Real-Time Process Monitoring Accelerates Process Development and Streamlines Process Control

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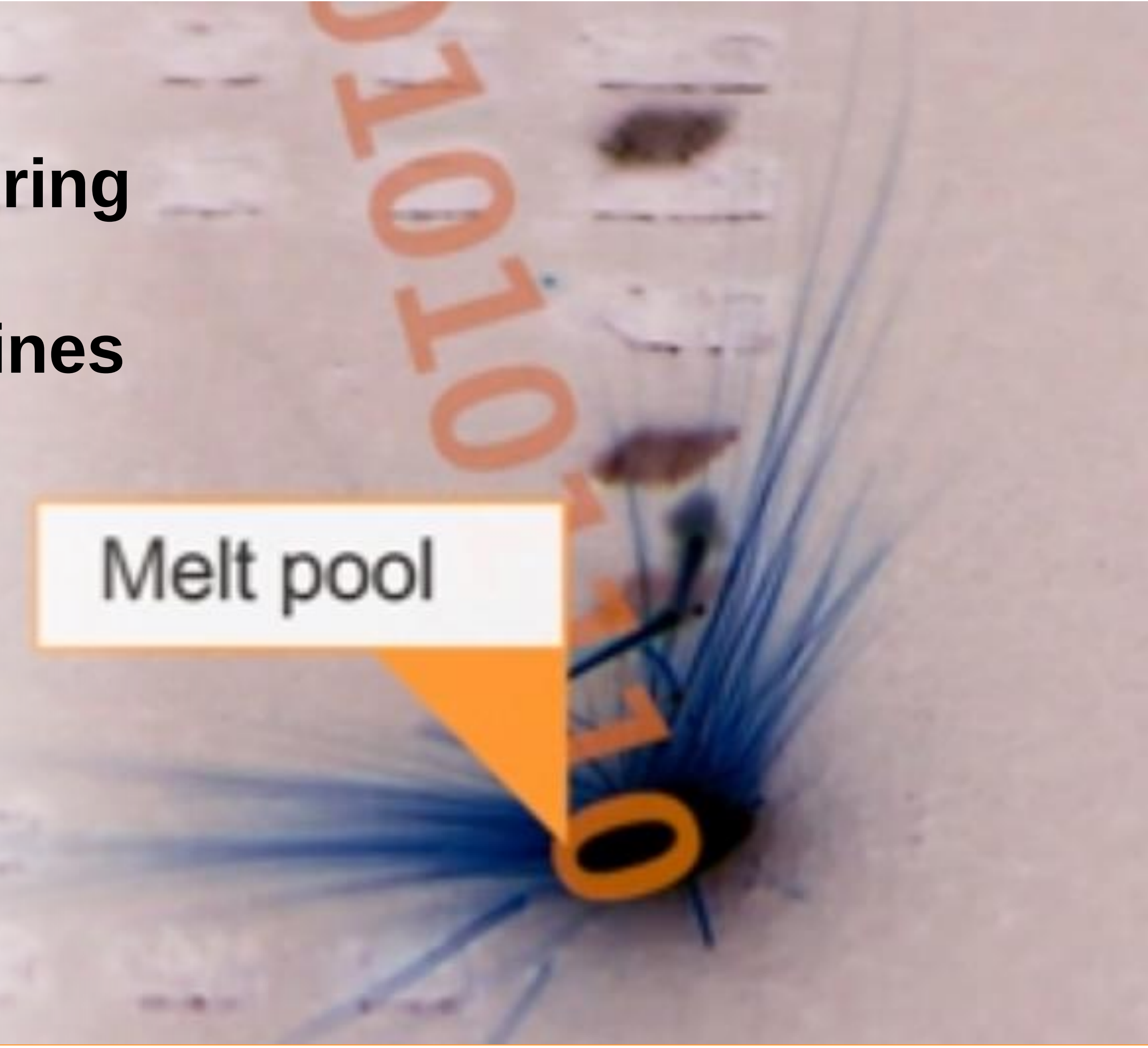
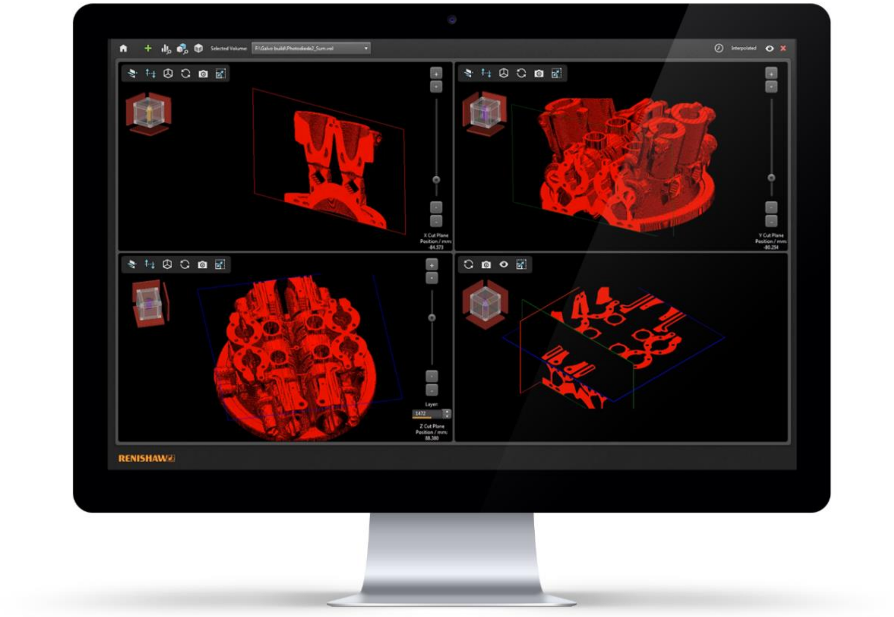


AM process development challenges

Laser powder bed fusion (LPBF) gives us great design freedom

BUT process development and qualification can be challenging

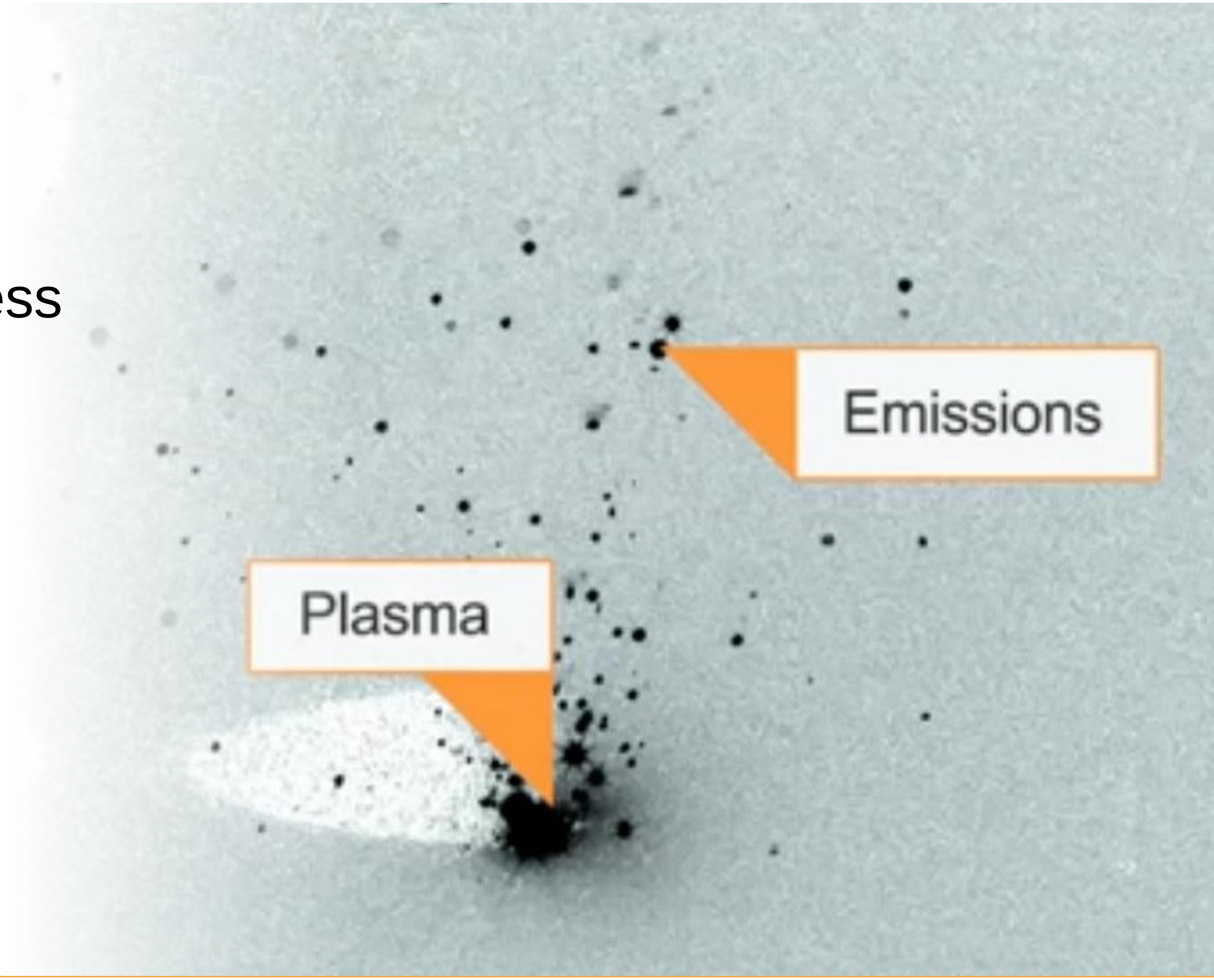
- LPBF works at small scale and high speed
- Process anomalies can produce defects that affect fatigue life
- Iterative cycle of process parameter optimisation, part re-design & testing
- Heavy reliance on post-build testing and costly production process control



New technologies give the opportunity to detect and identify defects through process design, and possibly to repair defects during the build

