Manufacturing Technology Centre

TECHNOLOGY LANDSCAPE FOR IN-PROCESS NDT FOR AM

Dr Ben Dutton (MTC)
Dr Mohd H. Rosli (MTC)
Sarah Everton (MTC, University of Nottingham)

Quality Control for AM Conference, 24-01-2017

mtc
Manufacturing
Technology Centre

HOLISTIC APPROACH TO AM QUALITY

Monitoring of inputs to process
Powder quality control, environment, etc.

In-situ monitoring of key build parameters
Laser energy, scan speed, temperature, melt pool, etc.
In-situ inspection of build area/layer
Surface of finished layer, bond with previous layer, porosity below layer, etc.

Post-build inspection

Post-build processing
Annealing, shot-peening, HIP, machining, etc.

Post-processing inspection

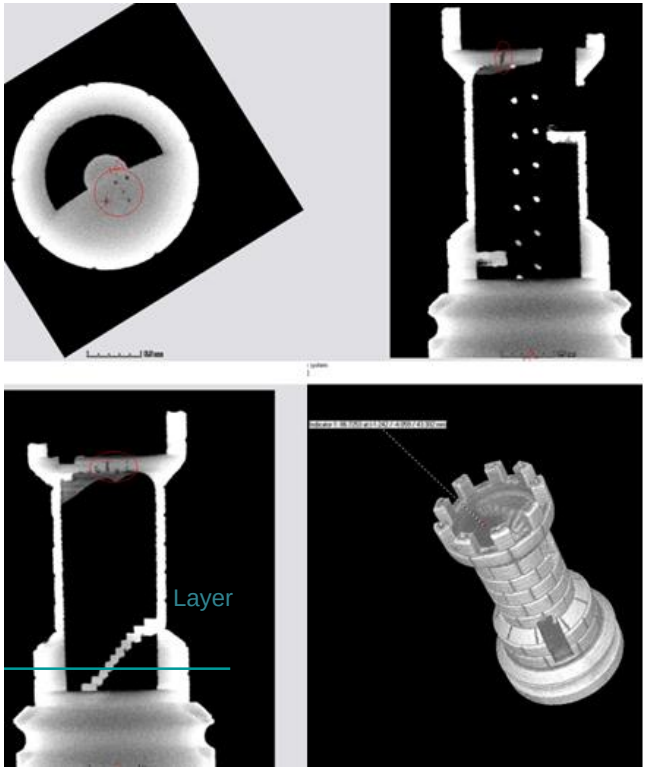
INTEGRITY OF METAL PARTS PRODUCED BY AM

Current State:

- Typically rely on post-build inspection;
- Commercial machines have limited in-situ monitoring.

Expected Progression:

- Integration of in-situ inspection within AM processes would enable immediate fault detection and the potential to initiate corrective action.



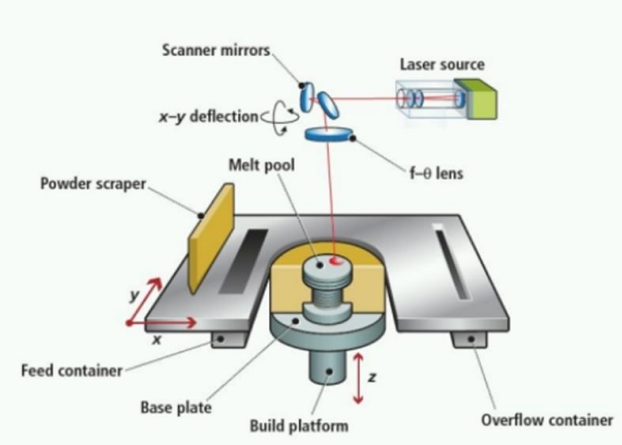
AM PROCESS

Process classification	Term used	Commercial name	Machine manufacturer
Powder bed fusion (PBF)	Laser-powder bed fusion (laser-PBF)	Direct metal laser sintering (DMLS)	EOS
		LaserCUSING	Concept Laser
		Laser melting (LM)	Renishaw
		Laser melting (LM)	Realizer
		Laser melting (LM)	Phenix
		Laser melting (LM)	Matsuura
		Selective Laser melting (SLM)	SLM Solutions
	Electron beam-powder bed fusion (electron beam-PBF)	Electron beam melting (EBM)	ARCAM
Directed energy deposition (DED)	Powder feed-directed energy deposition (powder-DED)	Direct metal deposition (DMD)	POM
		Laser engineer net shaping (LENS)	Optomec
		Laser consolidation	Accufusion
		Laser deposition	Irepa Laser
		Laser deposition	Trumpf
		Laser deposition	Huffman
	Wire feed-directed energy deposition (wire-DED)	Electron beam direct melting (EBDM)	Sciaky
		Shape metal deposition (SMD)	Other

