Co-funded by the Erasmus+ Programme of the European Union

Project No. 601217-EPP-1-2018-1-BE-EPPKA2-SSA-B

CU 01: DED-ARC

Session 4.3 – Part Quality

DED defects + inspection

Prepared by: Ben Dutton

FOR SAM PILOT ATTENDEES AND TRAINERS ONLY

MM17,21

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Content

- Typical defects in DED-arc
- Part inspection methods
- In-process inspection methods
- Standardisation

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Defects examples

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Potential quality issues with DED parts

1. Lack of integrity – defects such as LOF, cracking , porosity, foreign body contamination
2. Geometrical inaccuracy
3. Poor Surface finish

Finishing of parts (usually by machining) often means geometrical inaccuracy and poor surface finish is not critical as for PBF-LB

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DED defects by sub-process

Advanced Powder Materials 1 (2022) 100054

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A review on additive/subtractive hybrid manufacturing of directed energy deposition (DED) process

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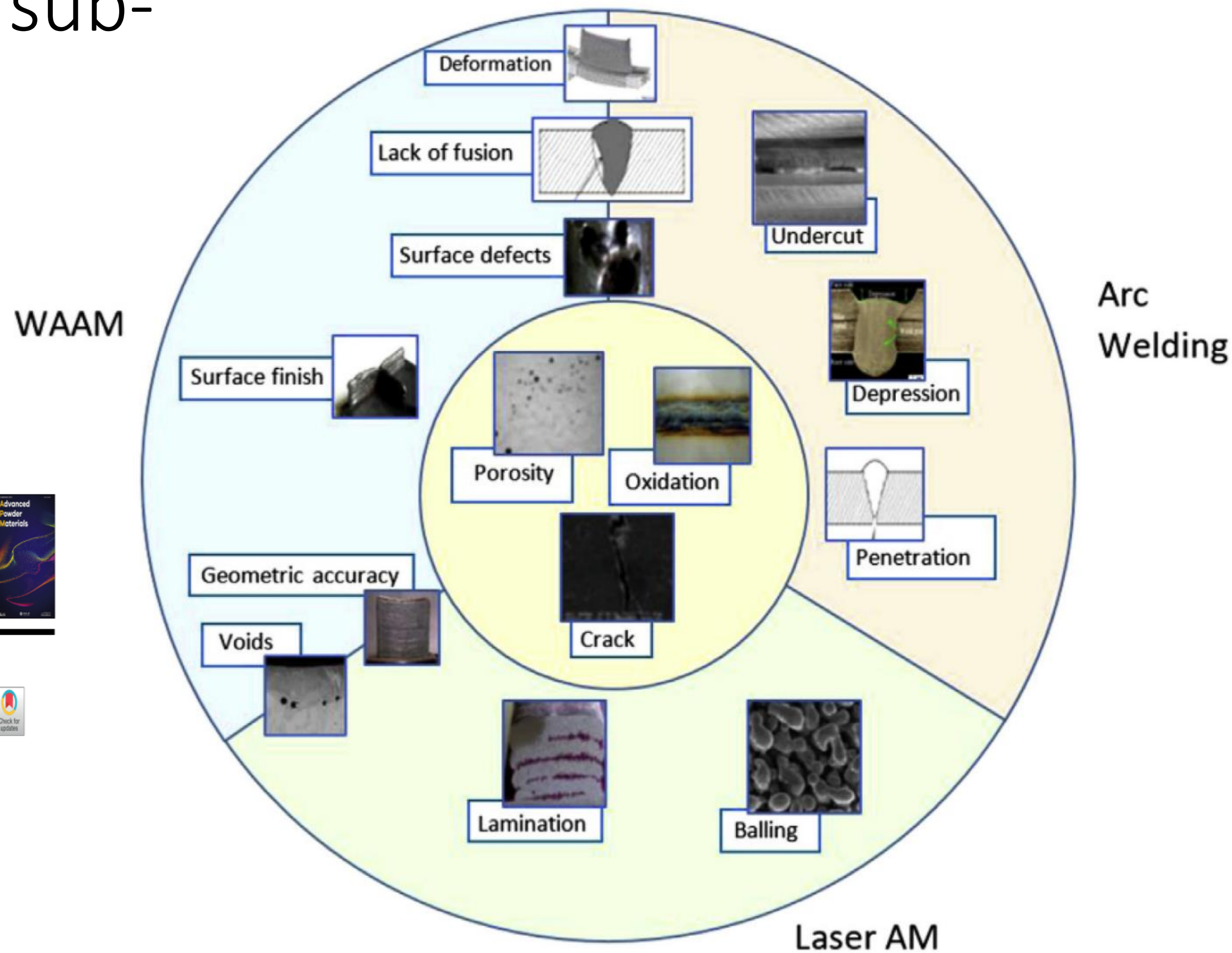

Fig. 12. Defects in DED processes [80].

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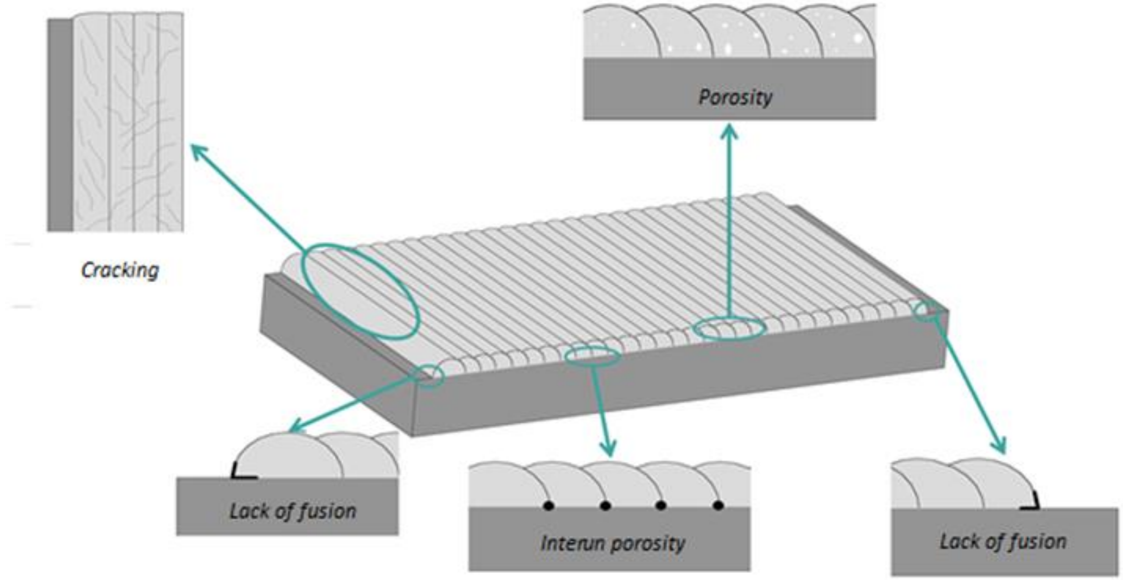
Part Integrity