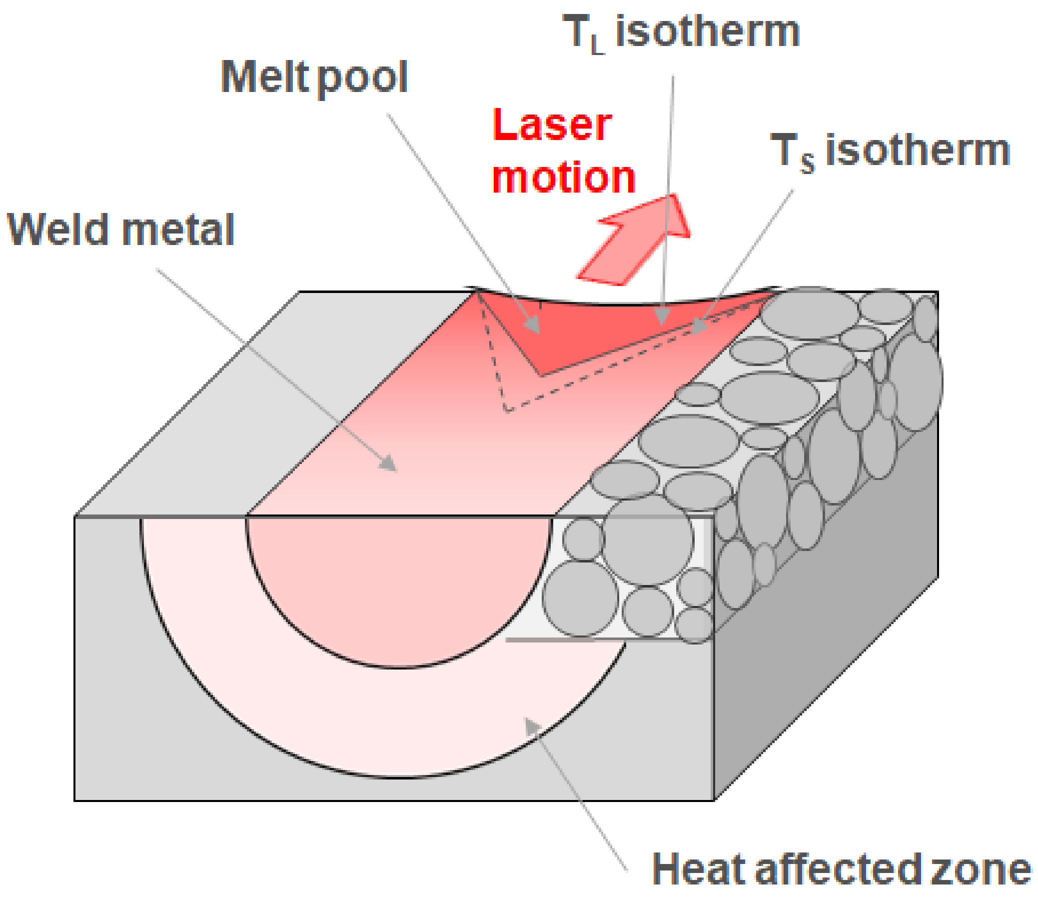
Agenda

- Where do LPBF process anomalies come from?
- What are the consequences of process anomalies?
- Process monitoring sensors
- Process data analysis tools
- Detecting variations in melting conditions
- Process improvement opportunities



LPBF process overview

- Parts built up in layers
- Focused beam creates a melt pool 150-200 microns wide
- Overlaps previous scans and re-melts previous layer
- Ideally want 100% density – no pores or defects
    - Requires consistent melting conditions
    - Several failure modes can produce defects

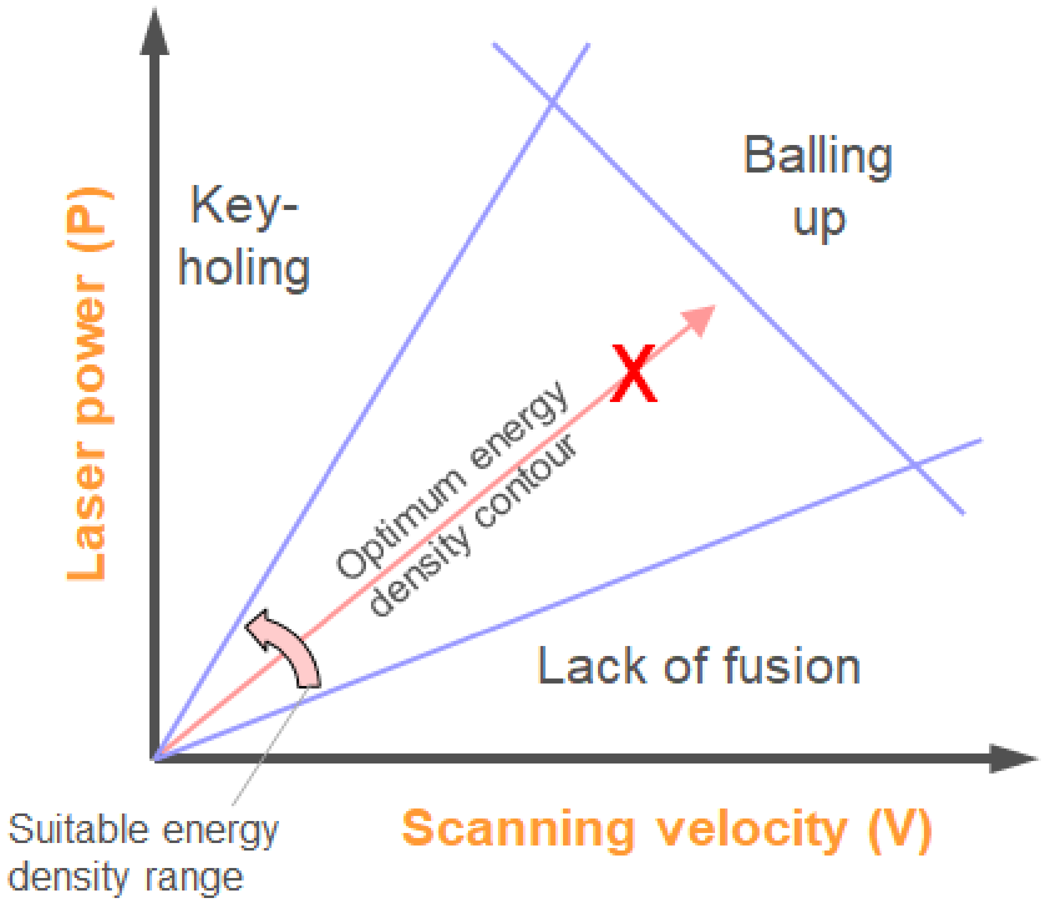


Delivering the correct amount of energy

Process parameters control the amount of energy delivered

- Insufficient power results in **lack of fusion**
- Too much power leads to **keyhole** formation
- Too much power and speed combined leads to break-down of the weld pool – ‘**balling up**’
- **Operating window** where full melting occurs without keyhole formation

X marks the spot where we achieve full density at high build rate

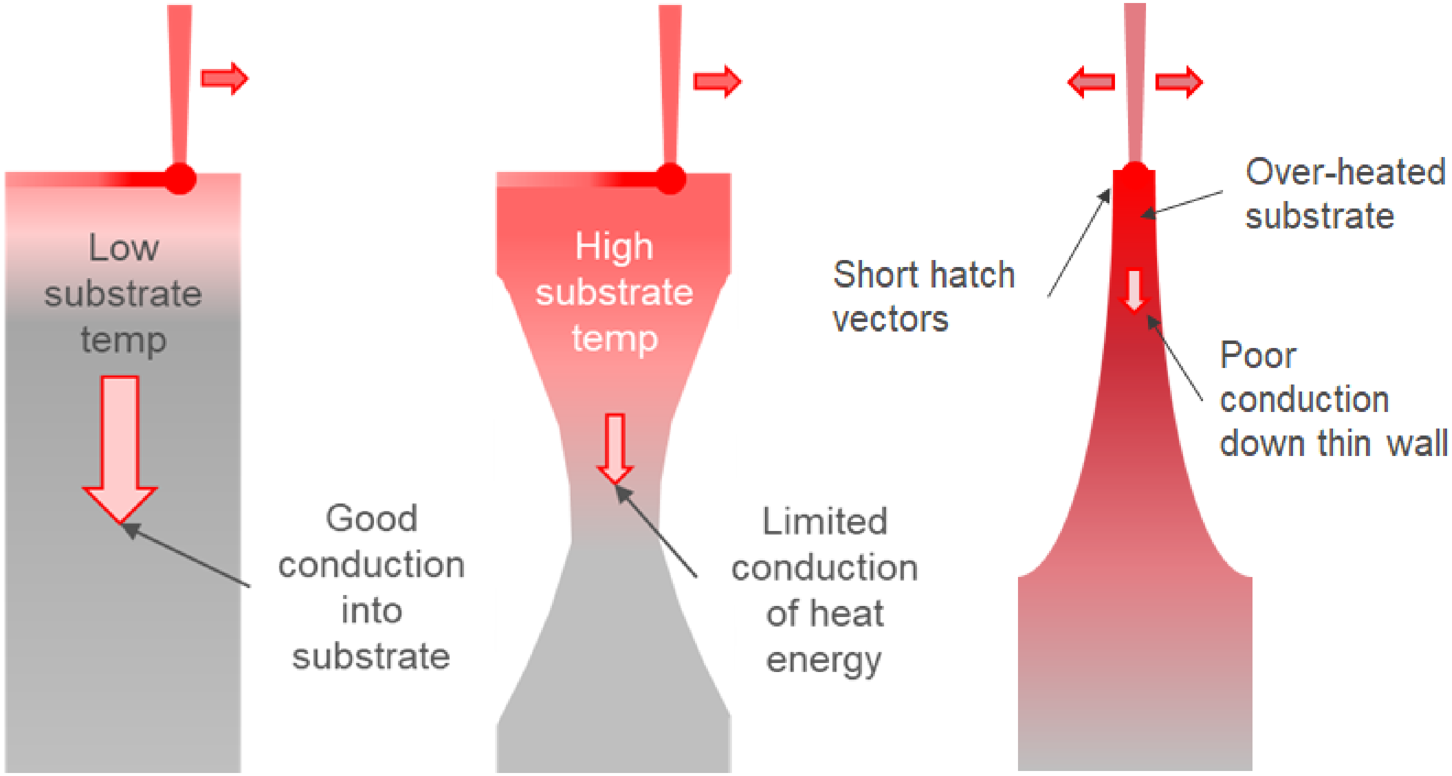


Impact of local part geometry

Substrate temperature affects material response to laser energy

- Heat is dissipated through conduction into substrate
- Geometry of previous layers affects conduction path
- Restrictions to heat flow and thin wall geometries tend to retain heat