S. K. Everton, et al, 'Review of in-situ process monitoring and in-situ metrology for additive manufacturing', Materials & Design, 2016

PROCESSES' EXAMPLES

- Powder Bed Fusion (showing laser melting)

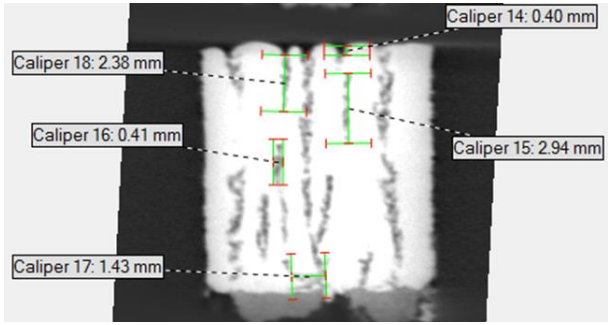


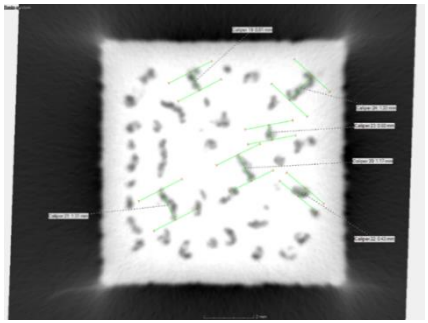
http://www.popular3dprinters.com/selective-laser-melting-slm/

- Direct Energy Deposition (showing blown powder)

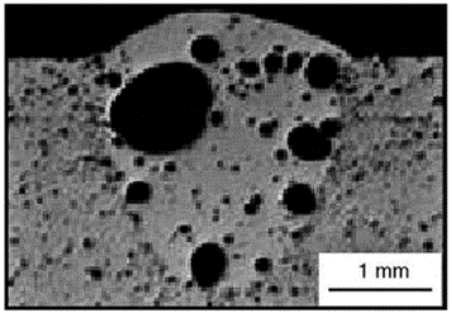
S. Stannard, 'Cladding and Additive Manufacturing Using Laser Applied Power Processes', AWS New Welding Technologies, 2010.

TYPICAL POWDER BED FUSION (PBF) DEFECTS

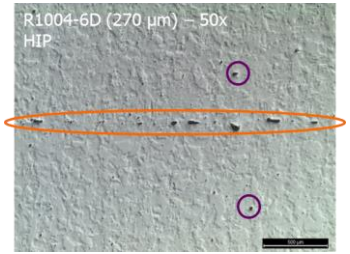




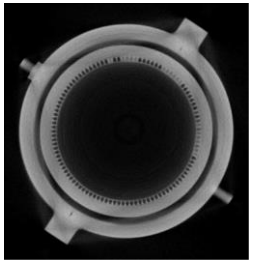
Cross layer



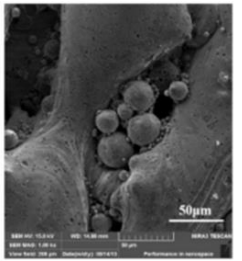
Porosity/void



Layer



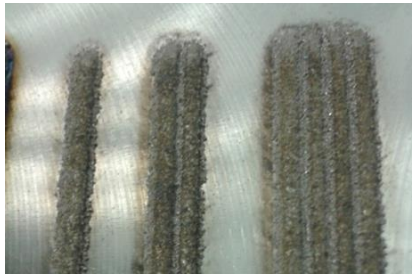
Trapped Powder



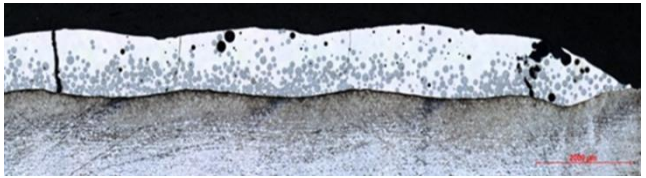
Unconsolidated powder

Other: lack of geometrical accuracy/steps in the part, reduced mechanical properties, inclusions and cracks. **B. Dutton, et at, 'NDT Standards for Additive Manufacture - a Review of Progress', WCNDT 2016**

