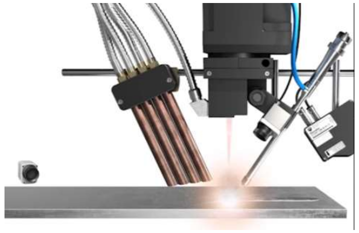
In-situ NDT for AM

Non-Contact Surface Mapping & Metrology

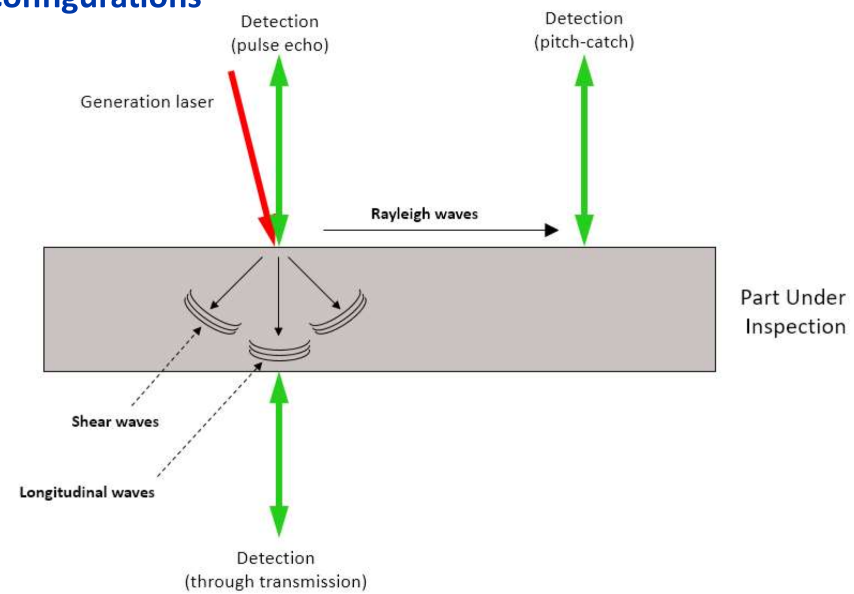


Laser Ultrasonic Testing



Principles of Laser Ultrasonic Testing

Three Inspection Configurations



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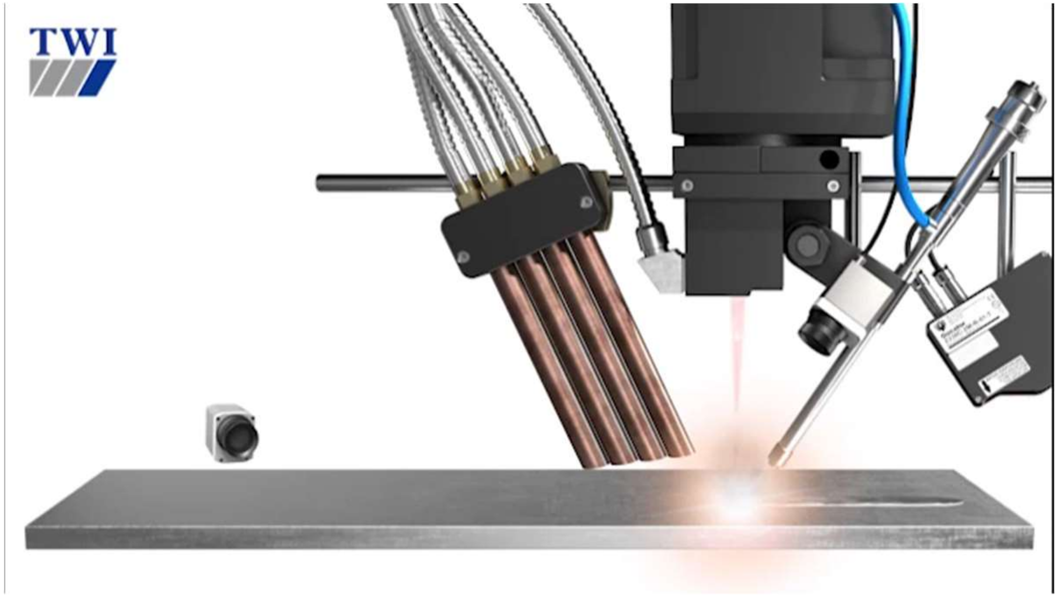
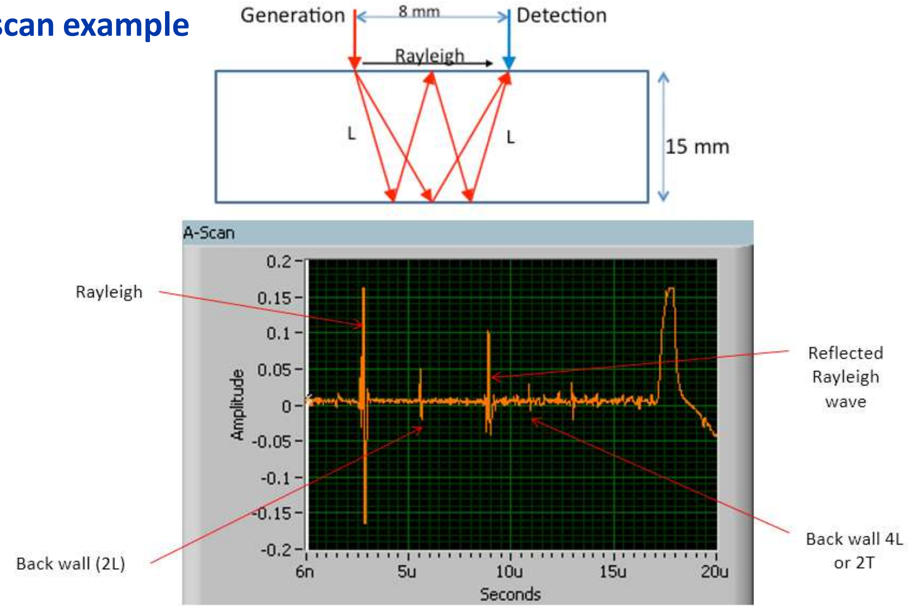
Concept of LUT in-process integration for Inspection of AM