- Lack of fusion (LOF) layering defects
- Porosity
- Cracking

- Some may be mitigated post-process



Source: S.J. Wolff et al. / Acta Materialia 132 (2017) 106e117

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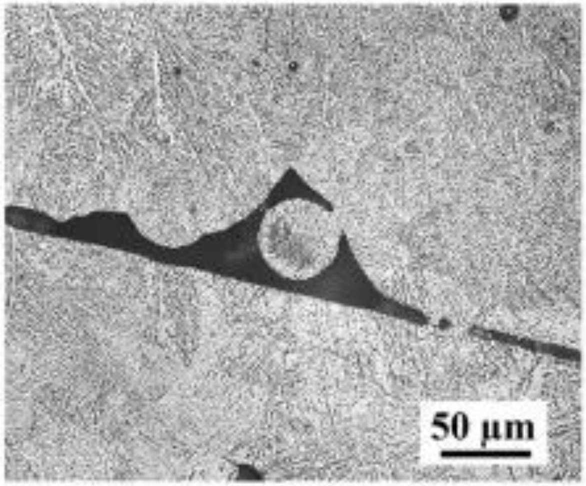
Lack of Fusion

Source: Y. Zhai et al. / Engineering Failure Analysis
(2016) 3–14



- Typically irregular shape
- Occurs between layers or coating/substrate interface
- Why does it occur?
    - Due to insufficient melting of substrate or previous layers
    - Oxides can also inhibit fusion
- How can we avoid?
    - Increase re-melting depth
    - Parameters optimisation

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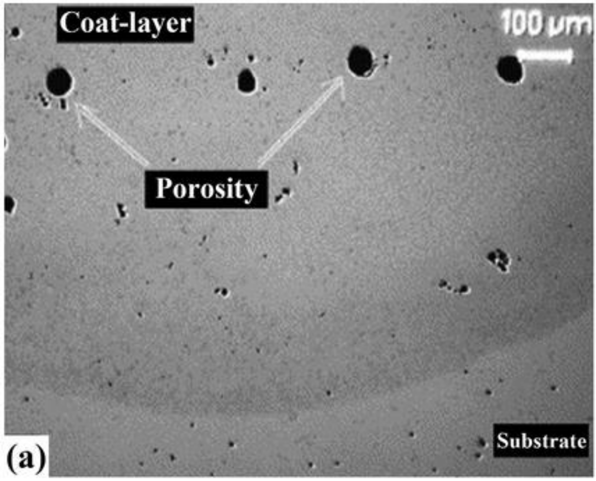
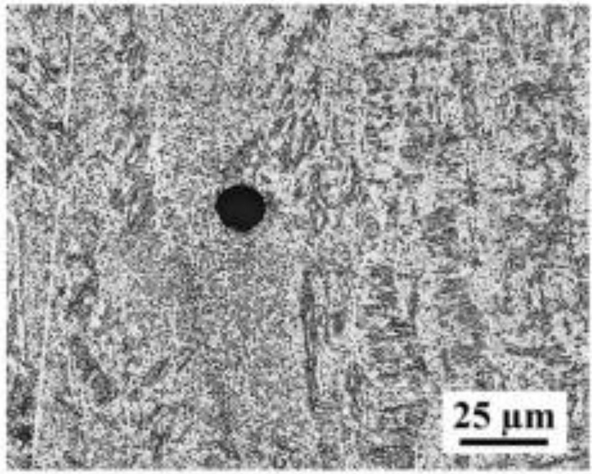
Porosity

- **Types of porosity**
  - **Interun – between layers (often associated with LOF)**
  - **Bulk – spherical**
- Causes
  - Entrapped gas in powder feed-stock
  - Poor shielding gases parameters
  - Over-melting/ vaporisation
  - Contamination/cleanliness
- Mitigation
  - Control of feed-stock
  - Parameter optimisation (Energy input/ Shielding gas)
  - Post processing (such as HIPing)

Source: K. Liu et al. / OptLasEng (2017)





Source: Y. Zhai et al. / Engineering Failure Analysis 69 (2016) 3–14

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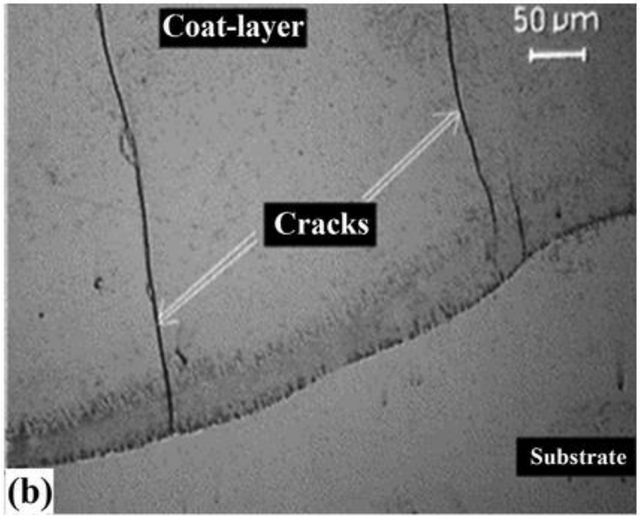
Cracking

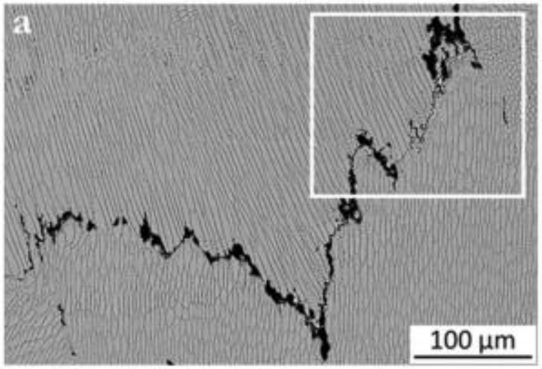
- Macro and microscale cracking

- Causes
  - Hot tearing
  - Liquation cracking
  - Differential thermal contractions

- Mitigation
  - Parameter optimisation (heating/cooling rates)
  - Pre-heating
  - Buffer layers for thermal property gradation
  - Material selection



Source: K. Liu et al. / OptLasEng (2017)



B.E. Carroll et al. / Acta Materialia 108 (2016) 46e54

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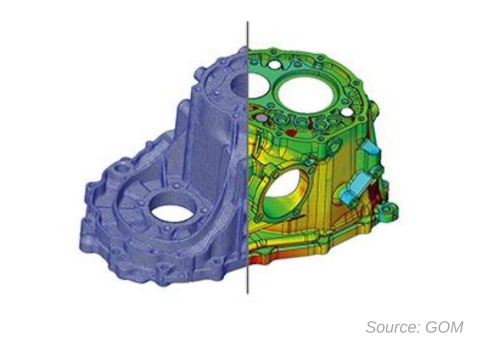
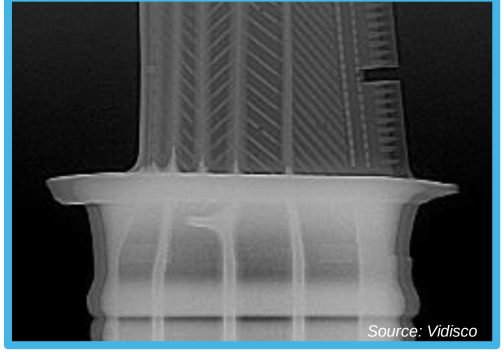
Introduction

- Post build inspection of AM components can be split into three fields:

Dimensional **metrology**	Surface **metrology**	Non-destructive testing (**NDT**)
Form validation	Assessment of surface topography	Measurement of internal structures
		
Source: GOM	Source: Mahr Metrology	Source: Vidisco

- Such inspection provides quality assurance in production and feedback on part quality during process development, allowing the AM process to be optimised

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Inspection (Metrology and NDT)

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Challenges of AM Inspection

- AM components are associated with inspection challenges directly related to the manufacturing process:
  - Geometrical complexity
  - Surface roughness
  - Defects of complex morphology
  - No intermediate stage for inspection
  - Part size