TYPICAL DIRECT ENERGY DEPOSITION (DED) DEFECTS



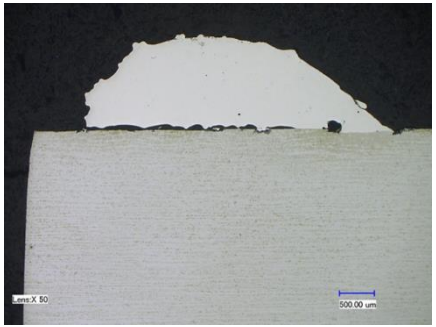
Poor surface finish



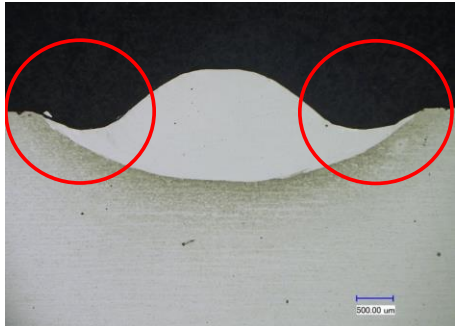
Porosity

Hole or void

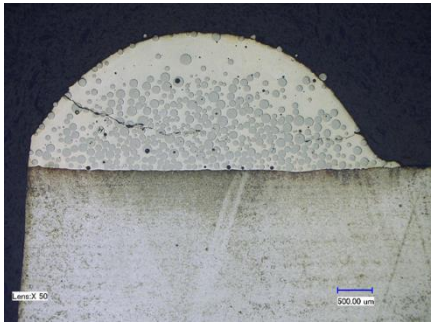
B. Dutton, et at, 'NDT Standards for Additive Manufacture - a Review of Progress', WCNDT 2016



Incomplete fusion



Undercuts at the toe of the welds between adjoining weld beads



Cracking

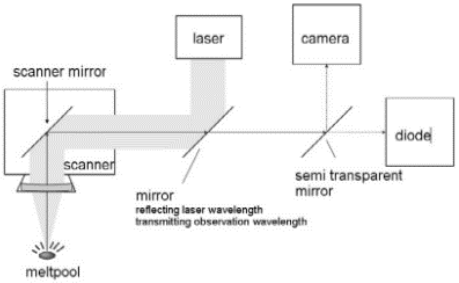
Other: lack of geometrical accuracy/steps in the part, non-uniform weld bead and inclusions.