IC

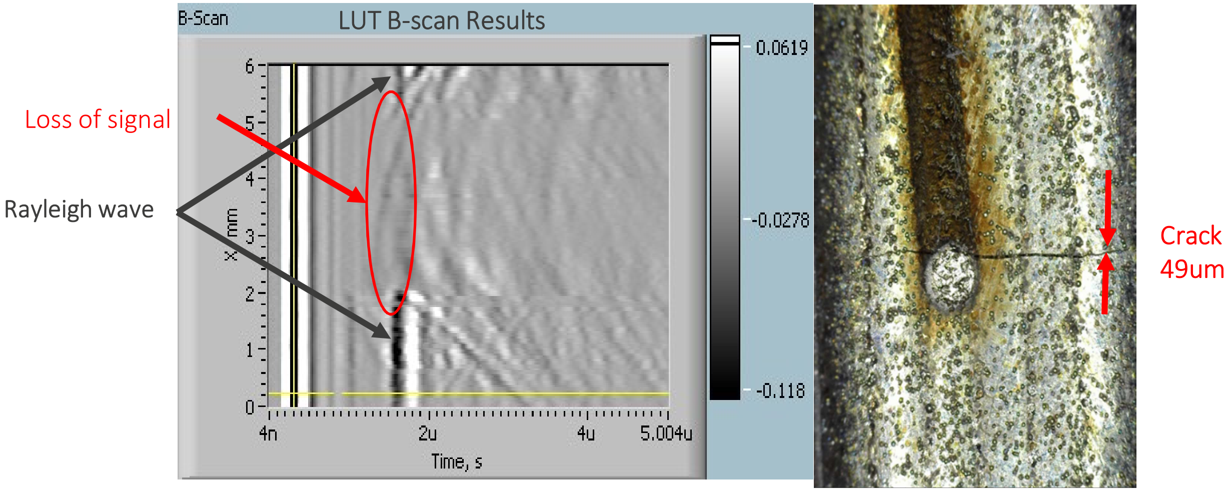
Principles of Laser Ultrasonic Testing

Pitch Catch A-scan example



IC

In-process inspection for part quality and validation of AM components using LUT Tristelle 5183- Naturally occurring defects – Test at Ambient Temp