Increased risk of key-hole formation is these regions



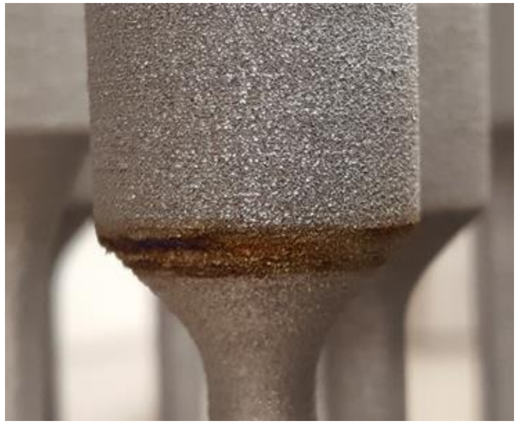
Hotter substrate narrows operating window

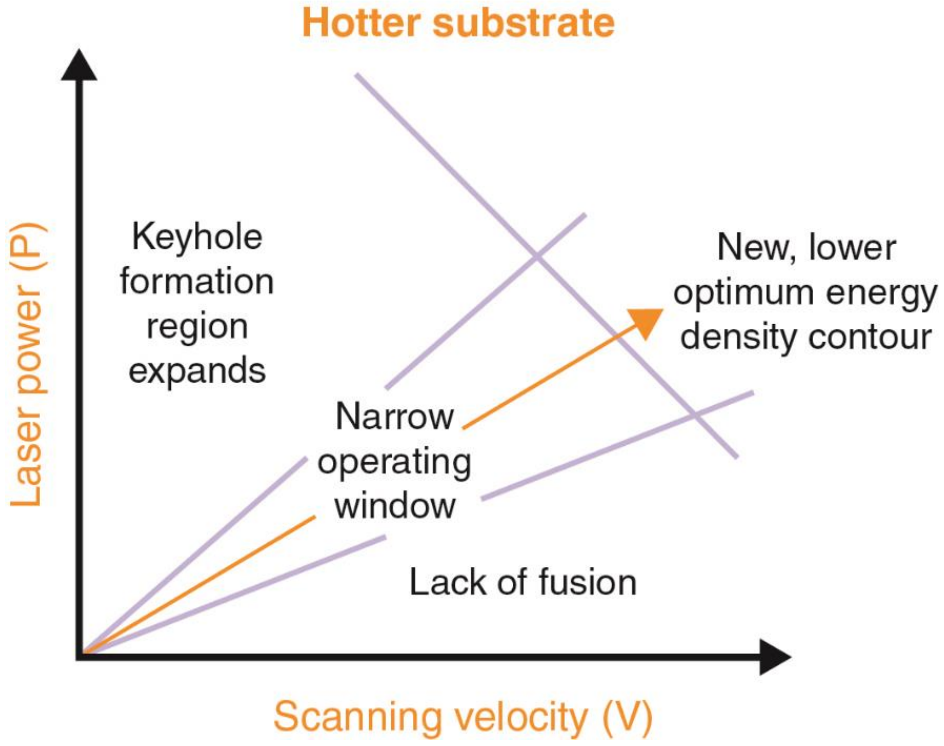
Key-hole region expands when substrate is hot

- Less energy needed to generate a melt pool
- Optimum energy input in these regions is lower

Discoloration of down -skins

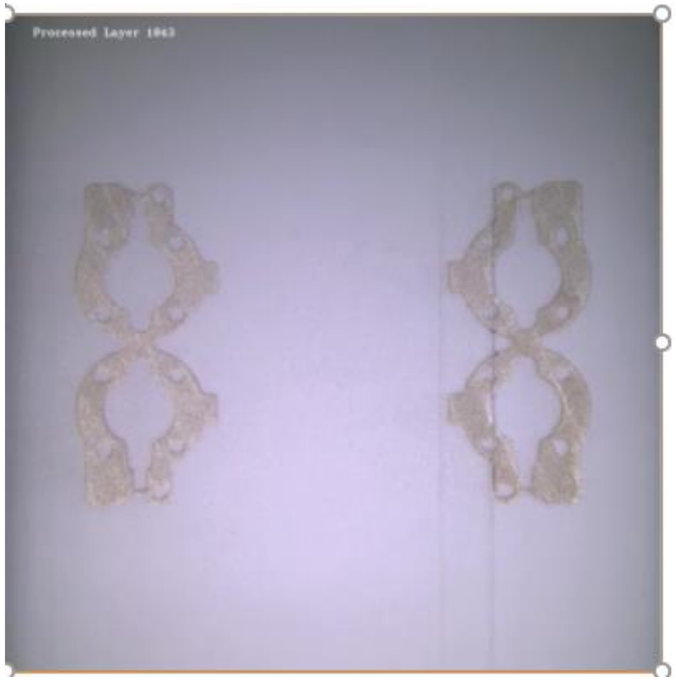
Process parameters must change to avoid over-melting



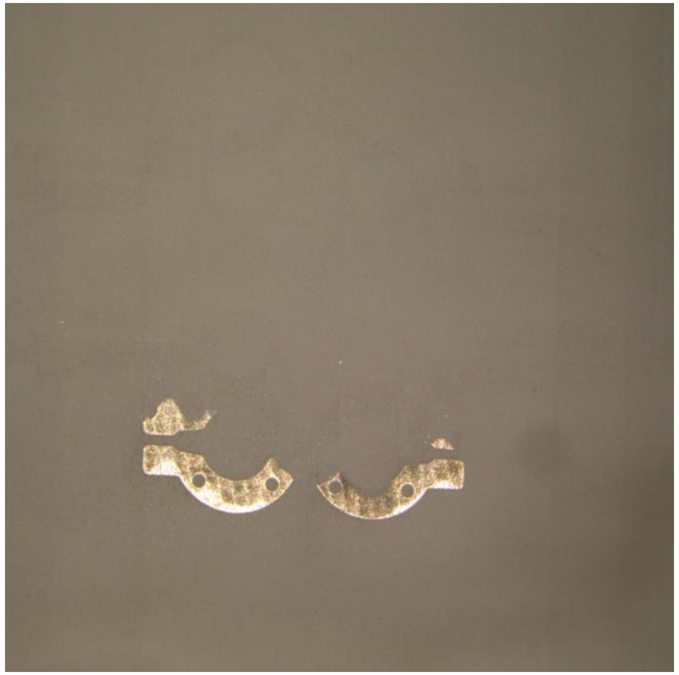


Dosing

- Re-coater wear or damage can lead to uneven dosing
- Poor powder flow can result in short dosing



Re-coater damage



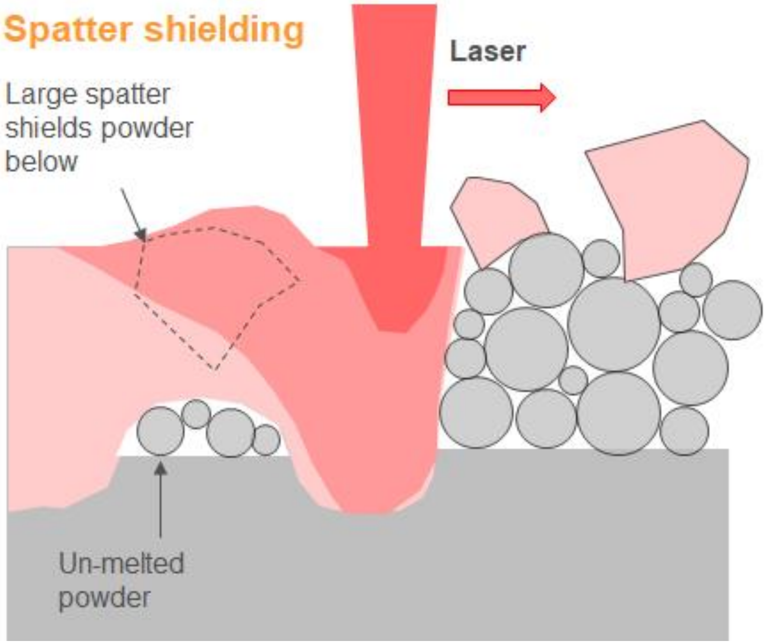
Start of layer

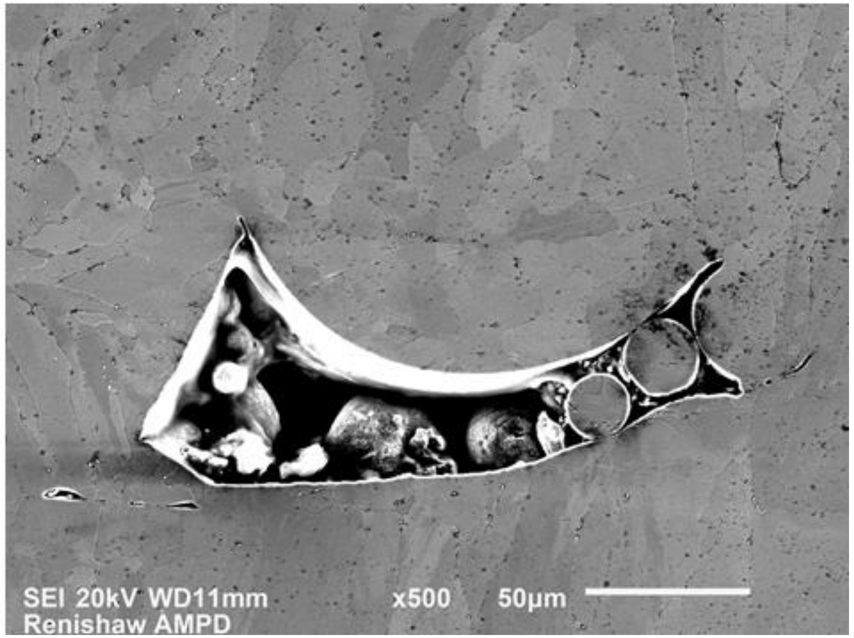
End of layer

Lack of fusion (1)