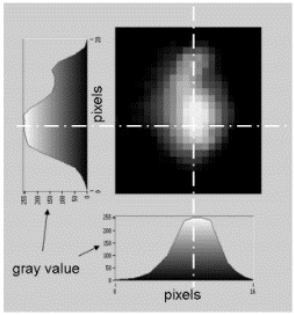
CURRENT IN-SITU DEVELOPMENTS

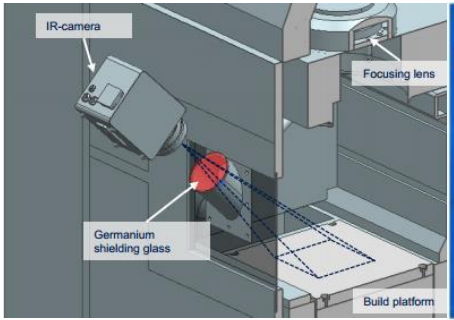
AM Process	Machine manufacturer	'Module' name	Failure mode monitored	Parameter altered	Equipment
PBF - EB	Arcam	LayerQam™ xQam™	Whole layer porosity Auto-calibrate the electron beam	N/a Electron beam	NIR **camera** X-ray detector
PBF-L	B6 Sigma, Inc. (specialist)	**PrintRite3D®** **INSPECT™**	Unknown	N/a	Thermocouple, high-speed **camera** & ?
	Concept Laser	QM melt pool	Melt pool monitoring	Laser Power	High-speed **CMOS-camera**
	EOS (working with MTU)	Optical tomography	Whole layer porosity	N/a	CMOS **camera**
DED	DEMCON	LCC 100	Melt pool monitoring	Laser Power	**Camera**
	DM3D Technology	DMD **closed-loop** feedback system	Melt pool monitoring and build height	Laser Power	Dual-colour pyrometer and three high-speed CCD **cameras**
	Laser Depth	LD-600	Depth measurement	Laser Power	In-line coherent imaging
	Promotec	PD 2000	Melt pool monitoring	N/a	**CMOS-camera**
		PM 7000	Melt pool monitoring	N/a	1D photo detector
	Stratonics	ThermaViz system	Melt pool temperature	Laser Power	Two-wavelength imaging **pyrometer**

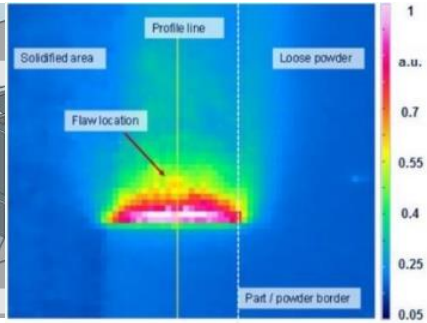
S. K. Everton, et al, 'Review of in-situ process monitoring and in-situ metrology for additive manufacturing', Materials & Design, 2016

IN-PROCESS MONITORING EXAMPLES FOR **LASER PBF** (1)









Coaxial **melt pool** monitoring w/high speed camera + photodiode

- Aims to reduce occurrence of over-melted zones and resulting spherical pores
- Resolution 10 µm per pixel
- Data acquisition rate manageable (636 MB s^{-1})
- Closed-loop feedback could be added to reduce occurrence of over-melted zones and resulting spherical pores
- Patented and exclusively licenced by **Concept Laser (GE)**

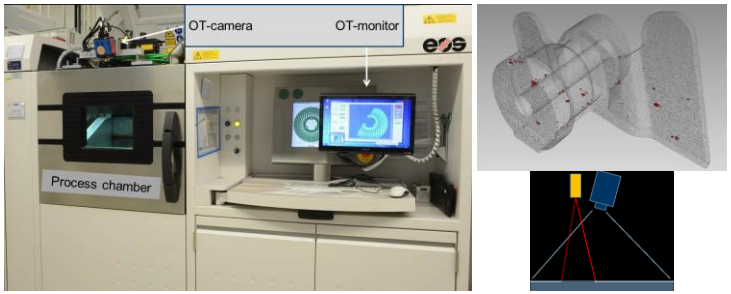
S. Berumen, et al., 'Quality control of laser- and powder bed-based Additive Manufacturing (AM) technologies', Physics Procedia, 2010.

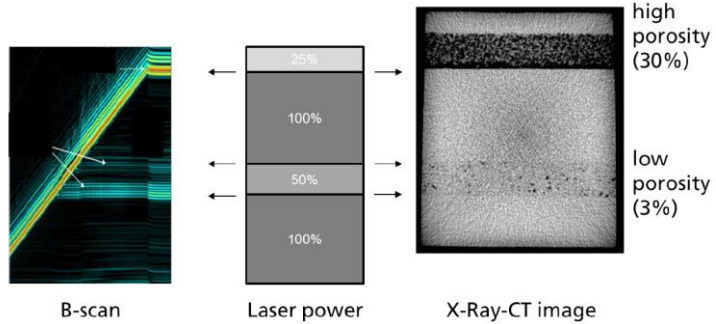
Non-coaxial whole layer monitoring IR camera

- Aims to identify any deviations during the build which could result in pores or voids
- Mounted externally
- Surface temperature profiles can be used to alter build settings for the following layer
- For the laser system, artificially seeded voids with 100 µm diameter could be detected
- Trade off: field of view vs. resolution

H. Krauss, at al., 'Thermography for monitoring the selective laser melting process'. 23rd International Solid Freeform Fabrication Symposium. 2012.