IC

Digital Radiography ticks the most boxes

Flaw classification	Method of Inspection
Poor surface finish	VT
Porosity	**RT**, **CT**, UT, PAUT
Incomplete fusion (bead to bead, or bead to underlying structure / substrate)	**RT**, **CT**, UT, PAUT, DPI
Geometrical inaccuracies (steps between layers, necking at intersections…)	VT, **RT**, **CT**
Undercutting at bead toes of weld between the adjoining weld beads	VT, ET, **RT**, **CT**, MPI, DPI
Holes and voids	**RT**, **CT**, UT, PAUT
Inclusions	**RT**, **CT**,
Cracking	VT, **CT**, **RT**, UT, PAUT, MPI, DPI, ET, LUT
Unconsolidated material / trapped powder	**CT**, **RT**

- VT (Visual Testing)
- RT (Radiographic Testing)
- CT (Computed Tomography)
- UT (Ultrasonic Testing)
- PAUT (Phased Array Ultrasonic Testing)
- MPI (Magnetic Particle Inspection)
- DPI (Dye Penetrant Inspection)
- ET (Eddy Current Testing)

DR & XCT Compared to other NDT Techniques

NDE Technique	Advantages	Disadvantages
Optical inspection techniques e.g. external surface inspections	Surface defects only	Rough surface may obscure identification of defects.
Ultrasonic techniques e.g. Conventional pulse-echo ultrasonic testing, phased array, immersion ultrasonic testing	Can potentially interrogate deeper into components for some materials. Can be used to detect defects, location and measurement	Limited by complex surface topography, complexity of internal structures (that can include air gaps), "grain/microstructure" scattering and attenuation at higher frequencies "Dead (detection) zone" at near surface Requires coupling e.g. water
Electromagnetic techniques e.g. Eddy current	Good at estimating surface crack depth	Limited by surface roughness Difficult to interpret signal
X-ray radiography e.g. Film and digital	Can detect deep or embedded defects DR can be near real time	Possible to miss defects if they are not oriented perpendicular to the radiation dimension
X-ray Computed Tomography	100% volumetric inspection Easy to visualise and measure defects and internal component structure	Limited by both the voxel size and the specimen size (small specimens allow higher resolution to detect smaller defects). Large samples require sectioning. Expensive! Can be slow

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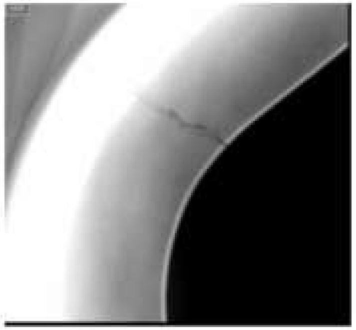
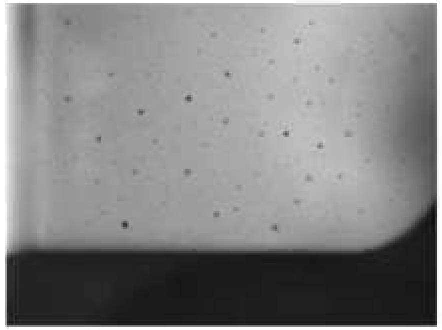
Defects Identifiable – 2D Digital Radiography



Cracks

Inclusions

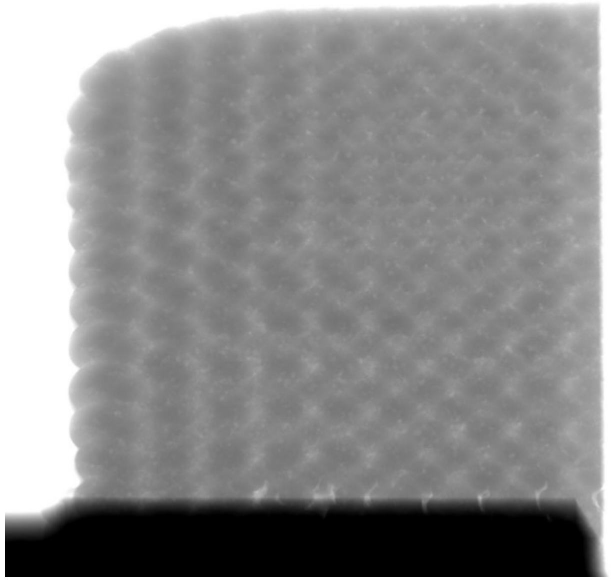


Voids

DR of Aluminium WAAM Sample

- Class-B (best) image quality achieved, based on cast materials
- Large amount of porosity observed
- Large voids near deposit-parent material interface

