The University of Nottingham

mtc Manufacturing Technology Centre

In-process metrology for AM

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Submission under review

Title: Review of in-situ process monitoring and in-situ metrology for additive manufacturing

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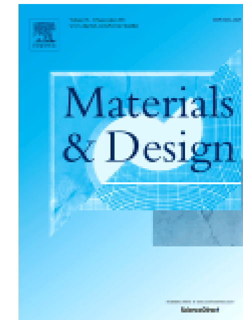


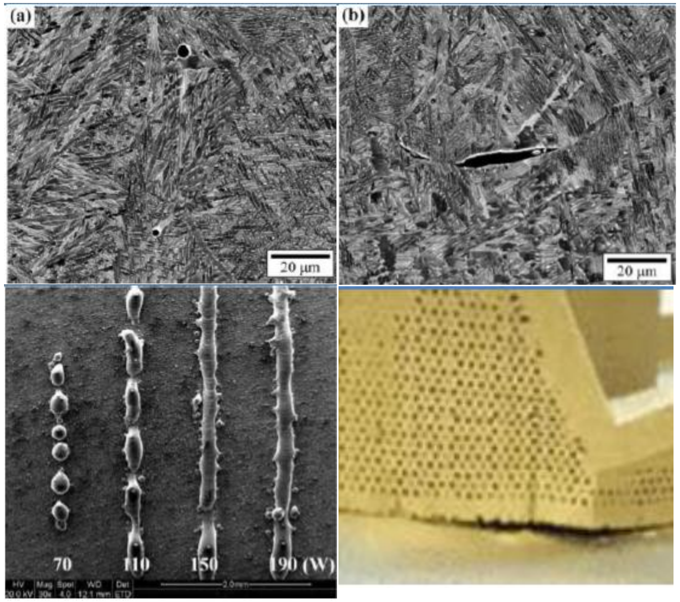
Highlights:

- An overview of the state-of-the-art in the methods for assessing the performance of AM processes is highlighted
- The need for new sensors and monitoring methods for emergent AM processes is introduced
- Typical material discontinuities resulting from well understood processes are explored and the case for in-situ monitoring methods is made
- The industrial opportunity for these advanced methods is explored alongside the new benefits for the metal based AM techniques which will make use of monitoring methodologies

AM material discontinuities

Typical "defects":

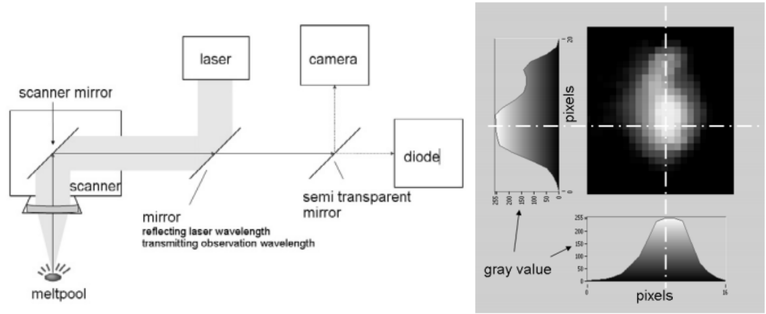
- Spherical pores
  - within layers
  - caused by under or over-melting
- Acicular pores
  - typically found between layers
  - caused by insufficient laser power
- Balling
  - caused by oxidation, insufficient laser power or excess scan speeds
- Cracking
  - caused due to excessive temperature gradients across powder bed and/or incorrect cooling regimes



Laser PBF

High speed camera w/ photodiode[1]

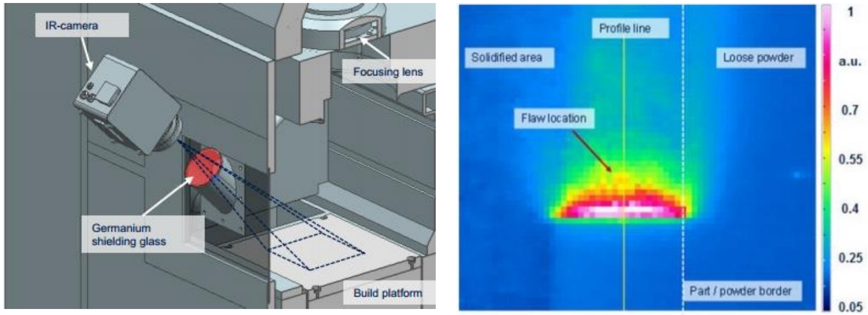
Aim: Reduce occurrence of over-melted zones and resulting spherical pores



- 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[2]

Infrared camera[3]

Aim: Identify any deviations during the build which could result in pores or voids