Spatter shielding

- Spatter emitted from the melt pool
- Some spatter lands on powder bed where it locally thickens the powder layer
- Laser may not fully melt extra material, leaving a lack-of-fusion pore below





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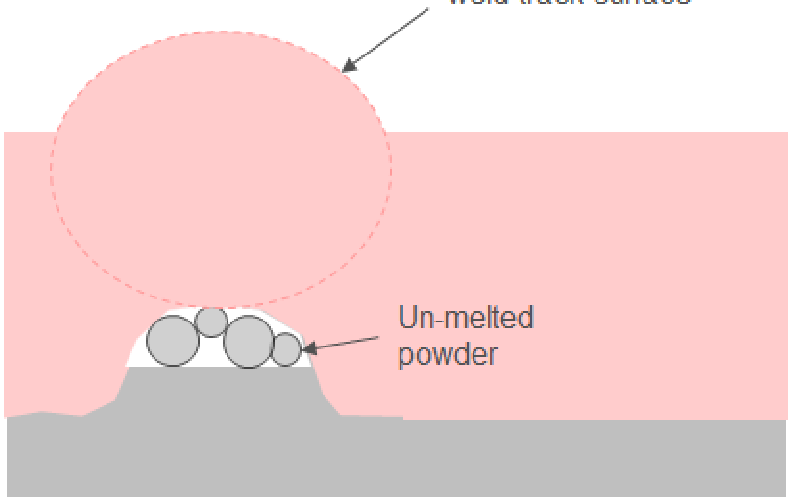
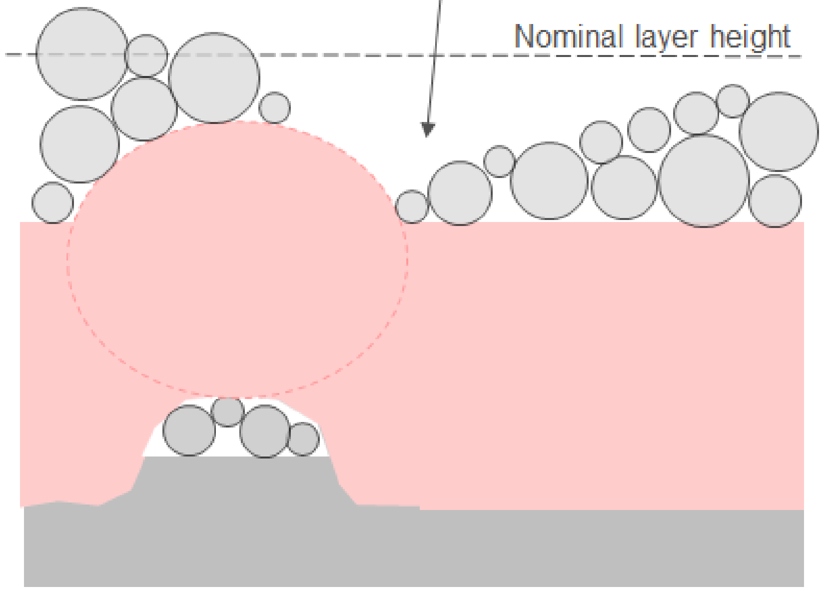
Lack of fusion (2)

Irregular dosing

- Spatter particles may stand proud of the rest of the layer
- May disrupt powder spreading on next layer
- Localized short dosing leaving insufficient material to create a weld track
- Potential key-hole porosity due to excess energy penetration





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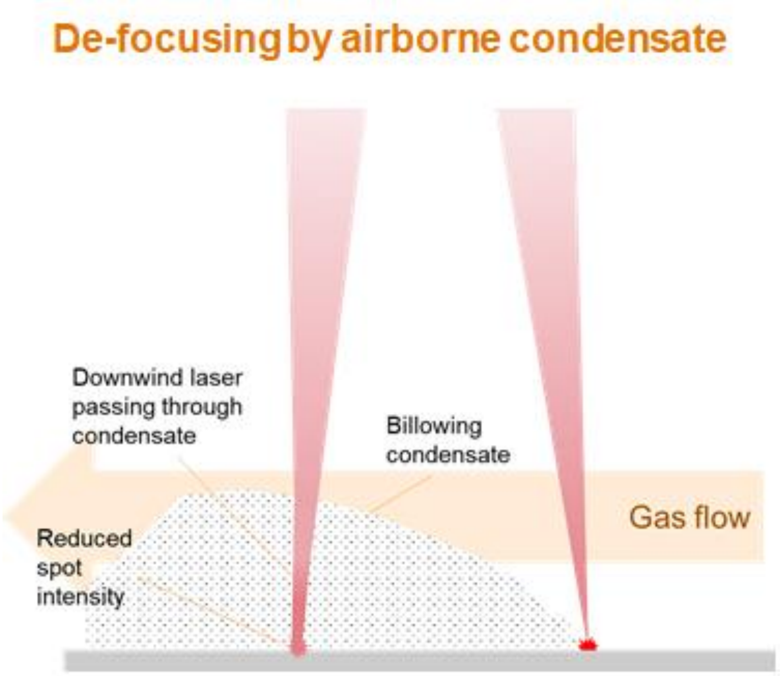
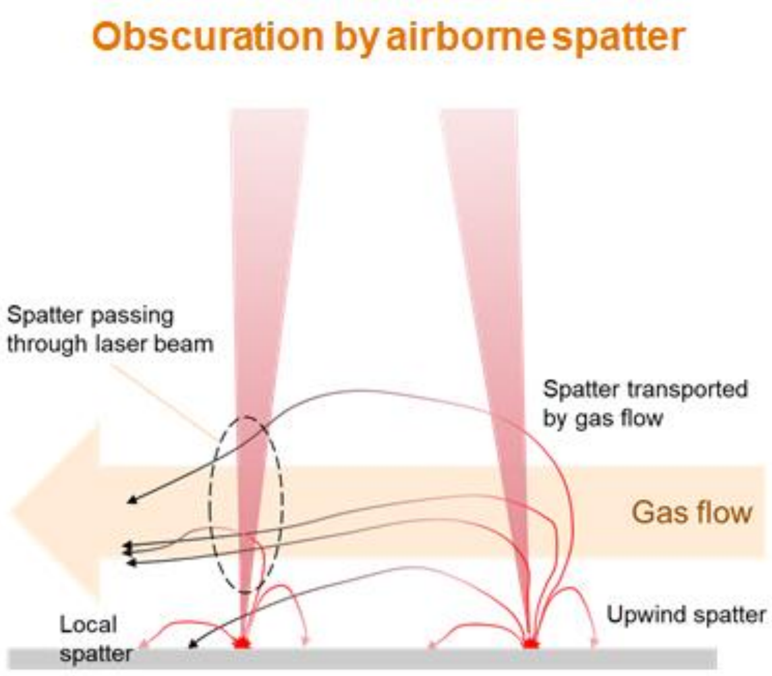
Lack of fusion (3)

Laser beam disruption

- Debris on optical window can block laser energy
- Downwind processing in multi-laser machines
  - Billowing condensate
  - Airborne spatter
  - Spatter shielding





Multiple sources of porosity in builds

- Some can be **avoided through process refinement**
- Some are **endemic** and must be **detected or corrected**

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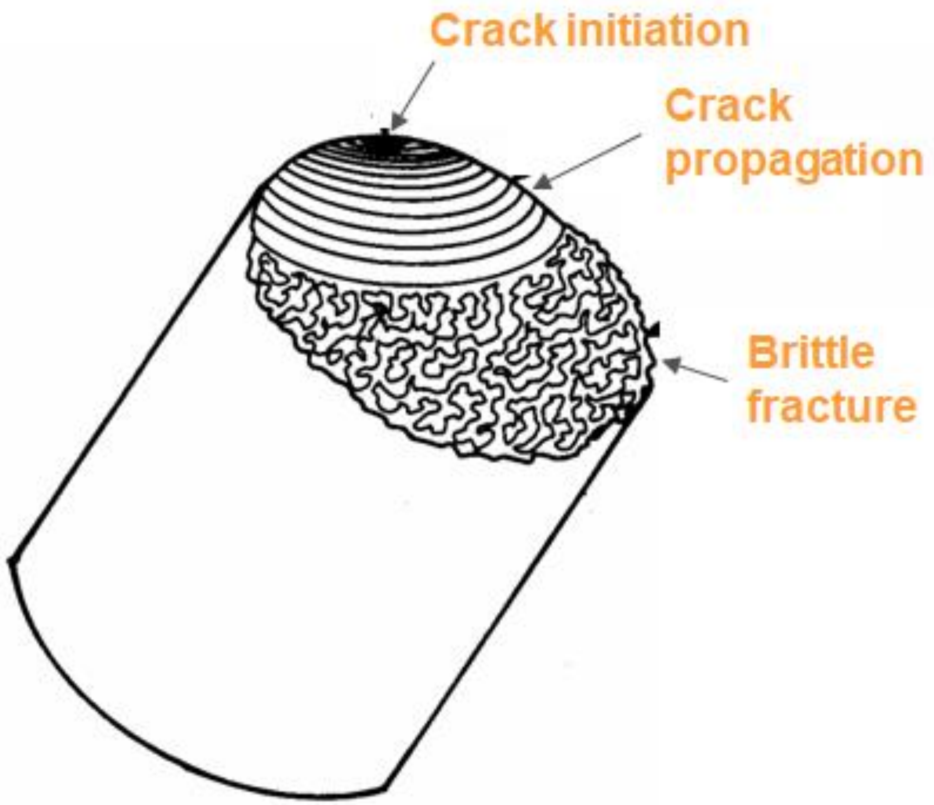
Consequences of process anomalies

Fatigue failure

- Progressive phenomenon associated with initiation and growth of cracks under cyclic stresses
- Failure can occur suddenly at low stress
- Irregularities above a critical size are crack initiators
  - Rough surface
  - Key-hole pores
  - Lack-of-fusion pores
- Presence of critical defects reduces fatigue life