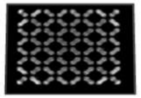
- No indication of level of porosity
- No depth information



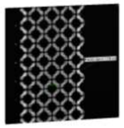
XCT

Identifying internal features

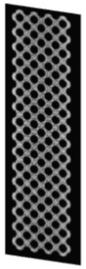
- Identify internal features in visually inaccessible locations
- Voids, inclusions and cracks
  - Colour coded based on size for visual ease
- Residual powder deposits
- Breaks or thinning in supporting struts of complex structures



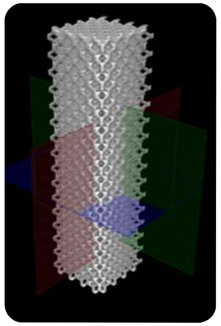
Top view



Right view

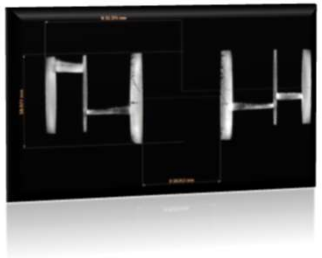


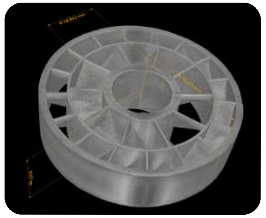
Front view



Accurate dimensioning

- Accurate dimensioning of internal and external features
- Ruled geometry elements fitted directly to CT data
- Minimisation / reduction of measurement uncertainty
- Fit CT data directly to CAD data
- Solve highly complex alignment tasks



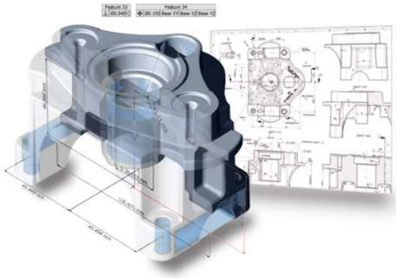


XCT

Compare to CAD models

- Import CAD data into CT environment for direct comparison
- Generation of STL files from CT data
- Detected defects accurately measured in 2D cross-sectional and 3D visualisations
- Use in FEA modelling

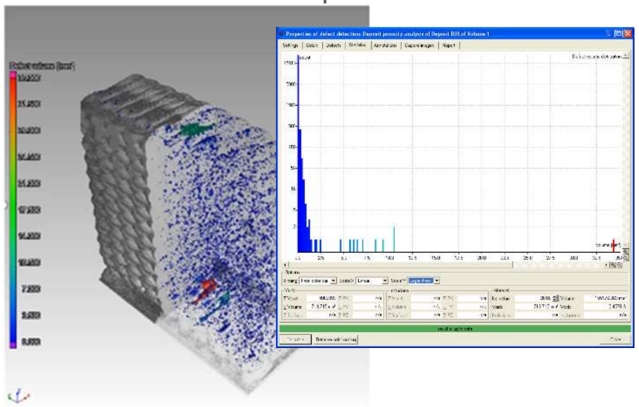
- Verify conformity
- Product / process development
- Reverse engineering