Source: ARUP

- *"If you can't inspect it, you can't use it."*

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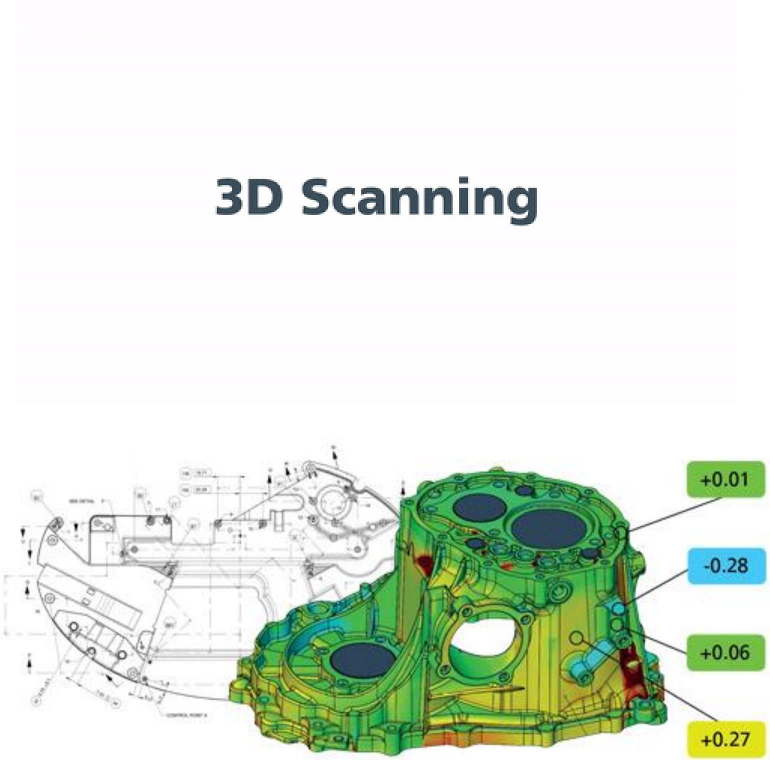
Dimensional Metrology: Non Contact

- Allows for the creation of 3D co-ordinate data and quantification of component deformation
- Geometry collected by:
  - CMM-mounted laser line scanner
  - Photography combined with structured light scanner
- Store data as a point cloud or a polygonal mesh – direct comparison to original CAD model



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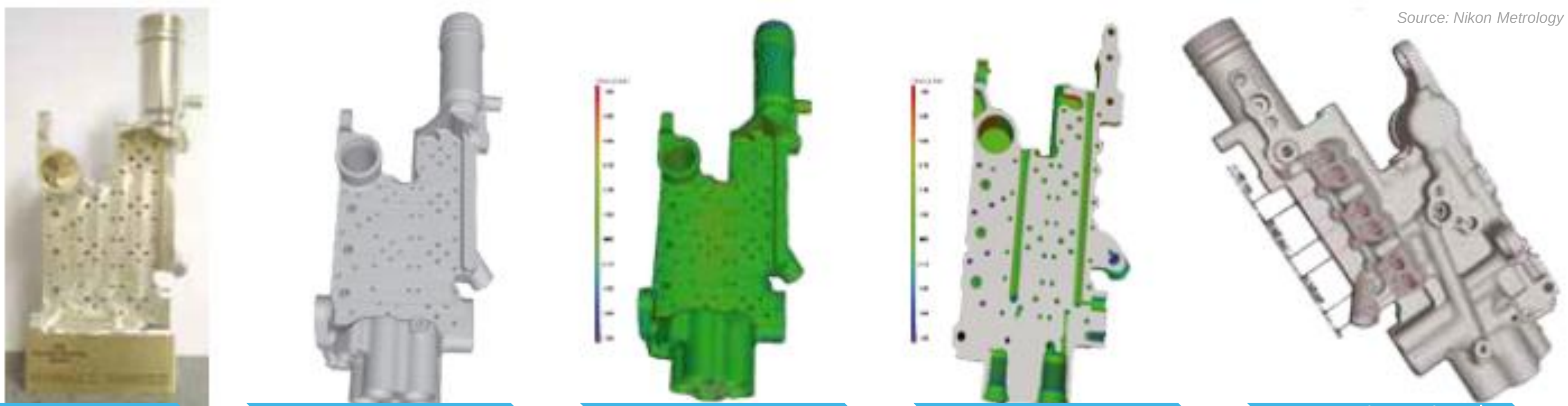
Volumetric Metrology

- X-ray Computed Tomography (XCT) can also be used for dimensional measurement:
  - Comparison of reconstructed model to original CAD
  - Possibly the only means of measuring complex internal geometries
  - Raises the possibility of a combined integrity and dimensional inspection

Source: Nikon Metrology



F1 car hydraulic manifold → CT volume reconstructio n → Compare directly to CAD model → Section of internal geometry → Dimensional report GD&T Geometrical dimensional and tolerance

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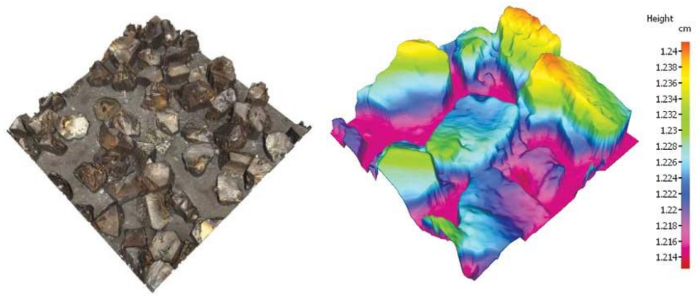
Surface Texture Measurement

- Optical surface texture instruments allow for the measurement of:
    - Form – both profile and 3D (radius, angle)
    - Profile roughness (Ra, Rz)
    - Surface roughness (Sa, Sz)
    - Differences between surfaces, e.g. pre- & post surface treatment
- Tactile surface profilometers allow for measurement of form & profile roughness



3D measurement of an abrasive in registered color and pseudo color visualization using Alicona InfiniteFocus

Source: Manufacturing News

Source: Alicona

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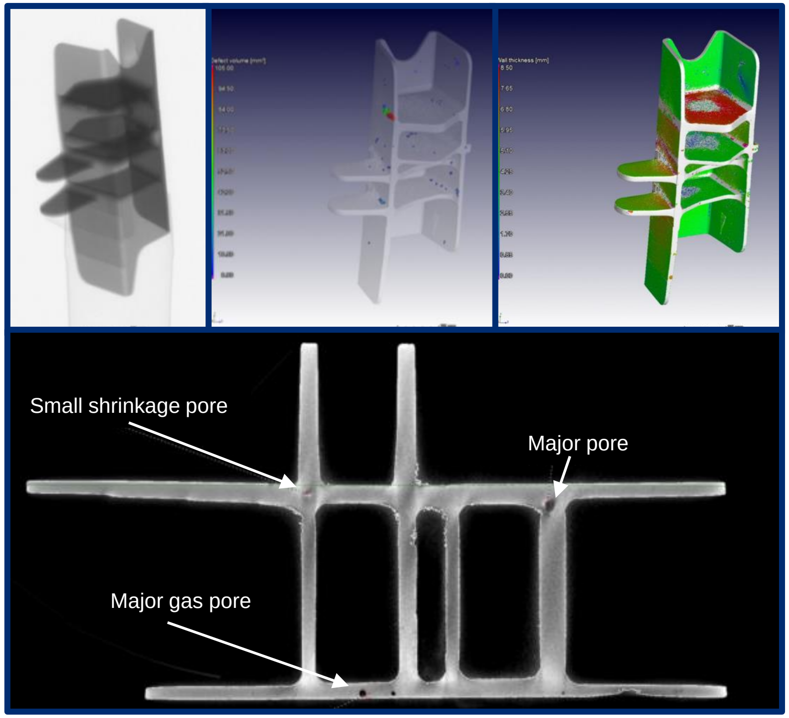
Volumetric NDT: XCT