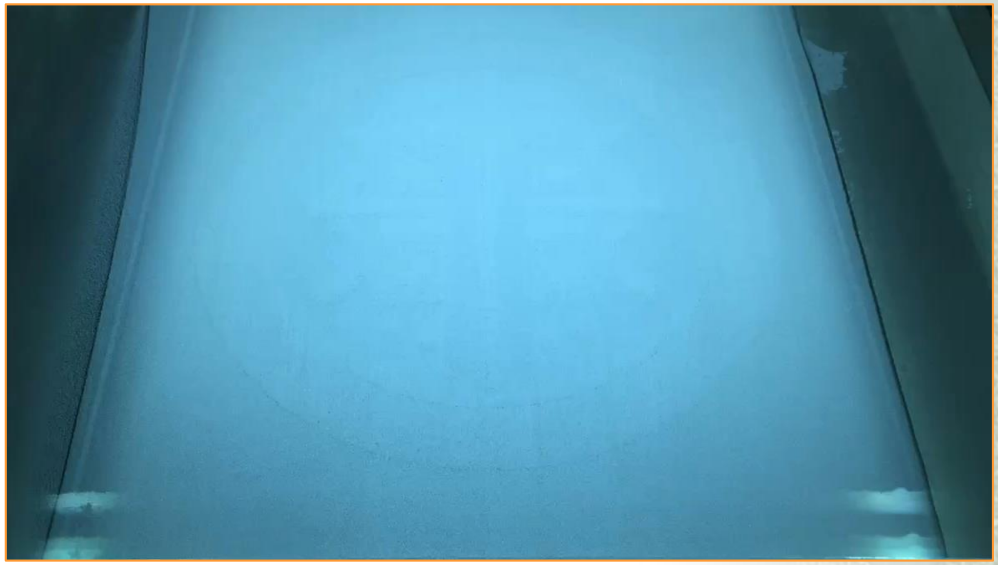
Can we ensure that AM parts are free from critical defects without exhaustive post-process testing?



RenAM 500Q multi-laser AM machine

Industrial AM machine with integrated real-time process monitoring

- 4 x 500W laser
- Build chamber camera for layer sensing
- LaserVIEW – laser power delivery
- MeltVIEW – melt pool monitoring



Build chamber camera

- Images of build chamber after recoating can be viewed as individual jpegs (2D only)
- **InfiniAM Visual** image analysis software with histogram showing contrast
- Identifies short dosing which could lead to defects in the finished part

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Real-time process monitoring

Multi-sensor

High-frequency data across a range of wavelengths

- Infrared thermal sensor
- Near-IR plasma sensor
- Laser input energy

Synchronised with actual galvo mirror positions to enable 3D modelling and visualisation

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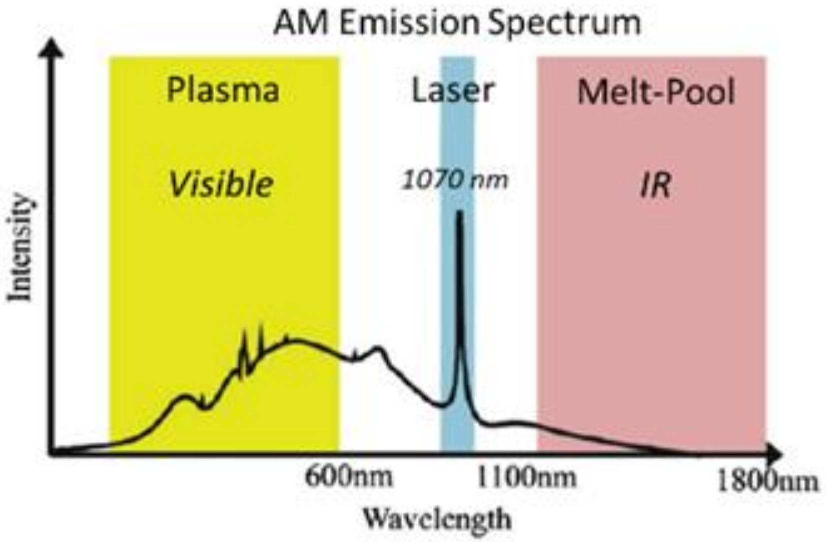
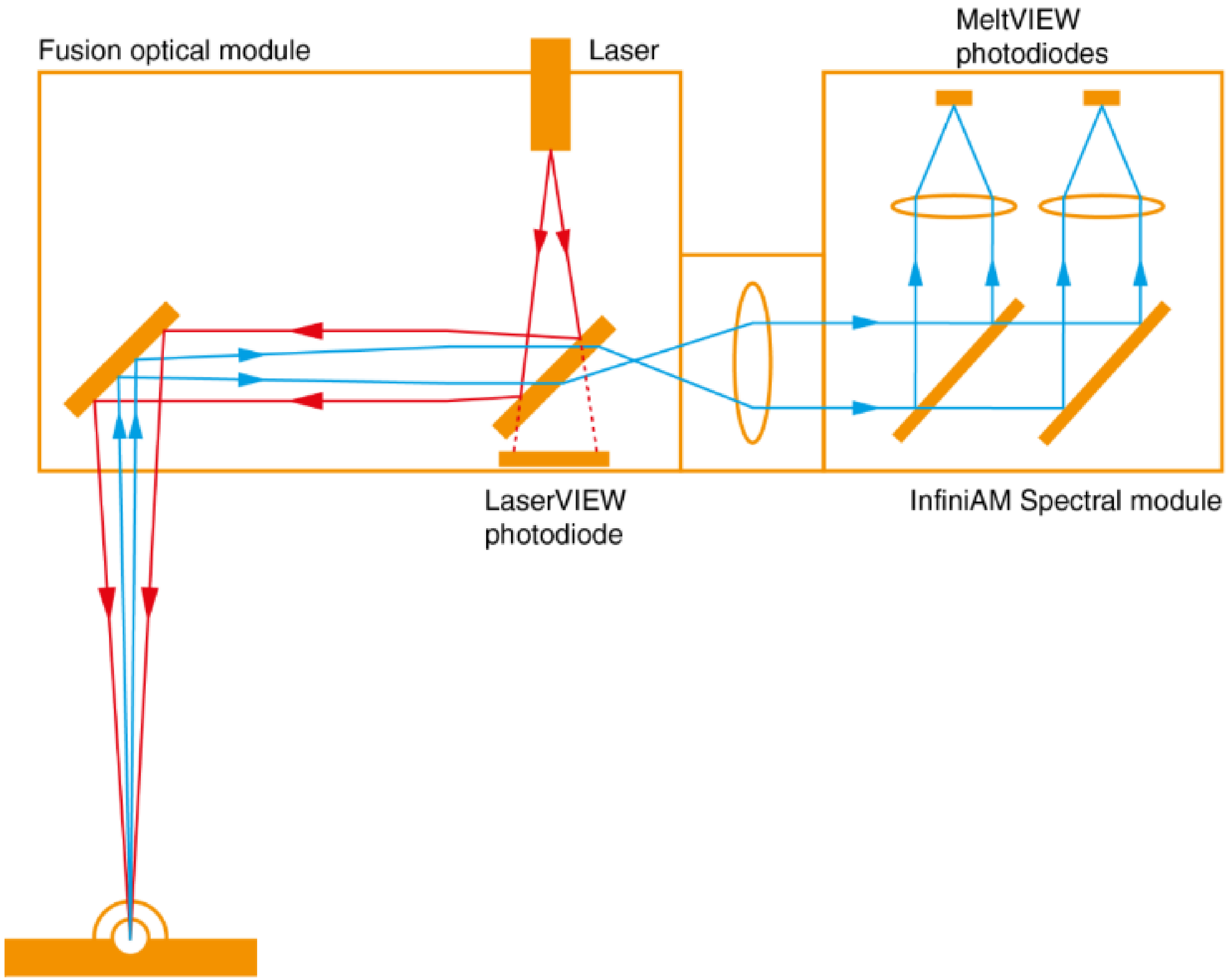
Optical scheme

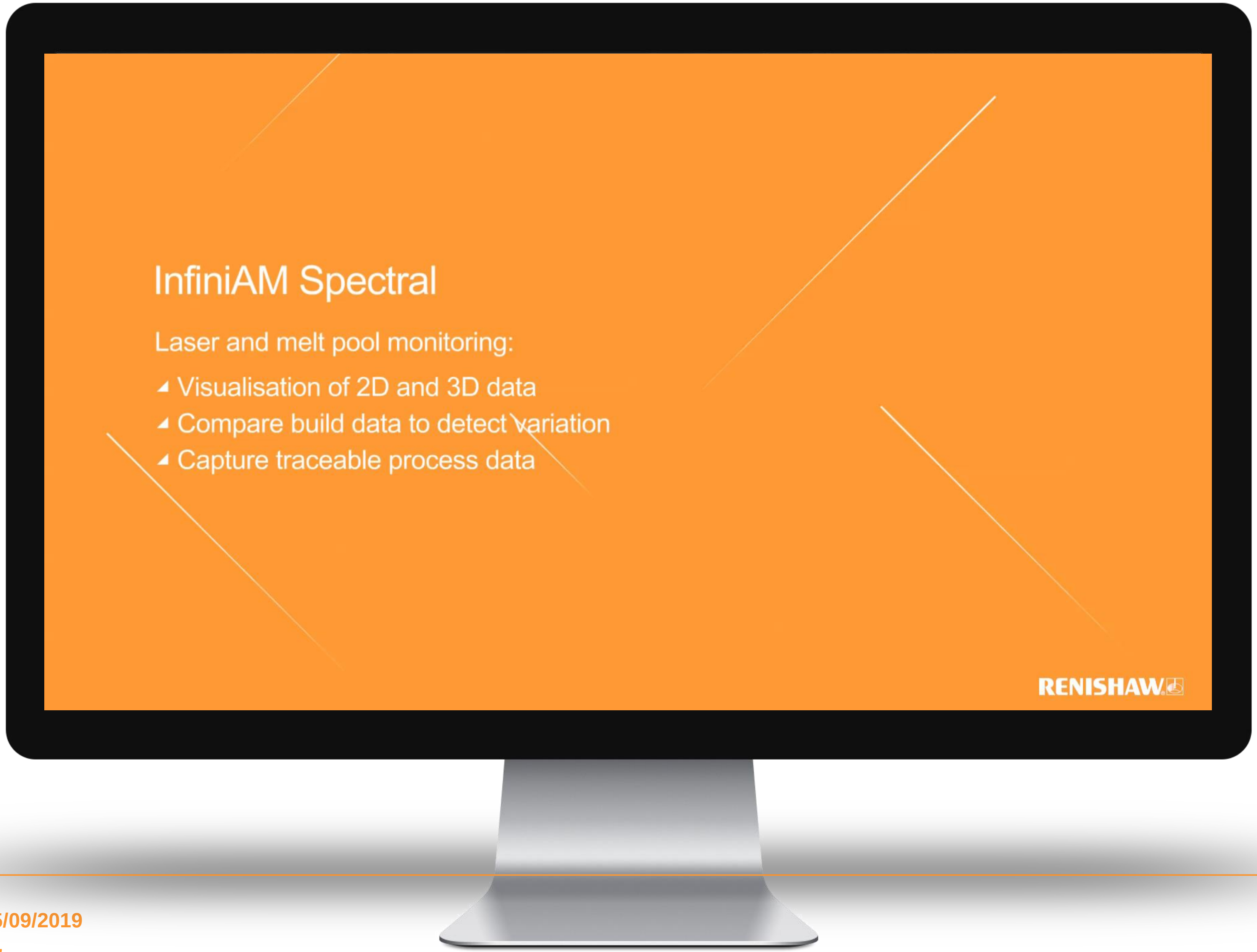
- All sensors are passive and do not impinge on optical delivery path
- Processing parameters unaffected