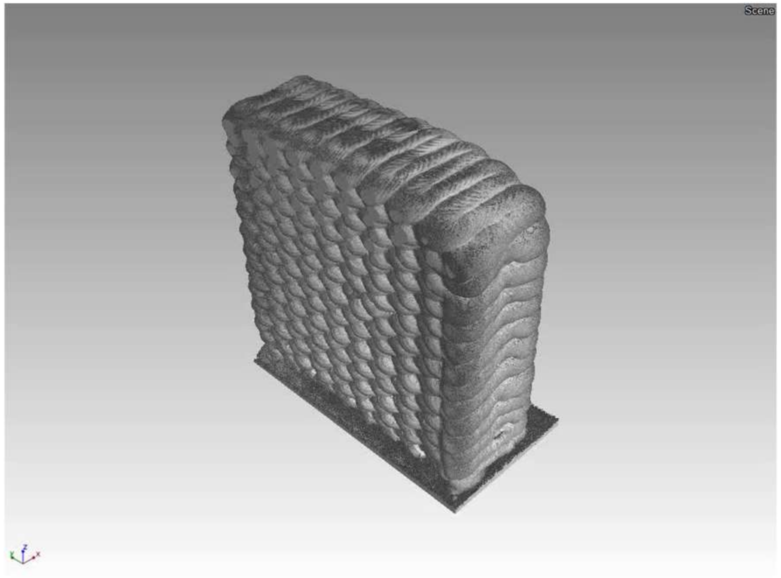
Automated statistical analysis

CT of WAAM Sample:

- Total of 18,000 voids over 0.005mm^3
- Largest void 34mm^3
- 0.46% porosity
- 99.54% complete fill
- Voxel resolution: 56µm



3D CT Video of Sample



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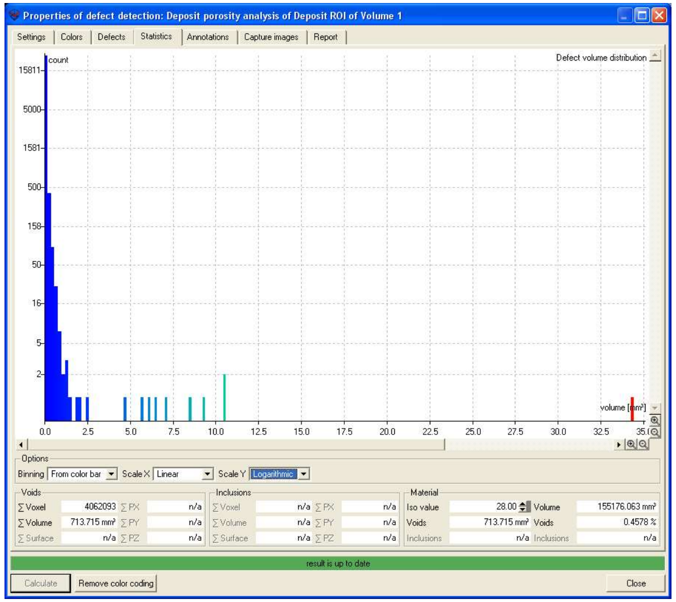
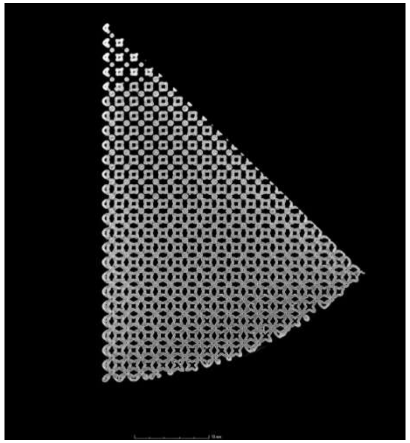
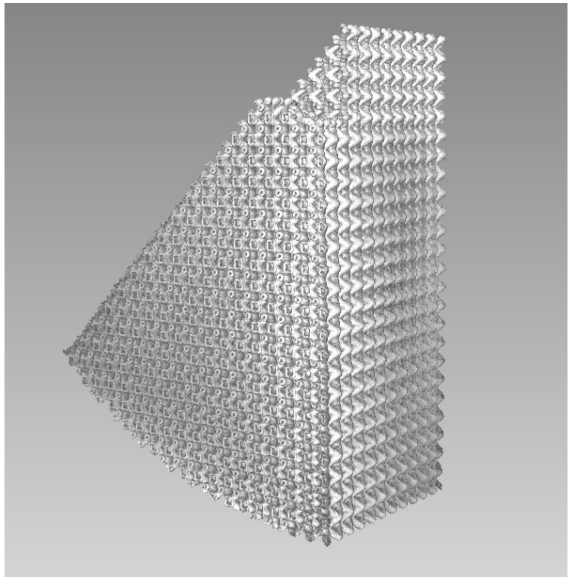