- X-ray computed tomography (XCT) widely used for the volumetric inspection of AM parts
  - X-ray projection images as component is rotated
  - Reconstruction algorithm used to combine images
  - Analysis to identify 3D locations, shapes, and sizes of defects present
  - Used to identify foreign contaminations
  - **But resolution is limited to sample size**



Source: CT Scanner Facility at Stellenbosch University

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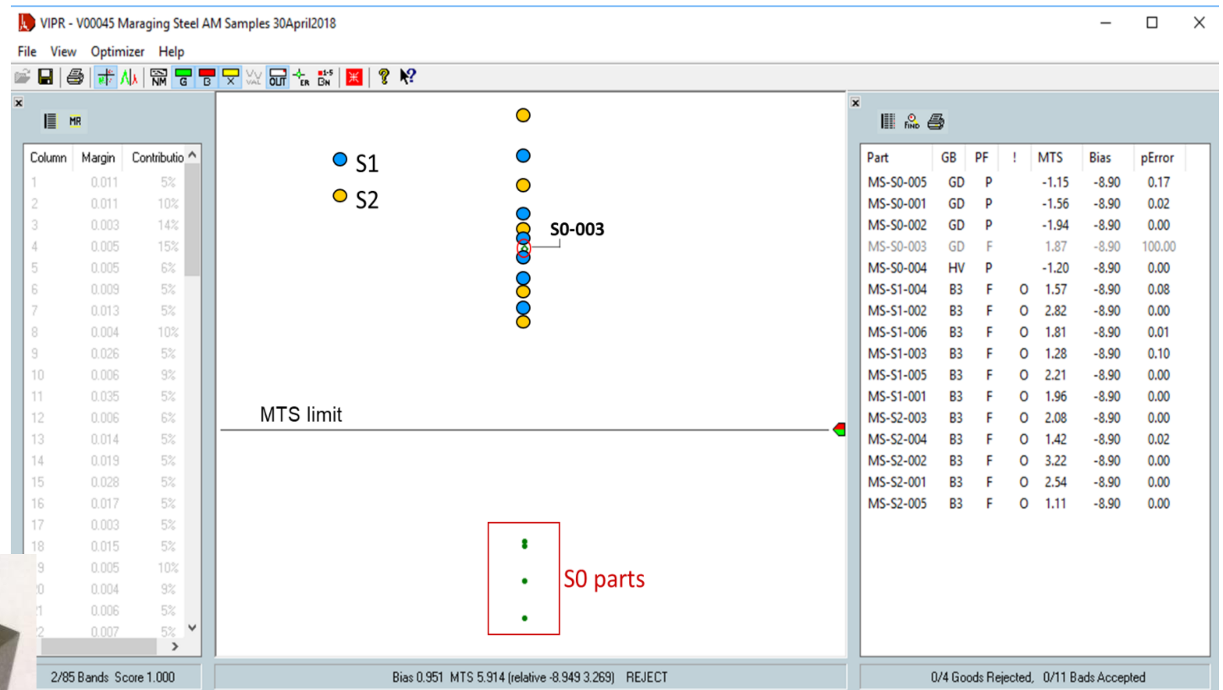
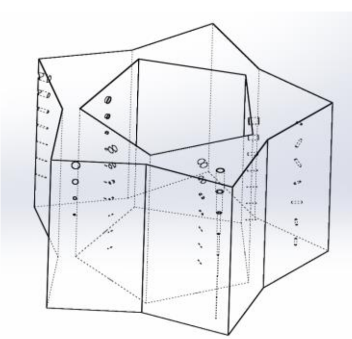
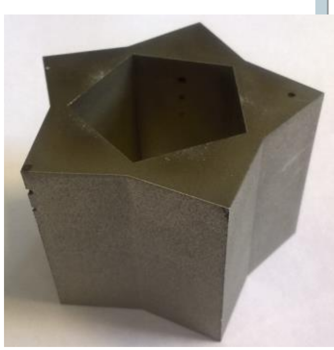
Volumetric NDT: PCRT/RAM

- PCRT demonstrated capability to differentiate between seeded (S1 & S2) and the non-seeded defect (S0) star artefacts.
- RAM showed similar capabilities.







Courtesy ISO/ASTM JG59 TR 52905, 'Additive Manufacturing — Non-Destructive Testing and Evaluation — Standard Guideline for Defect Detection in Metallic Parts', balloting.

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Comprehensive NDT Techniques (1/2)

Method	Material	Defect location	Global screening defect location	Configuration	Physical principle	Digital data	Cost 1 (low) – 5 (high)
VT	Any solid	Surface	Screening Detects location	On/offline	Optical	No	1
LT	Any solid	Through	Detects location	Offline	Optical	No	2–5
PT	Any solid	Surface/ Near surface	Detects locations	Offline	Optical	No	1
DI	Any solid	Surface		On/offline	Optical	Yes	2
MT	Magnetic solid	Surface/ Near surface	Detects locations	Offline	Optical	No	1
ERT	Conductive solid	Surface subsurface	Detects location images	On/offline	Electro-magnetic	Yes	3
DCPD	Conductive solid	Surface subsurface	Detects location images	On/offline	Electro-magnetic	Yes	2
ACPD	Conductive solid	Surface/ Near surface	Detects location	Offline	Electro-magnetic	Yes	2
ET	Conductive solid	Surface/ Near surface	Detects location	On/offline	Electro-magnetic	No	2
AEC	Conductive solid	Surface and near surface	Detects and image location	On/offline	Electro-magnetic	Yes	3
MUT	Low sound absorption solid	Surface and subsurface	Detect location	On/offline	Ultrasound	No	2
PAUT	Low sound absorption solid	Surface and subsurface	Detects and image location	On/offline	Ultrasound	Yes	3
IUT	Low sound absorption solid	Surface and subsurface	Detect location	Offline	Ultrasound	Yes	3
EMAT	Conductive solid	Surface subsurface	Detects location images	On/offline	Electromagnetic Acoustic	Yes	3
LUT	Any low sound absorbing solid	Surface subsurface	Detects location images	On/offline	Ultrasound	Yes	4

Source:
BSI PAS 6011:2020 'Additive manufacturing – Non-destructive testing for use in directed energy deposition – Guide'

9.1 Traditional methods

NDT methods that are widely used in industry include:

- Visual testing (VT);
- Leak testing (LT);
- Penetrant testing (PT);
- Eddy current testing (ET);
- Magnetic particle testing (MT);
- Digital imaging (DI);
- Manual ultra sound testing (MUT);
- Immersion ultrasonic testing (IUT);
- Phased array ultrasound testing (PAUT);
- Film radiographic testing (FR);
- Digital radiographic testing (DR);
- Computed Radiography (CR); and
  NOTE CR can be considered a form of DR.
- Acoustic emission (AE).