Meas. Sci. Technol. 21 (2010) 105705



Process monitoring data visualisation & analysis

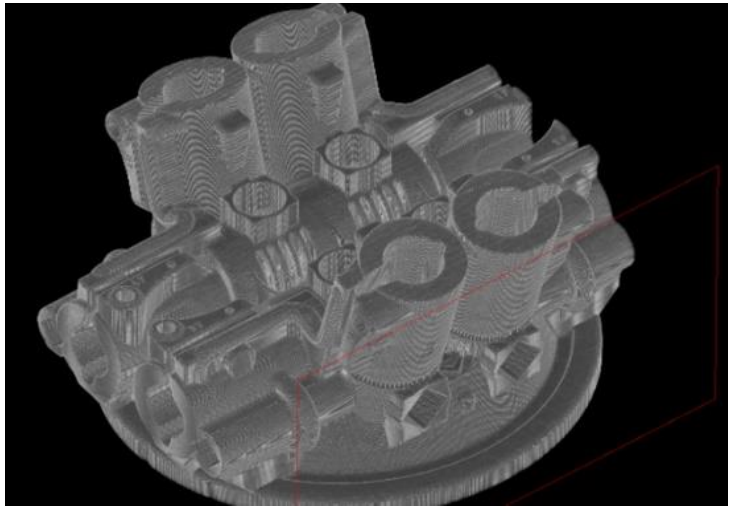


Analysis software

- Collect and view process data live as the build progresses
- View and compare data from previous builds
- Software tools to change thresholds and reveal anomalous data
- Guide post process quality assurance techniques
- Keep records by capturing traceable process data

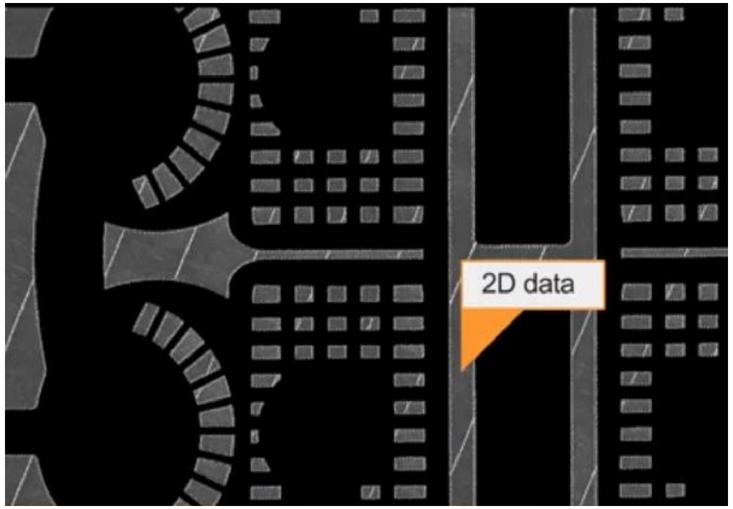
Process monitoring data visualisation & analysis

3D visualisation



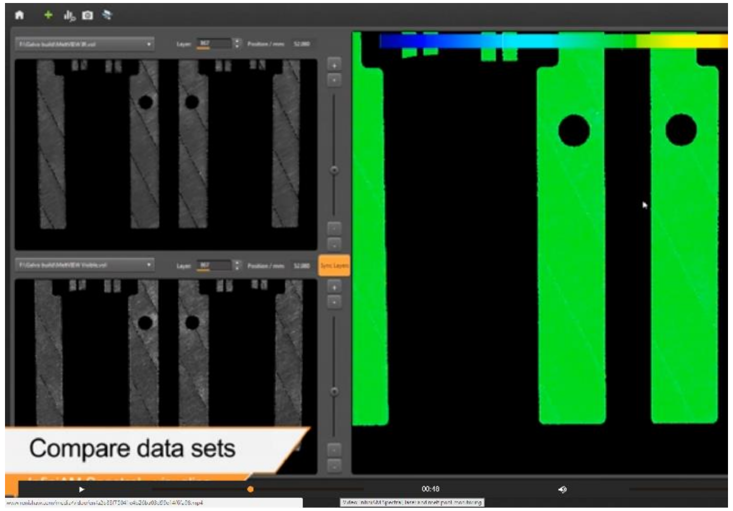
- View whole part
- Zoom / slice
- Threshold to view hidden detail

2D layer analysis



- Investigate anomalies
- Scroll through layers to understand defect propagation

Build-to-build comparison



- Investigate anomalies
- Scroll through layers to understand defect propagation

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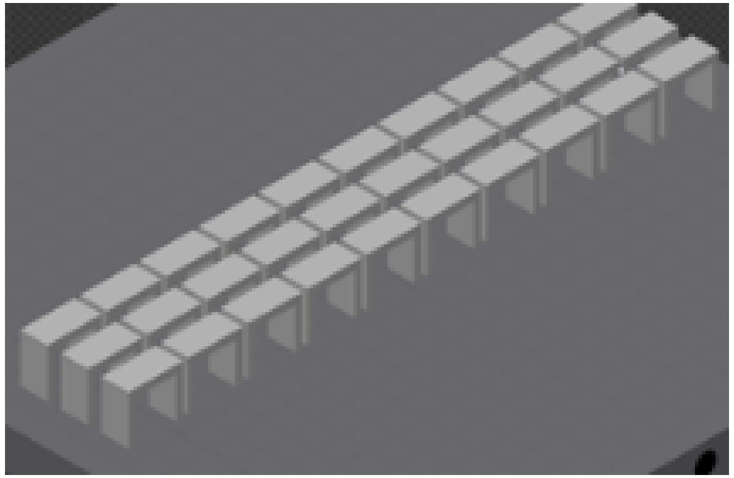
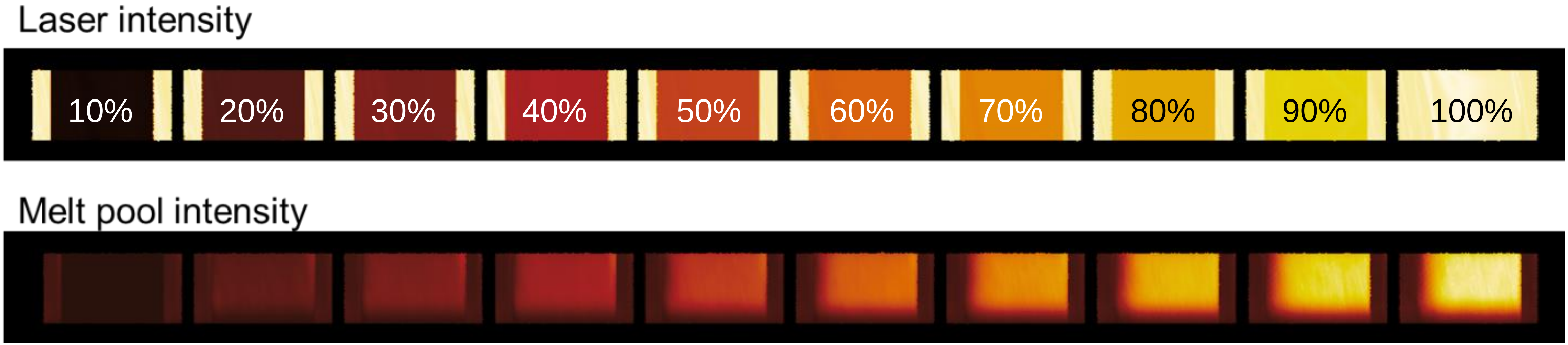
Detecting melting variation - downskins

Bridge artefacts with horizontal overhang

- Downskin laser power varied from 10% to 100% of bulk power
- 20% of bulk power generates consistent melt pool signature
- High powers lead to significant heat build-up