CT of Ti64 SLM Lattice Segment

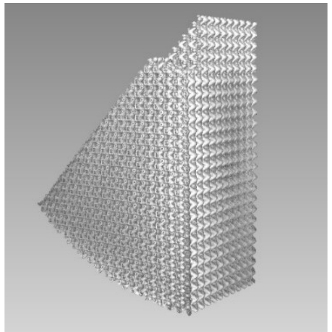
- Small sample, 48 x 38 x 22 mm
  - Allows high resolution CT scan
- Voxel resolution: 29μm

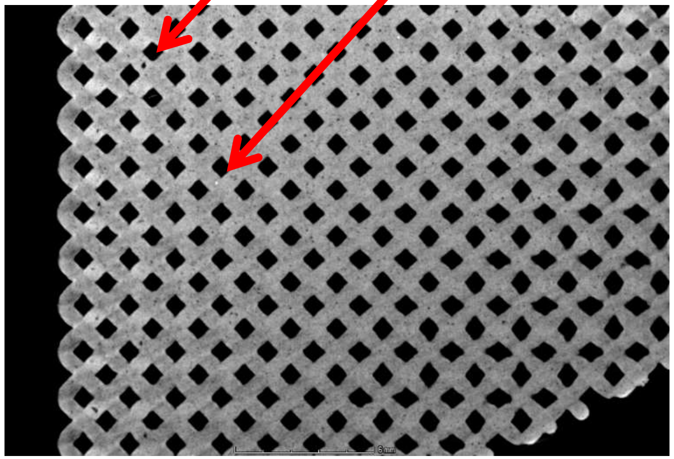




CT of Ti64 SLM Lattice Segment

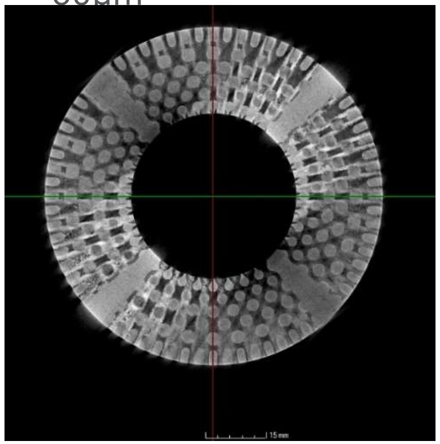
- Small sample, 48 x 38 x 22 mm
- high resolution CT scan
- 29µm voxel size