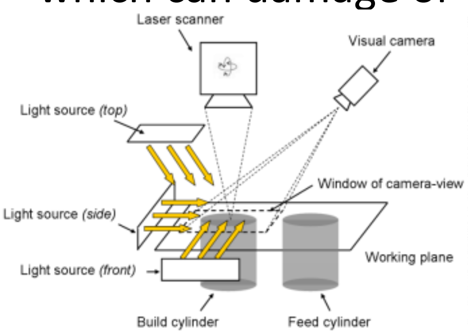


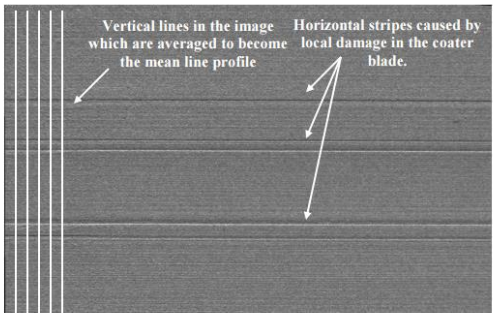
- Mounted externally
- Surface temperature profiles can be used to alter build settings for the following layer
- For the laser system, artificially seeded voids with 100 µm diameter could be detected
- Trade off: field of view vs. resolution

Laser PBF

High speed camera[4]

Aim: Observe anomalies in powder bed caused by "curling up" of deposited material which can damage or wear recoater blade

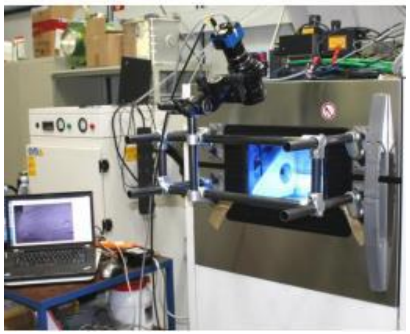


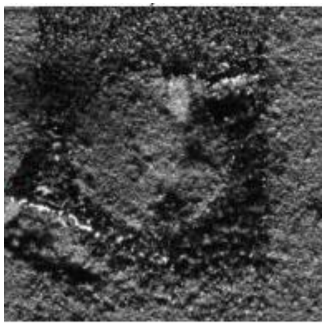


- Mounted internally
- Simple calibration algorithm used to eliminate perspective distortion
- Multiple light sources required to provide illumination

High speed camera[5]

Aim: Observe anomalies in powder bed caused by "curling up" of deposited material which can damage or wear recoater blade



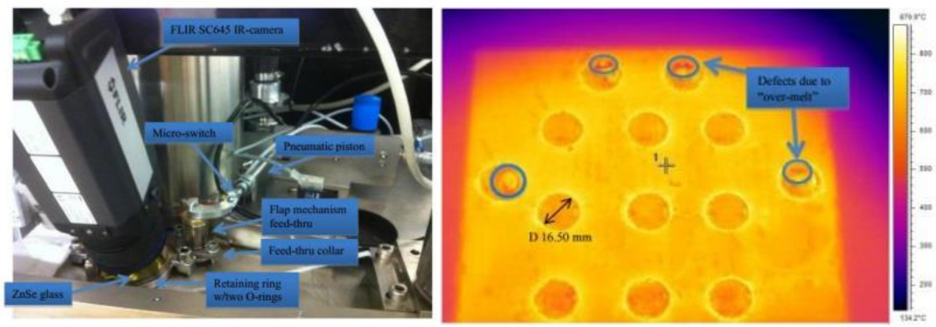


- Mounted externally
- No modification of the operating system required
- Field of view limited to area of small bed
- Perspective distortion corrected using four-point homography

Electron beam PBF

Infrared camera[6]

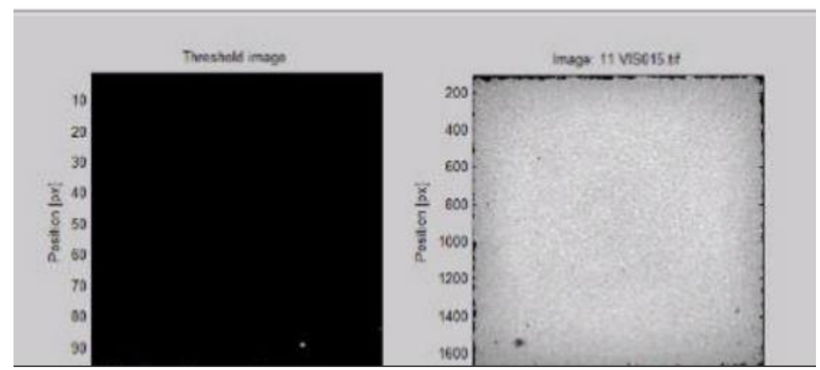
Aim: Identify any deviations in temperature gradient across bed during the build which could result in pores or voids



- Mounted externally
- Surface temperature profiles can be used to alter build settings for the following layer
- A semi-automatic feedback loop was created
- Integration with ARCAM system required to protect from metallisation

Visual camera system[7]

Aim: Identify and monitor porosity created during build

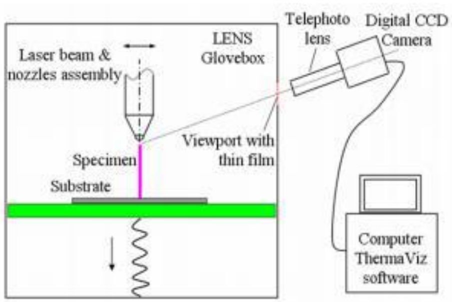


- LayerQam™ system - integrated within Q20 machine
- Camera-based monitoring
- Capable of resolving defects approx. 100 µm over full build area
- Image taken before and after each build layer
- 3D model built from images