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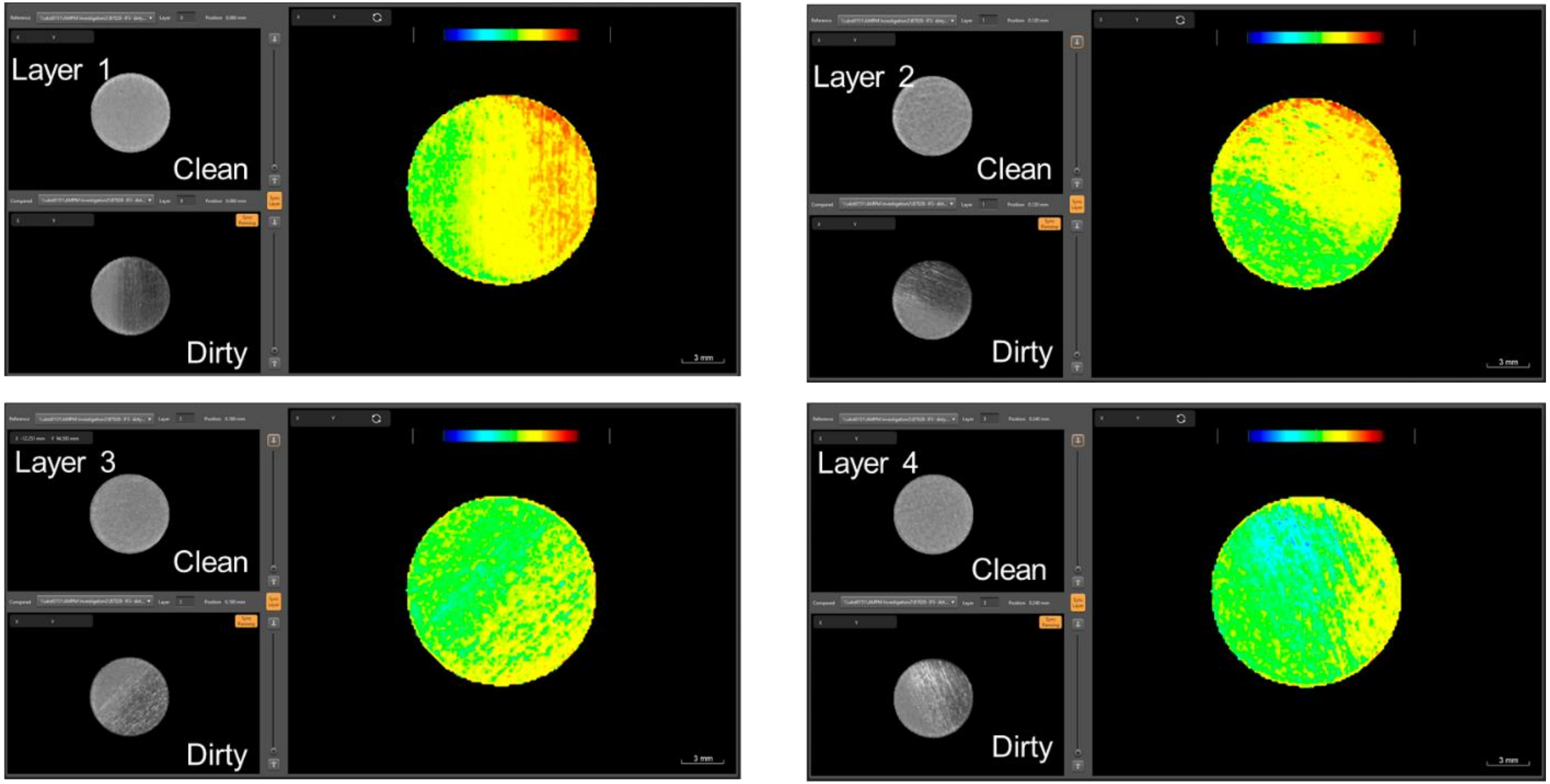
Detecting melting variation – optical window cleanliness

Laser obscured

- Build-to-build comparison
- Persistent differences in one bed location
- Spot anomalies in first few build layers – stop & fix



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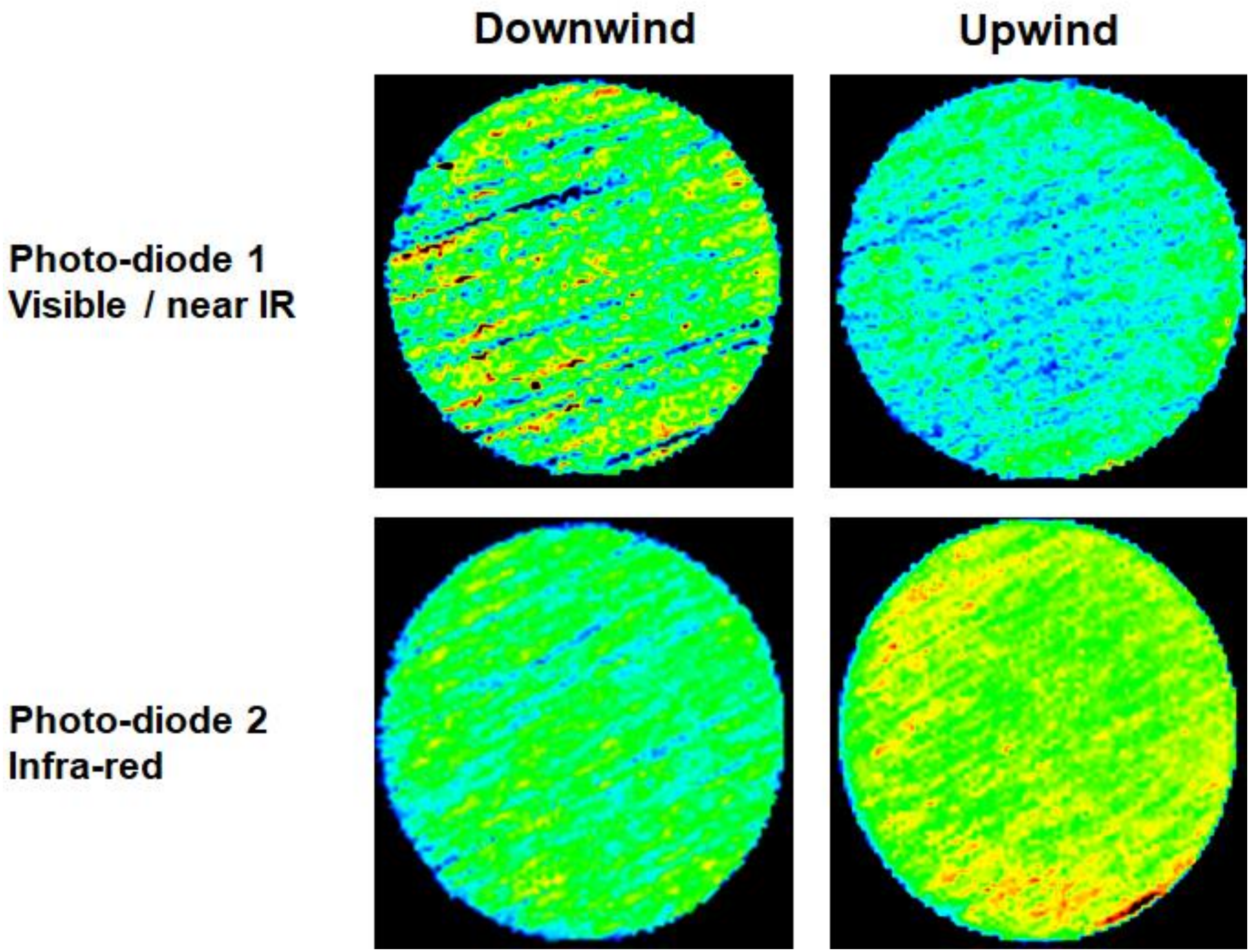
Detecting melting variation – downwind melting

Laser obscured

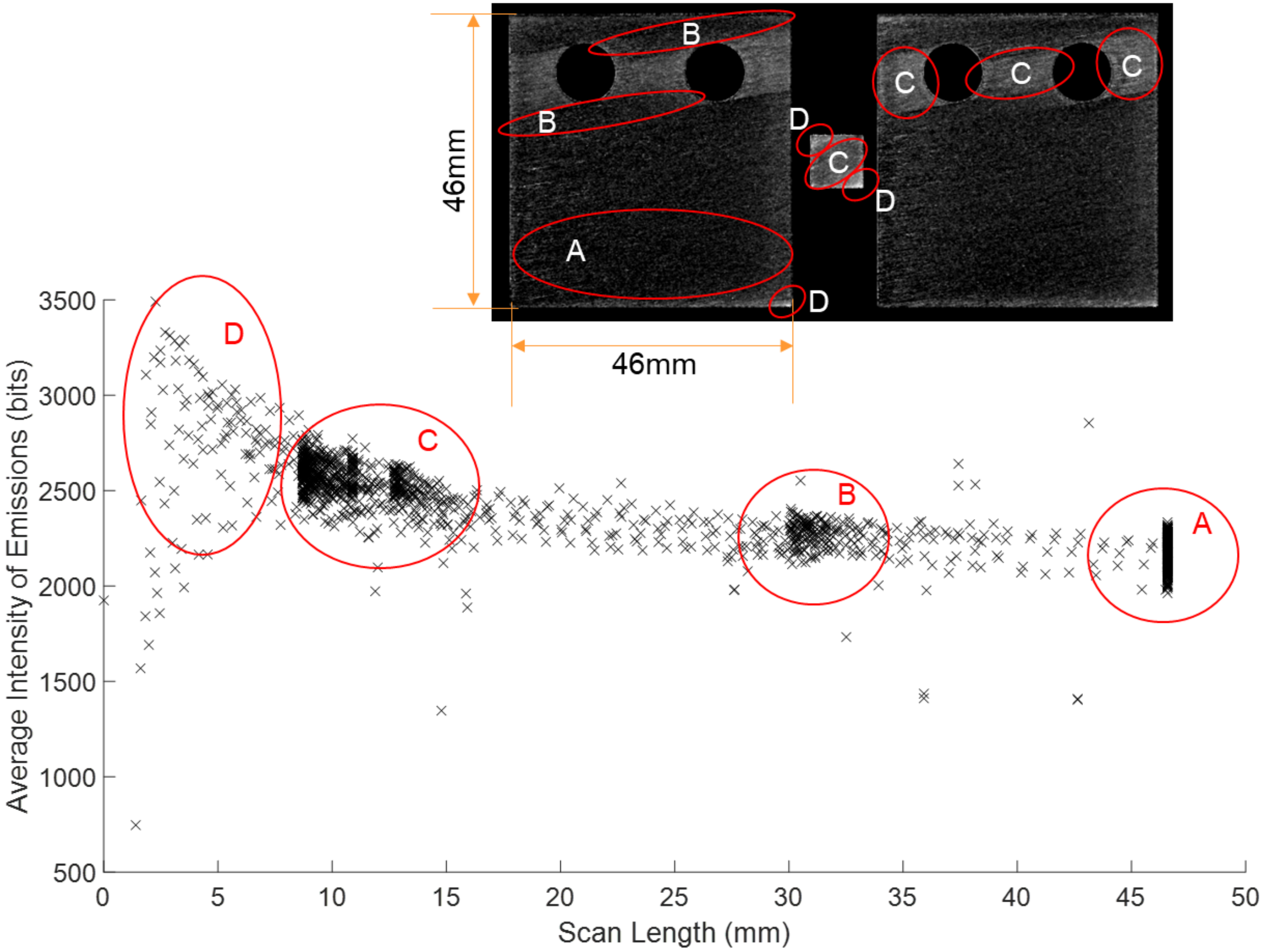
- Downwind laser processing through upwind laser emissions
- MeltVIEW sensors respond differently
- Visible sensor exhibits more noise, with high spots corresponding to spatter particles passing through downwind laser beam
- IR sensor shows lower intensity in downwind part – less energy reaching the bed