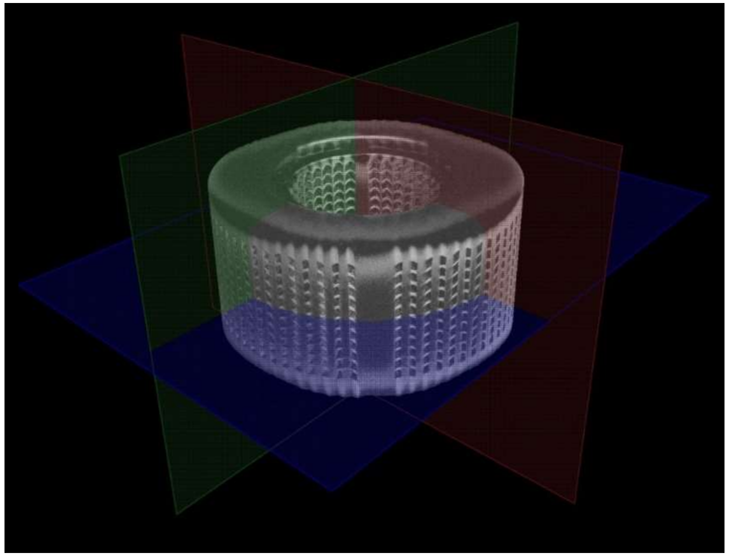




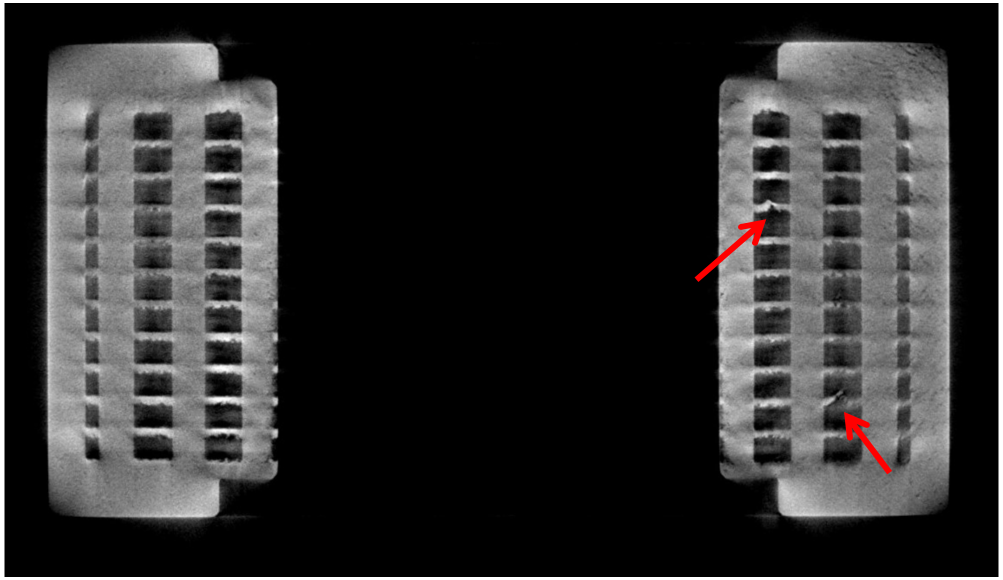
CT of Ti64 SLM Part

- 20 x 84mm Ø
- Voxel resolution: 60µm





Deformed and Broken Strands



Digital Radiography limitations

- 2D DR –
  - if flaw is in wrong orientation with respect to X-ray beam can miss defect - Solution to take multiple shots
  - Difficult part geometry presents a challenge

- XCT –
  - Limitation on part size, material thickness
    - Solution increase radiation energy, panel shift, offset CT, Laminography

Existing Standards and Guidelines (General)

- ISO
  - **ISO/ASTM TR 52905:2023**: Additive manufacturing of metals - Non-destructive testing and evaluation - Defect detection in parts
  - **ISO/ASTM TR 52906:2022:** Additive manufacturing — Non-destructive testing — Intentionally seeding flaws in metallic parts
  - **ISO/ASTM 52941:2020:** AM - System performance and reliability - Standard test method for acceptance of powder-bed fusion machines
- ASTM
  - **ASTM E3166-20e1** - Standard Guide for Non-destructive Examination of Metal Additively Manufactured Aerospace Parts After Build
  - **ASTM E3353-22** - Standard Guide for In-Process Monitoring Using Optical and Thermal Methods for Laser Powder Bed Fusion
  - **(Work item) ASTM WK69731** - New Guide for Additive Manufacturing -- Non-Destructive Testing (NDT) for Use in Directed Energy Deposition (DED) Additive Manufacturing Processes

Recommendations (for Standards)

NDT standards specific for AM are currently limited, however, we still can explore the suitability of various NDT techniques for different AM materials and defects, as shown below:

1. **Ultrasonic Testing (UT): ISO 13588:2019.** This is also relevant for AM, especially for complex geometries.
2. **Radiographic Testing (RT): ISO 17636-1:2022.** This standard can be applied to AM parts for detecting internal defects.
3. **Computed Tomography (CT): ASTM E1441-11(2017).** This is widely used for AM parts, especially for complex internal structures
4. **Eddy Current Testing (ECT): ISO 15548-1:2013**. Useful for surface and near-surface defect detection in conductive materials used in AM.
5. **Liquid Penetrant Testing (LPT): ASTM E1417/E1417M-21.** Applicable for surface defect detection, particularly in AM processes that may introduce surface anomalies.
6. **Magnetic Particle Testing (MPT): ASTM E1444/E1444M-16:** Effective for detecting surface and near-surface defects in ferromagnetic materials, relevant in some metal AM processes.

Conclusions

- There isn't one NDT technique that fits all
  - Consideration needs to be made if in-line or post inspection
- Digital Radiography ticks most boxes for NDT of AM
  - XCT is the only technique that can give a true volumetric inspection. Limitation is part size and geometry
- NDT standards specific for AM are currently limited

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Questions?

Thank you for listening

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