IN-PROCESS MONITORING EXAMPLES FOR **LASER PBF** (2)





NIR Tomography MTU on EOS

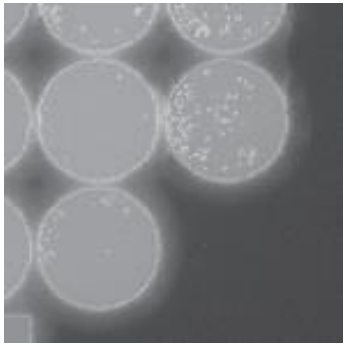
- Aim is to observe anomalies in powder bed surface due to porosity or cracks
- Mounted externally
- Complete platform view
- 3D image reconstructed
- NIR region
- 900 – 940 nm filter
- 100 x 100 µm resolution

MTU contact UT

- Aim is to observe anomalies in powder bed due to porosity
- **Mounted under the build**
- Correlation of ultrasonic signals with porosity
- Limited to simple geometries such as reference parts/features during a build
- 40 µm resolution
- Future work on 2D arrays to generate 3D images

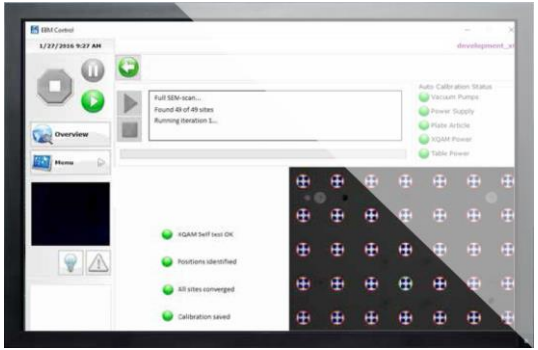
H. Rieder, et al., 'On- and Offline Ultrasonic Inspection of Additively Manufactured Components', WCNDT 2016

IN-PROCESS MONITORING EXAMPLES FOR **ELECTRON BEAM PBF**



NIR camera

- Aim is to identify and monitor porosity across the bed created during build
- Arcam LayerQam™ system - integrated within Arcam Q20 machine
- Integrated camera-based monitoring
- Capable of resolving defects approx. 100 µm over full build area
- Image taken before and after each build layer
- 3D model can be built from images

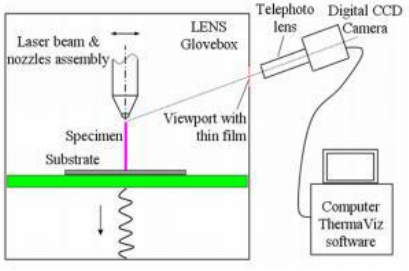


X-ray detector

- Aim is to auto-calibrate the electron beam
- Arcam xQam™ system - integrated within Arcam Q20 machine
- Integrated X-ray detector
- **Automated process**, operator independent

http://www.arcam.com/wp-content/uploads/justaddbrochure-web.pdf

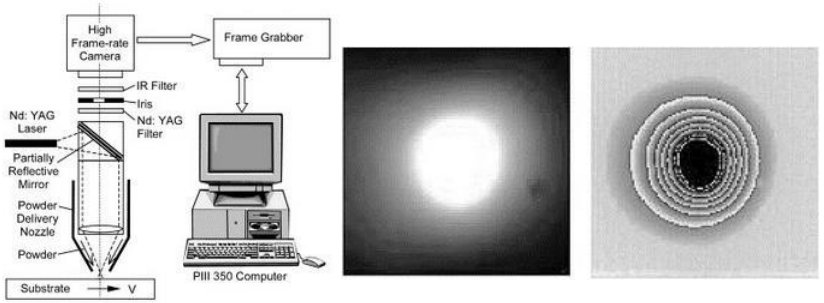
IN-PROCESS MONITORING EXAMPLES FOR **POWDER DED**



CCD camera pyrometry

- Aim is to control bead geometry by correlating melt pool size with layer thickness
- Externally mounted with **closed loop control**
- Demonstrated by several research groups
- Filters needed to minimise noise factors such as the metallic vapor and heated air zone above the molten pool

T. Hua, et al., 'Research on molten pool temperature in the process of laser rapid forming', Journal of Materials Processing Technology, 2008.