9.2 New methods

Methods of NDT that are under evaluation for DED AM include:

- Infrared imaging (IR);
- Direct current potential drop (DCPD);
- Alternating current potential drop (ACPD);
- Eddy current array testing (ECAT);
- Electrical resistance tomography (ERT);
- X-ray computed tomography (XCT); and
- Laser thermography (LTT).

9.3 Emerging methods

Emerging NDT methods with potential application for DED AM include:

- Electromagnetic acoustic (EMAT);
- Laser ultrasonic testing (LUT);
- Nonlinear acoustic (NLA);
- Microfocus X-ray computed tomography (MFXCT);
- X-ray backscatter (XBT);
- Neutron imaging (NIT);
- Vibro-thermography (VTT)
- Eddy current thermography (ECTT); and
- Process compensated resonance testing (PCRT).

Comprehensive NDT Techniques (2/2)

Method	Material	Defect location	Global screening defect location	Configuration	Physical principle	Digital data	Cost 1 (low) – 5 (high)
NLA	Any low sound absorbing solid	Surface subsurface	Detects location images	On/offline	Ultrasound	Yes	3
FR	Any moderately high density solid	Surface and subsurface	Detects location images	Offline	Radiographic	No	3
DR	Any moderately high density solid	Surface and subsurface	Detects and image location	Offline	Radiographic	Yes	3
XCT	Any moderately high density solid	Surface subsurface	Detects and image location	Offline	Radiographic	Yes	4
MFXCT	Any moderately high density solid	Surface subsurface	Detects and image location	Offline	Radiographic	Yes	4
XBT	Any moderately high density solid	Surface and subsurface	Detects and image location	On/offline	Radiographic	Yes	4
NI	Any low or high density solid	Surface and subsurface	Detects and image location	Offline	Radiographic	Yes	5
LTT	Any solid	Surface subsurface	Detect location	On/offline	Thermographic	Yes	2
VTT	Any solid	Surface subsurface	Detect location	On/offline	Mechanical thermographic	Yes	2
ECTT	Conductive solid	Surface near surface	Detect location	On/offline	Electro-magnetic Thermographic	Yes	3
AE	Solid with propagating effect	Surface subsurface	Detect	On/offline	Acoustic Emission	Yes	1
PCRT	Any solid	Surface subsurface	Detects location	On/ offline	Mechanical	Yes	3

Source:
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NDT method I believe have more potential

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Source:
BSI PAS 6011:2020 'Additive manufacturing – Non-destructive testing for use in directed energy deposition – Guide'

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In-process inspection

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Future of AM Inspection

In-process Monitoring (Indirect) vs Inspection (Direct)

- In-process monitoring (**Indirect** Inspection) methods typically rely on visual and/or thermal methods and can be improved with Modelling & ML, but **may miss the actual process change that created a defect**. These methods are mostly **surface based** detection and **following layers may heal or make them bigger by re-melting**.

- In-process inspection method (**Direct** Inspection) are **sensitive to both surface and subsurface defects**, where the latter are **permanent** and will not be eliminated, which are the ones that would be found on the **final part inspection**.

- We at the **MTC are assessing both approaches:**
  - **Indirect (melt-pool monitoring, camera based, etc.)**
  - **Direct (Laser Ultrasound (LU) and Eddy Current (EC), etc.)**

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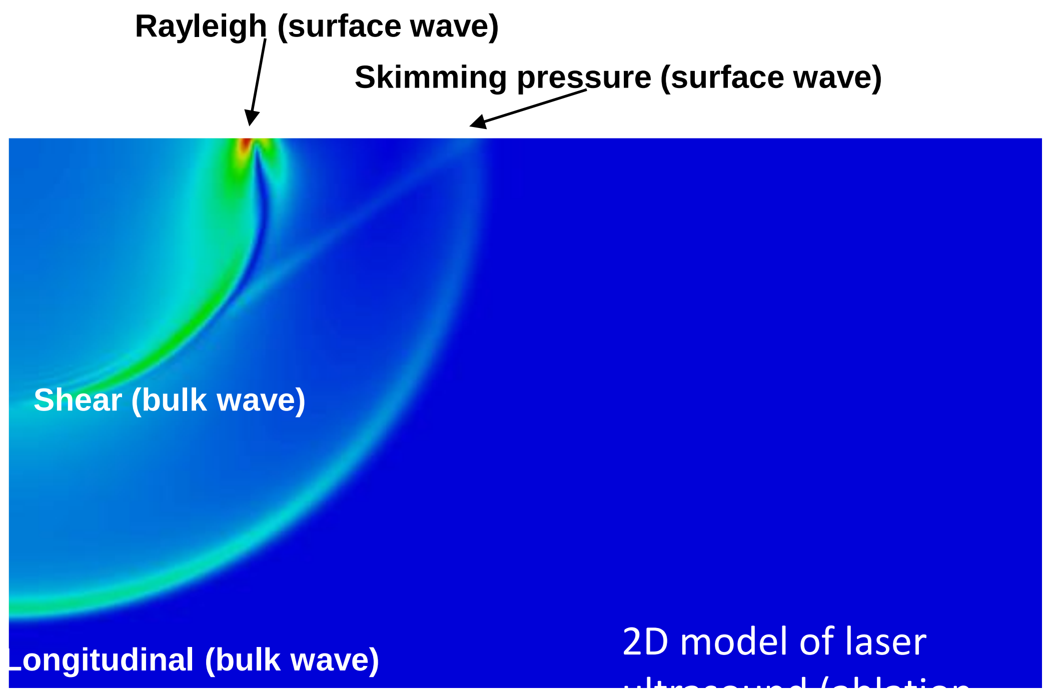
Introduction to Laser Ultrasound

- **Non-contact, non-invasive** (no water or gel required), high temperature capable
- Coverage of both surface and bulk
- Suitable for complex geometries (200 µm laser spot diameter)
- Can handle irregular surfaces (max. angle to normal 40 deg)
- More information can be extracted simultaneously (wide bandwidth)
- Sharper imaging compared to contact UT(no ringing)
- Less energy than phased array (PA) contact UT



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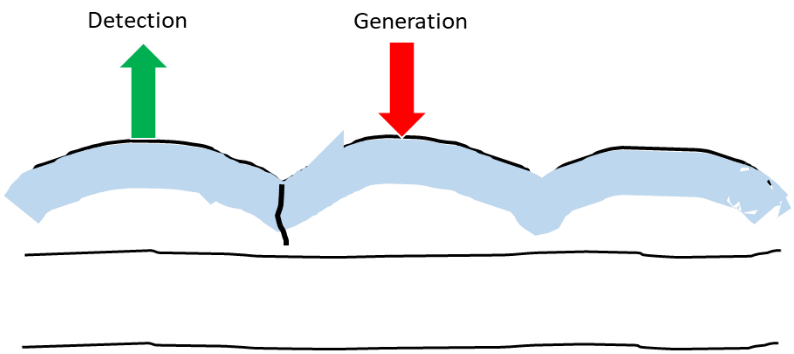
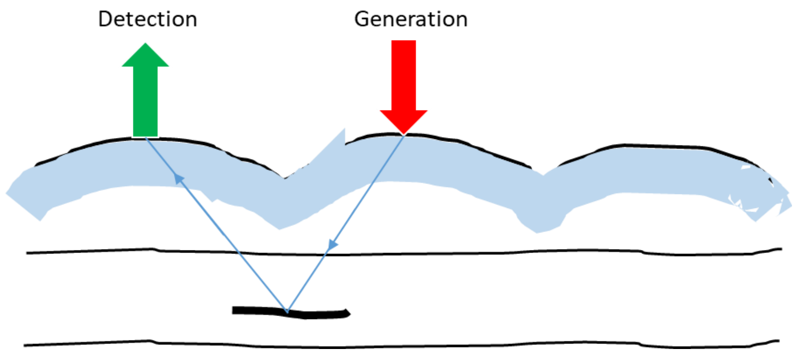
LUT interaction with DED defects



1. **Defect between cladding beads**

The Rayleigh wave travels around the defect, and thus this causes a delay in the arrival time, decrease in amplitude or in some cases may be totally blocked.