Powder DED

Pyrometry[8-10]

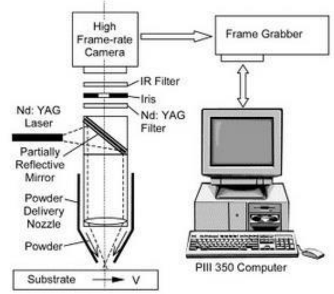
Aim: Control of bead geometry by correlating melt pool size with layer thickness

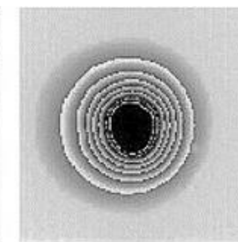


- Externally mounted with closed loop control
- Demonstrated by several research groups
- Filters needed to minimise noise factors such as the metallic vapour and heated air zone above the molten pool
- Laser radiation was found to distort images

Infrared camera[11]

Aim: Assess temperature distribution across the meltpool to maintain uniformity and improve build accuracy



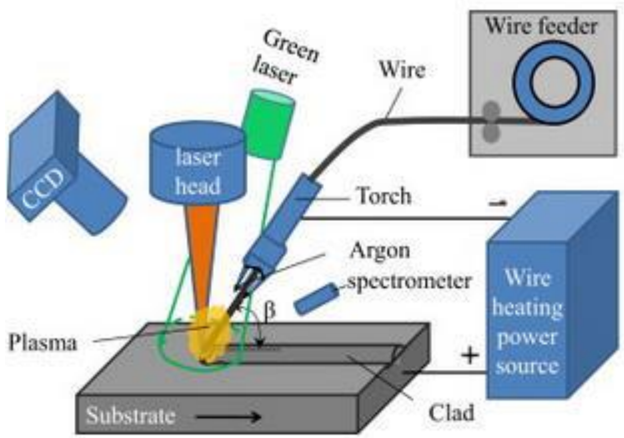


- Mounted co-axially
- 128 x 128 pixel resolution of melt pool area
- Filter needed to protect camera from processing laser
- Automated image processing and control
- Can be used in combination with visual build height control loop

Wire DED

CCD camera with illuminating green laser [12]

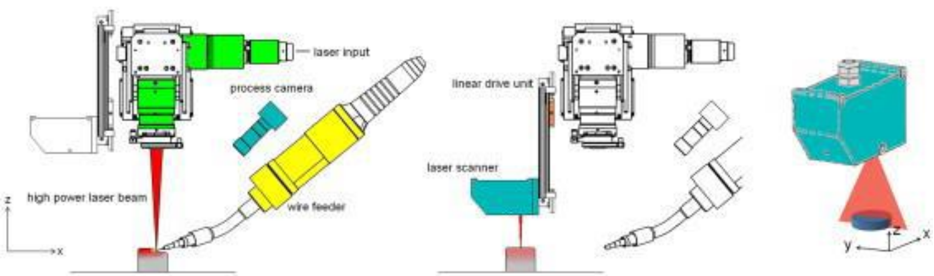
Aim: Image meltpool and detect the emission signal of the plasma plume



- Images correlated with resulting clad quality (surface appearance, clad dilution, hardness, microstructure)
- Optical Emission Spectroscopy used to detect an increase in plasma electron temperature was found to imply an arc or splatter

Laser triangulation [13]

Aim: ensure stable deposition to obtain a flat surface for each deposited layer



- Any deviations in layer heights are detected using laser triangulation and the wire feed rate adjusted for the subsequent layer
- 3D model of intended component required to calculate deviations

Alternative methods

Options for detection of microstructure and sub-surface material discontinuities:

- Acoustic emission testing (AET)[14]
  - crack size and position
  - not currently possible in real-time
  - trialled on powder DED samples
- Laser ultrasonics (LU)
  - suitable for pore/void detection[15,16]
  - spatially resolved acoustic microscopy for microstructural analysis [17,18]
  - both trialled on PBF samples
- Backscatter x-ray (XBT)[19,20]
  - crack detection
  - trialled on powder DED samples
- Neutron diffraction[21]
  - could be used to determine residual strains
  - suggested as an alternative to XCT for wire-DED and laser-PBF in particular
  - limited by availability of portable sources

Summary

- Many visual and thermal in-process inspection methods have been developed for AM processes
  - most are limited to surface inspection
  - alternative methods for subsurface inspection have been trialled on AM components (ex-situ)
  - many developed solely to aid understanding of process
- Closed-loop inspection desirable
  - limited examples of real-time, closed-loop inspection (height control for DED, temperature gradient across laser PBF build area)

- Challenges
  - poor spatial resolution
  - limited fields of view
  - high temporal load
  - large data sets

SOLUTION

Develop more novel methods whilst utilising *a priori* knowledge of both the part and build process, in combination with existing methods, new sensors and simulation

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