IR camera 11

- Aim is to assess temperature distribution across the melt pool to maintain uniformity and improve build accuracy
- Mounted co-axially
- 128 x 128 pixel resolution of melt pool area
- Filter needed to protect camera from processing laser
- Automated image processing and control

D. Hu, et al., 'Sensing, modeling and control for laser-based additive manufacturing', International Journal of Machine Tools and Manufacture, 2003.

SUMARY OF CURRENT IN-PROCESS METHODS

- Mostly visual and IR camera in-process methods have been developed for AM
  - Generally limited to surface inspection (in-situ);
  - Alternative methods for subsurface inspection have been trialled on AM components (ex-situ);
  - Mainly developed to aid understand process.

- Closed-loop inspection
  - Limited examples of real-time, closed-loop inspection (control the bead/melt pool size and electron beam energy).

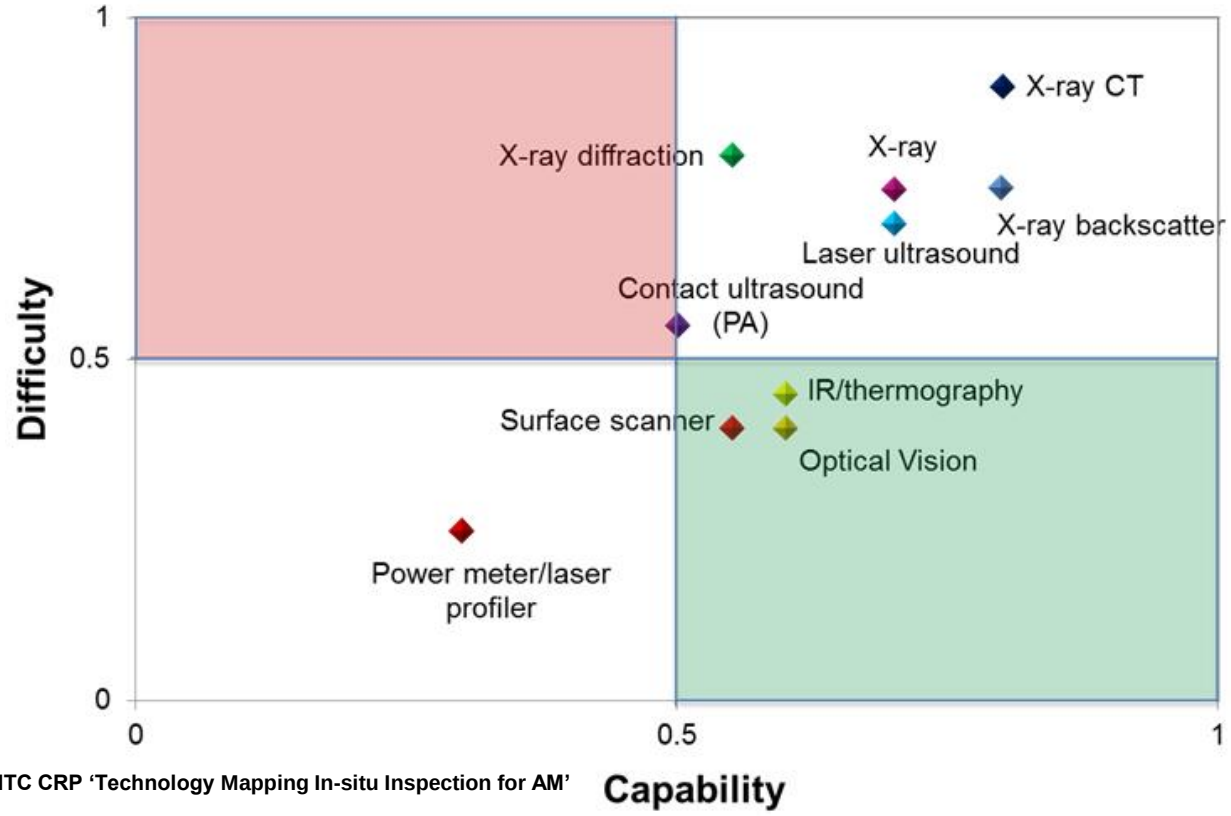
EMERGING METHODS FOR MICROSTRUCTURE AND SUBSURFACE DISCONTINUITIES DETECTION POTENTIAL

- Laser ultrasonics (LU)
  - Potential for subsurface pore/void detection particularly close to surface;
  - Spatially resolved acoustic microscopy for microstructural analysis;
  - Both trialled on PBF samples.