1. **Defect in the cladding layer or between the layers**

Bulk waves (shear and longitudinal) can be reflected or diffracted from the defect and then detected by the detection laser.
The distance travelled is longer than Rayleigh waves, therefore they will arrive later in time.

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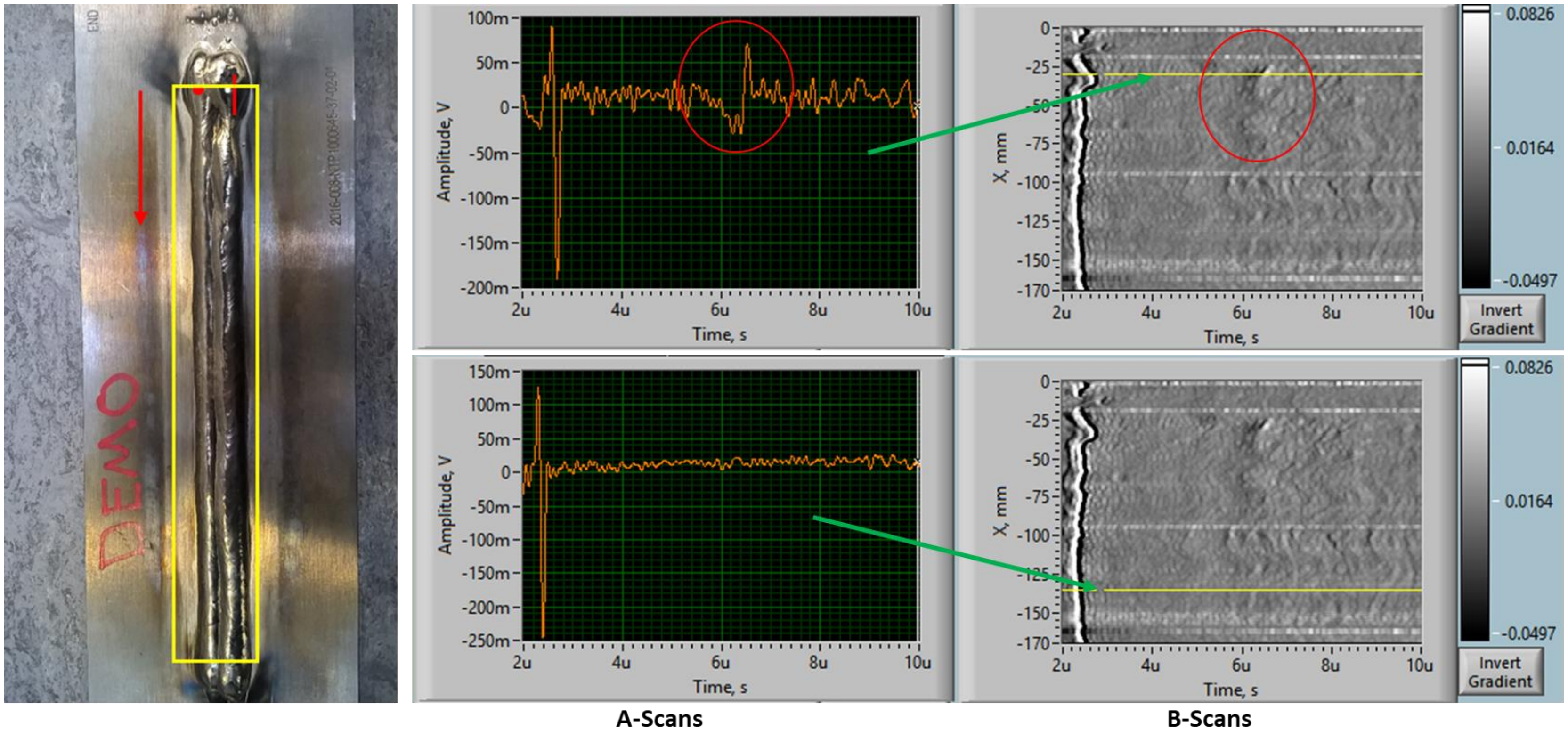
Laser Ultrasound on a DED AM Titanium sample with LOF defects



Courtesy of AMAZE EU project

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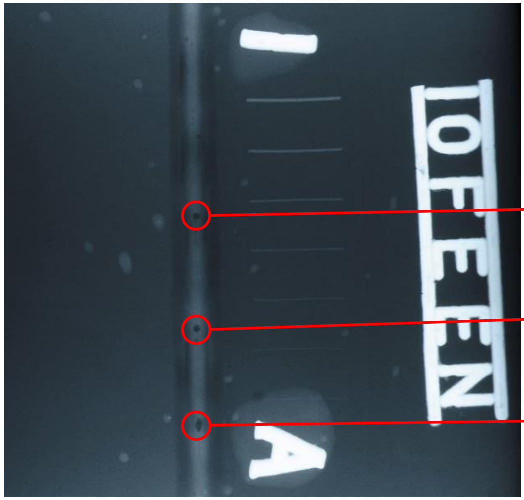
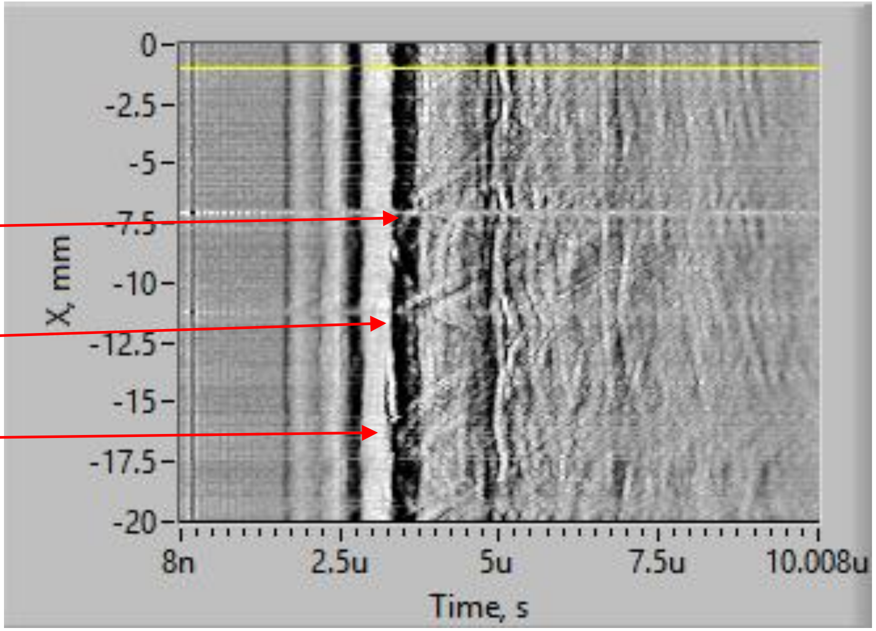
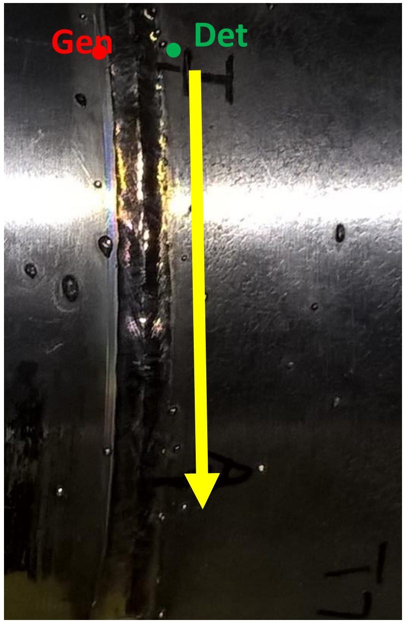
- Three distinct pores visible in the X-ray image and the corresponding parabolic indications on the LUT B-scan.