- X-ray Backscatter (XBT)
  - Potential for surface and close to surface defect detection;
  - Arcam xQam future development is for in-process material characterization tool much like an SEM.

- Neutron diffraction
  - Could be used to determine residual stress.

IN-PROCESS INSPECTION TECHNOLOGY MAP OF CAPABILITY VS INTEGRATION DIFFICULTY



B. Dutton, et al., MTC CRP 'Technology Mapping In-situ Inspection for AM'

MTC's IN-PROCESS INSPECTION PROJECTS

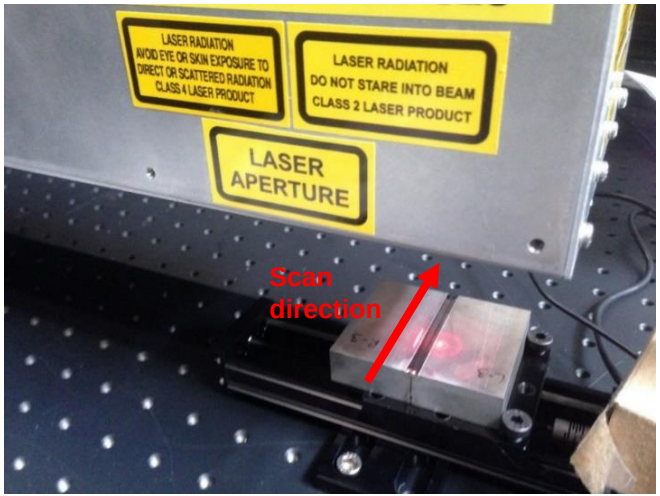
- COMPLETED
  - Technology Mapping In-situ Inspection for AM
  - **NDT of Blow Powder Repair in Additive Layer Manufacture (LU of welds)**
  - Laser Ultrasonic Inspection of a Welded Disc Assembly (LU of welds)

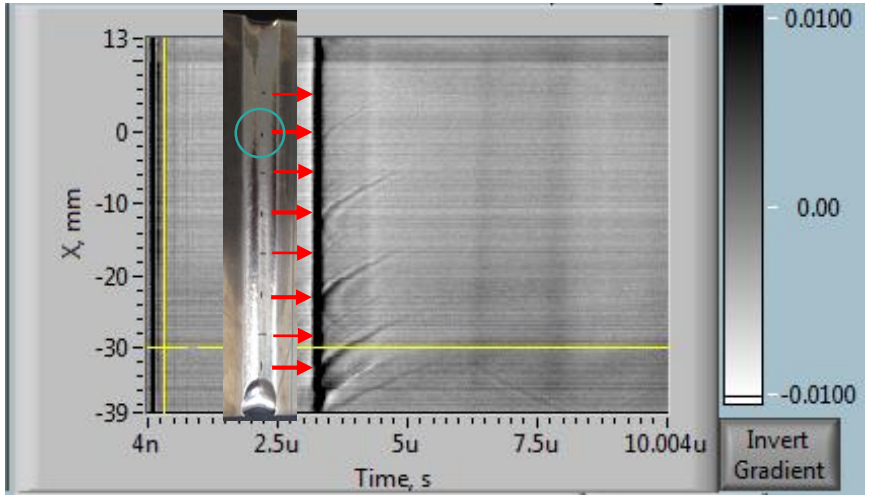
- CURRENT
  - **EU FP7: AMAZE (AM PBF [LM, EBM], DED)**
  - EU H2020: RADICLE (Laser welding)
  - **IUK: AURORA (AM DED)**
  - IUK: OLIVER (Laser welding)
  - **EU H2020: OpenHybrid (AM DED)**

COMPLETED: LASER ULTRASOUND MEASUREMENTS WELDING PROJECT

Exploring In-Process Inspection Capability for Laser Welded Samples

- Inspection of calibration samples with surface defects where images show:
  - Laser ultrasound scan process;
  - Sample with surface as laser welded with calibration notches;
  - B-scan of sample showing surface wave disturbance produced by corresponding notches.