X-ray showing three distinct internal pores (~400 µm)



LUT B-Scan with corresponding indications of porosity defects



Weld sample with marks showing the scanned area

Courtesy of OLIVER IUK project

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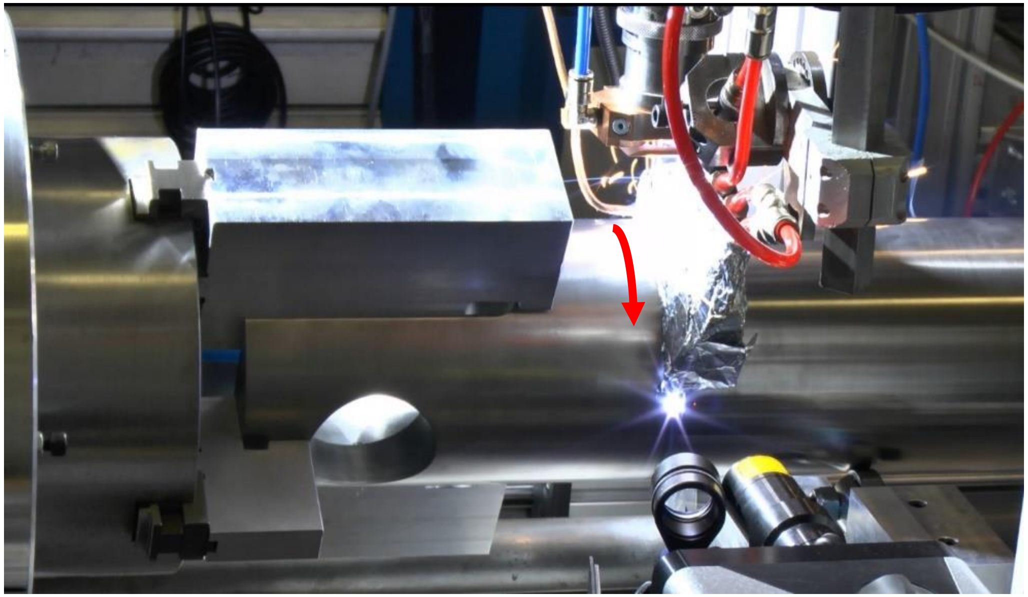
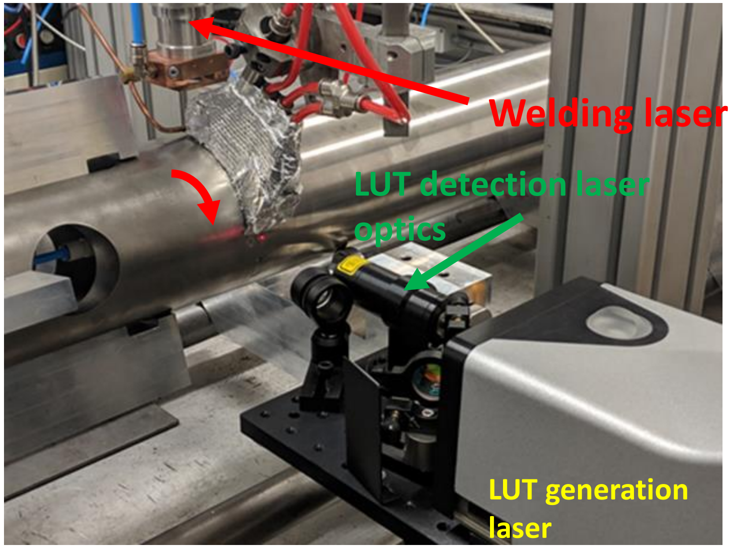
In-process NDT: LUT on laser welding **AT PROCESS SPEED**



- Video capture of the in-process inspection of the welding part
- Bright spot is plasma generated by the generation laser on contact with the surface of the part



- Mounting of generation and detection lasers
- The red spot is the guide laser (shows the point at which the detection laser hits the part)
- Rotation of the part was towards the inspection lasers from the welding laser

Courtesy of OLIVER IUK project

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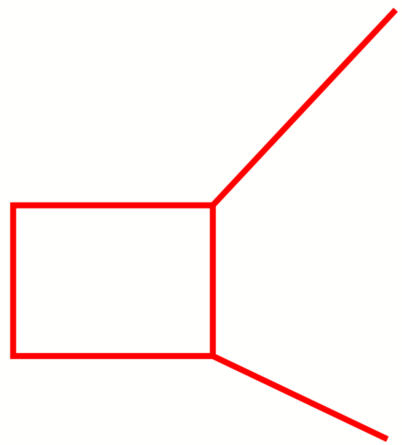
LU inspection at process speed

Thermal image



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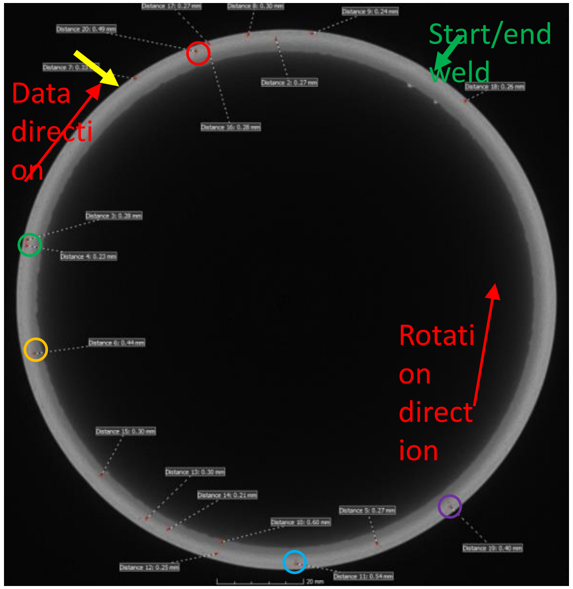
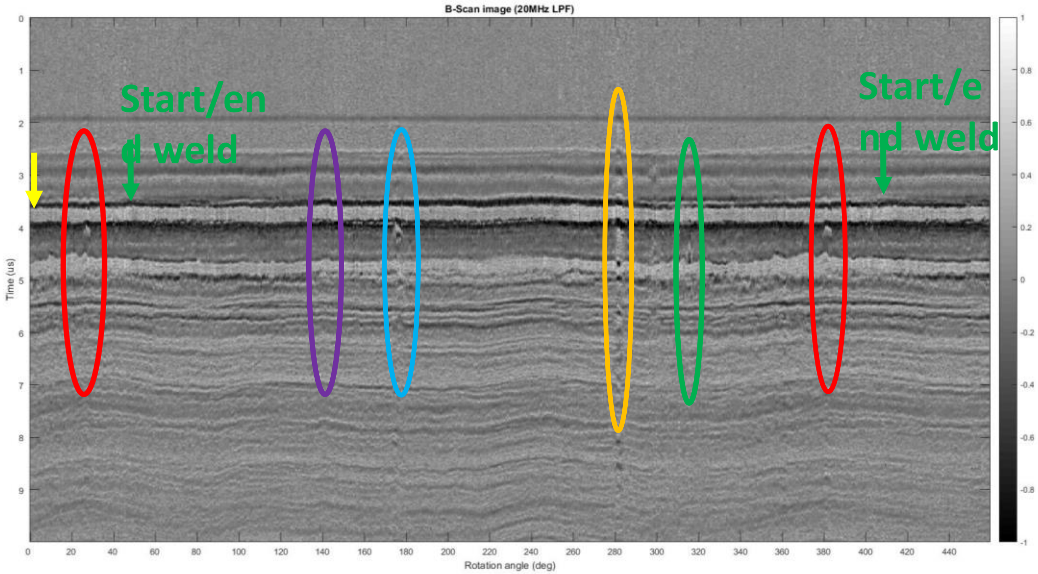
In-process NDT: LUT on laser welding <u>**AT PROCESS SPEED**</u>





1. XCT slice (left) of TISCIS weld and LUT B-Scan (right), where the more visible indications, correspond to the larger defects (voids), are highlighted: Red: 480 µm, Purple 400 µm, Blue: 540 µm, Amber: 440 µm, Green: 280 µm. A small indication from the Start/End of weld is also detected as a small undercut.
2. Smaller voids detected by XCT (down to 210 µm) were not clearly identified by LUT at this speed but are not required to be detected even in the most stringiest case which corresponds to 0.3t or 0.3 x 5000 µm = 1500 µm.
3. As validated by XCT the largest defects were well bellow the stringiest requirements.

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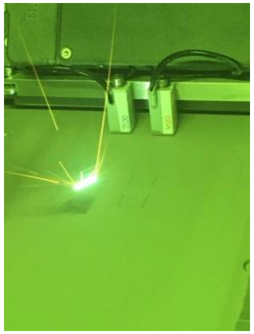
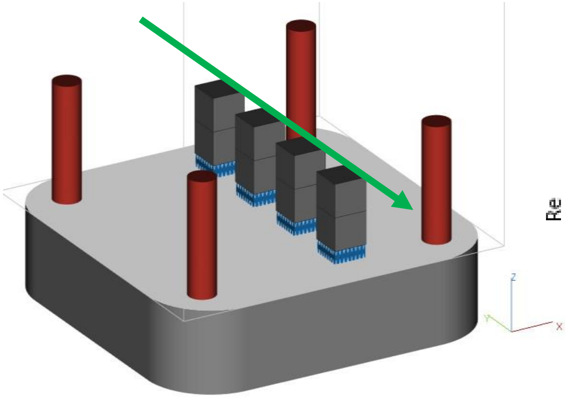
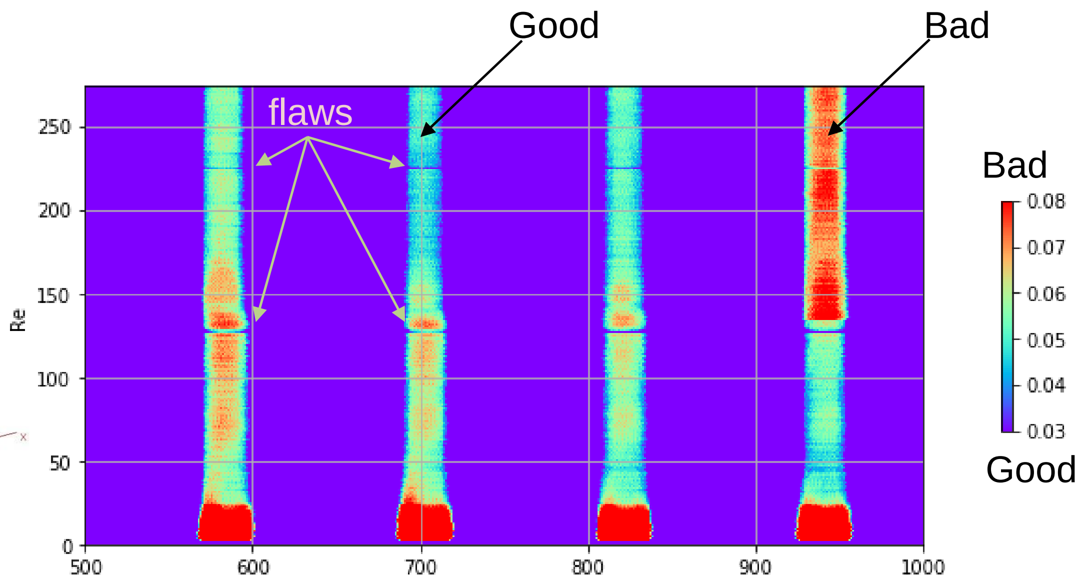
Wireless EC System on L-PBF (potentially could be tried on DED too)







In-situ real time image of the quality of the part

Courtesy M. Spurek et al., ETHZ, inspire, and AMiquam

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Comprehensive NDT Techniques (1/2)

Traditional methods (NDT methods that are widely used in industry include)

- Visual testing (VT);
- Leak testing (LT);
- Penetrant testing (PT);
- Eddy current testing (ET);
- Magnetic particle testing (MT);
- Digital imaging (DI);
- Manual ultra sound testing (MUT);
- Immersion ultrasonic testing (IUT);
- Phased array ultrasound testing (PAUT);
- Film radiographic testing (FR);
- Digital radiographic testing (DR);
- Computed Radiography (CR);
- Acoustic emission (AE).

1. Who can identify a potential in-process monitoring/inspection method?
2. And which are (indirect/direct)?

Source:
BSI PAS 6011:2020 'Additive manufacturing – Non-destructive testing for use in directed energy deposition – Guide'

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Comprehensive NDT Techniques (2/2)

Traditional methods (NDT methods that are widely used in industry include)

- Visual testing (VT);
- Leak testing (LT);
- Penetrant testing (PT);
- Eddy current testing (ET); **Direct**
- Magnetic particle testing (MT);
- Digital imaging (DI);
- Manual ultra sound testing (MUT);
- Immersion ultrasonic testing (IUT);
- Phased array ultrasound testing (PAUT);
- Film radiographic testing (FR);
- Digital radiographic testing (DR);
- Computed Radiography (CR);
- Acoustic emission (AE). **Indirect**

1. Who can identify a potential in-process monitoring/inspection method?

2. And which are (indirect/direct)?

Source:
BSI PAS 6011:2020 'Additive manufacturing – Non-destructive testing for use in directed energy deposition – Guide'

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Standardisation

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DED Related Standards

DED

- BSI PAS 6011-2020 'Non-destructive testing (NDT) for use in directed energy deposition (**DED**) additive manufacturing processes – Guide' (**Led by BSI, proposed/contributed by B. Dutton**) **Published**

Includes DED

- ISO TC261/ASTM F42 JG59 DTR 52905, 'Additive Manufacturing — Non-Destructive Testing and Evaluation — Standard Guideline for Defect Detection in Metallic Parts' (**Led by B. Dutton**) **Balloting**

Only PBF

- ASTM E3166 (E07 WK47031), 'New Guide for Nondestructive Testing of Metal Additively Manufactured Metal Aerospace Parts After Build' (**Led by Jess Waller and contributed by B. Dutton**) **Published**

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Thank you & Questions ?

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