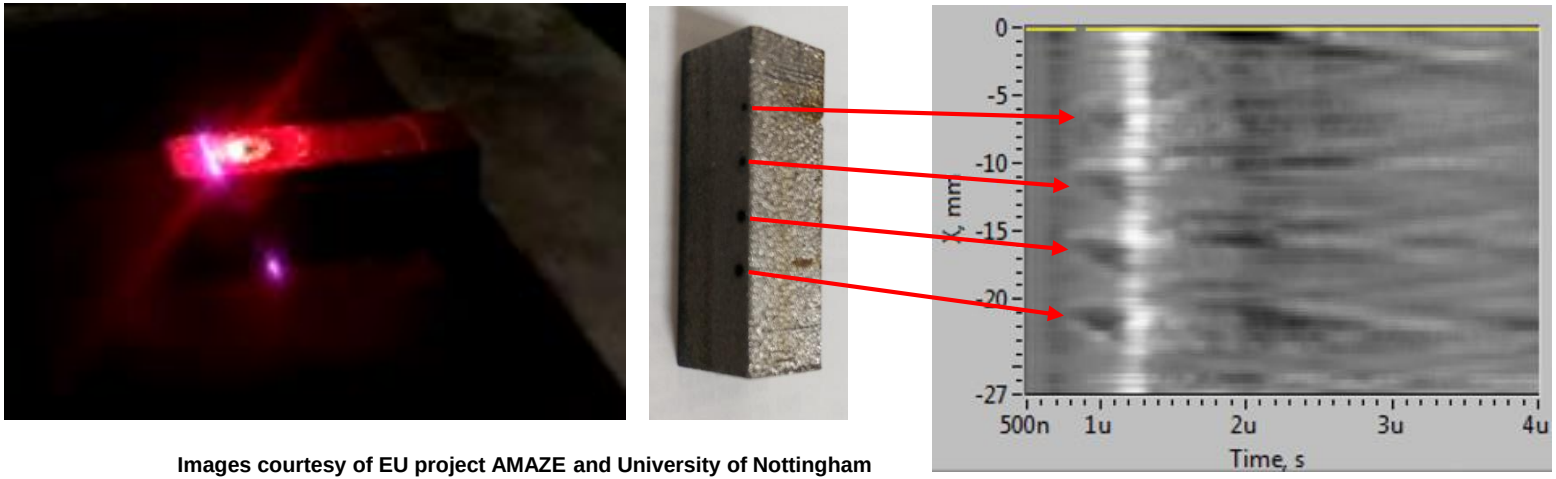


Acknowledgement to John Boswell from Rolls-Royce.

CURRENT: LASER ULTRASOUND MEASUREMENTS ON POWDER BED LASER MELTING (PBLM) SAMPLES

Exploring In-Process Inspection Capability for Additive Layer Manufacturing

- Inspection of calibration samples with subsurface defects where images show:
  - Laser ultrasound scan process;
  - Sample with surface as built by SLM with calibration side drilled holes;
  - B-scan of sample showing surface wave disturbance produced by corresponding drill holes.



Images courtesy of EU project AMAZE and University of Nottingham

CURRENT: IN-PROCESS INSPECTION FOR DED

AURORA – **Au**tomated **R**emanufacturing **o**f **Rai**l Components

- A two year Innovate UK project lead by Lucchini Unipart Rail Limited;
- Flexible remanufacturing cell for rail components;
- Cladding (DED), machining and in-process part inspection.

http://gtr.rcuk.ac.uk/projects?ref=102393

CURRENT: IN-PROCESS INSPECTION FOR DED/HYBRID

OPENHYBRID – Development of a novel hybrid AM approach which will offer unrivalled flexibility, part quality and productivity.

- A three year Horizon 2020 project lead by The MTC;
- Single manufacturing system undertaking a wider range of processes in a seamless automated operation;
- Flexibility in terms of materials, ability to switch between powder and wire feed-stock within a single part;
- Diverse range of platforms to produce parts from 2 cm to 20 m in length.

http://cordis.europa.eu/project/rcn/205504_en.html

Dr Ben Dutton

ben.dutton@the-mtc.org

+44 (0)7753309184

www.the-mtc.org

mtc Manufacturing Technology Centre

CATAPULT High Value Manufacturing