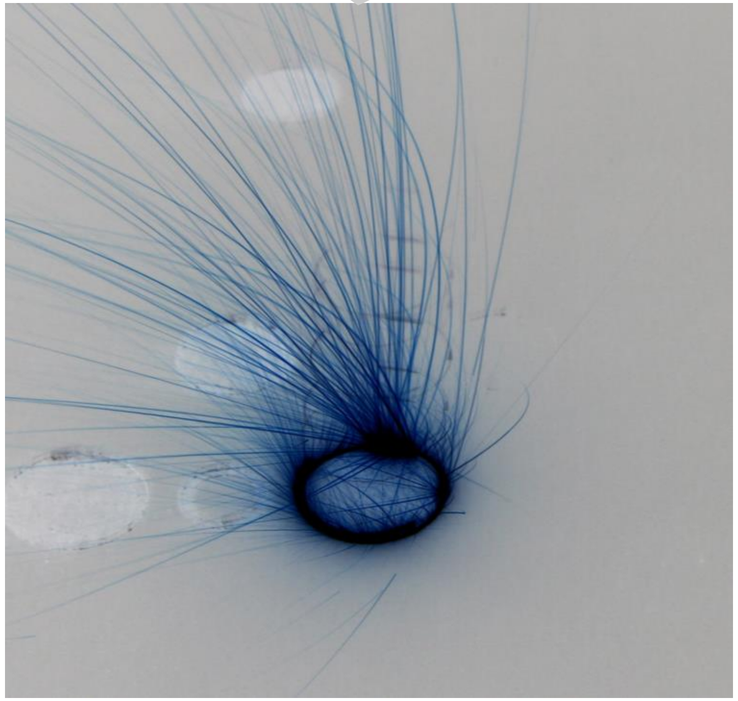
Detecting melting variation – scan vector length

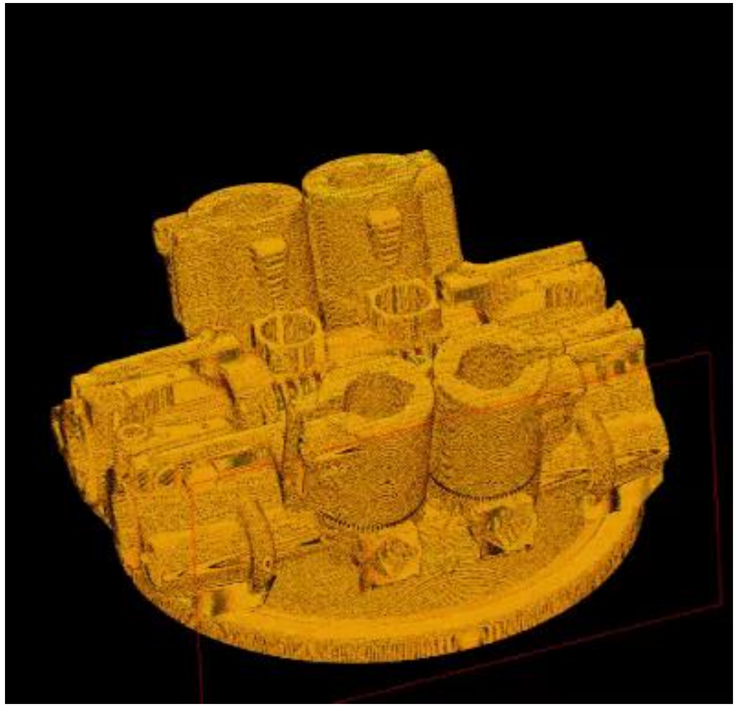
Intensity varies with vector length

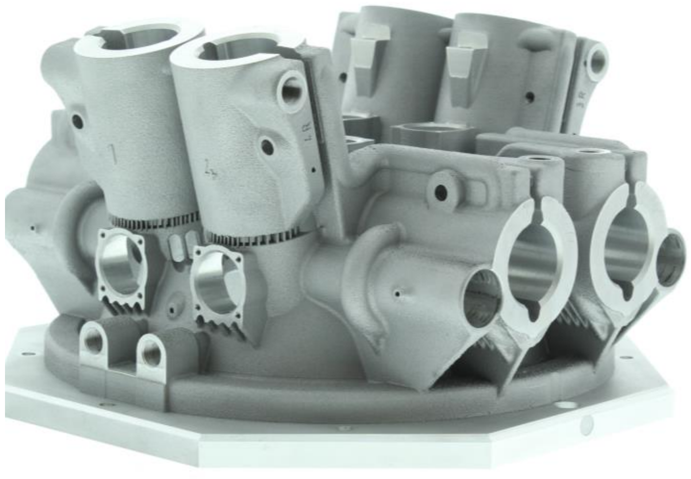
- Average value of melt pool intensity plotted against vector length
- Longer vectors allow more time for previous hatch to cool before it is re-melted – lower melt pool intensity
- Shorter vectors get hotter
- Very short vectors will not form a full melt pool – data more variable
- Vector intensity could be used to locally vary laser power to produce more consistent melting



Process improvement opportunities (1)







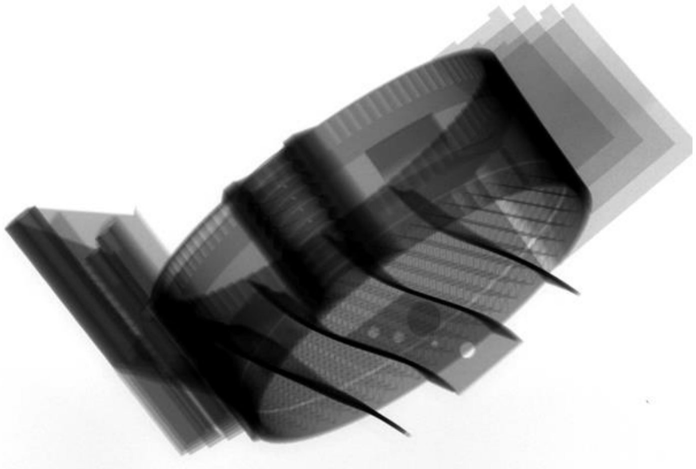
Understand - gain insight into process performance

Record - compare and store traceable process data

Improve - check quality during the build to optimise output

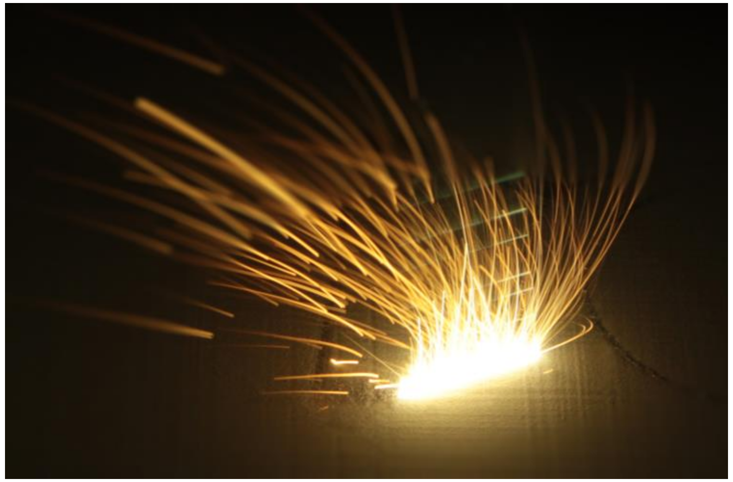
Process improvement opportunities (2)

Directed CT inspection



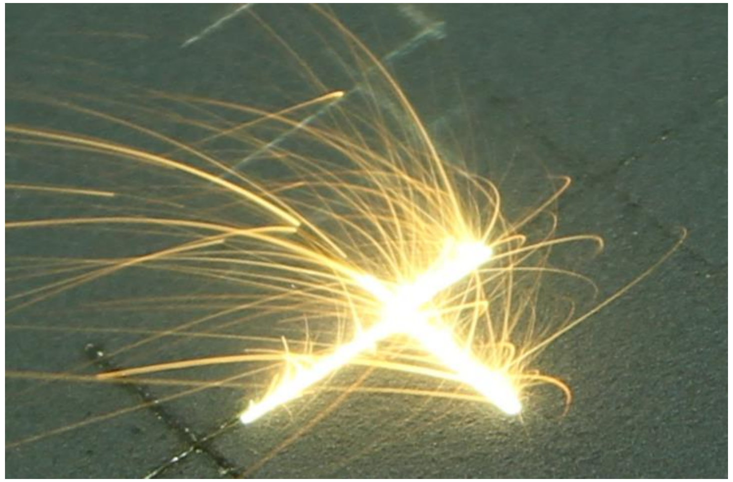
- Comparison with known good builds to highlight anomalies
- CT scan only anomalous regions

Adapt laser power



- Adjust power to produce constant melt pool intensity
- Driven by simulation or real-time process feedback

In-layer defect correction



- Local variation detected
- Re-process defect regions at end of layer

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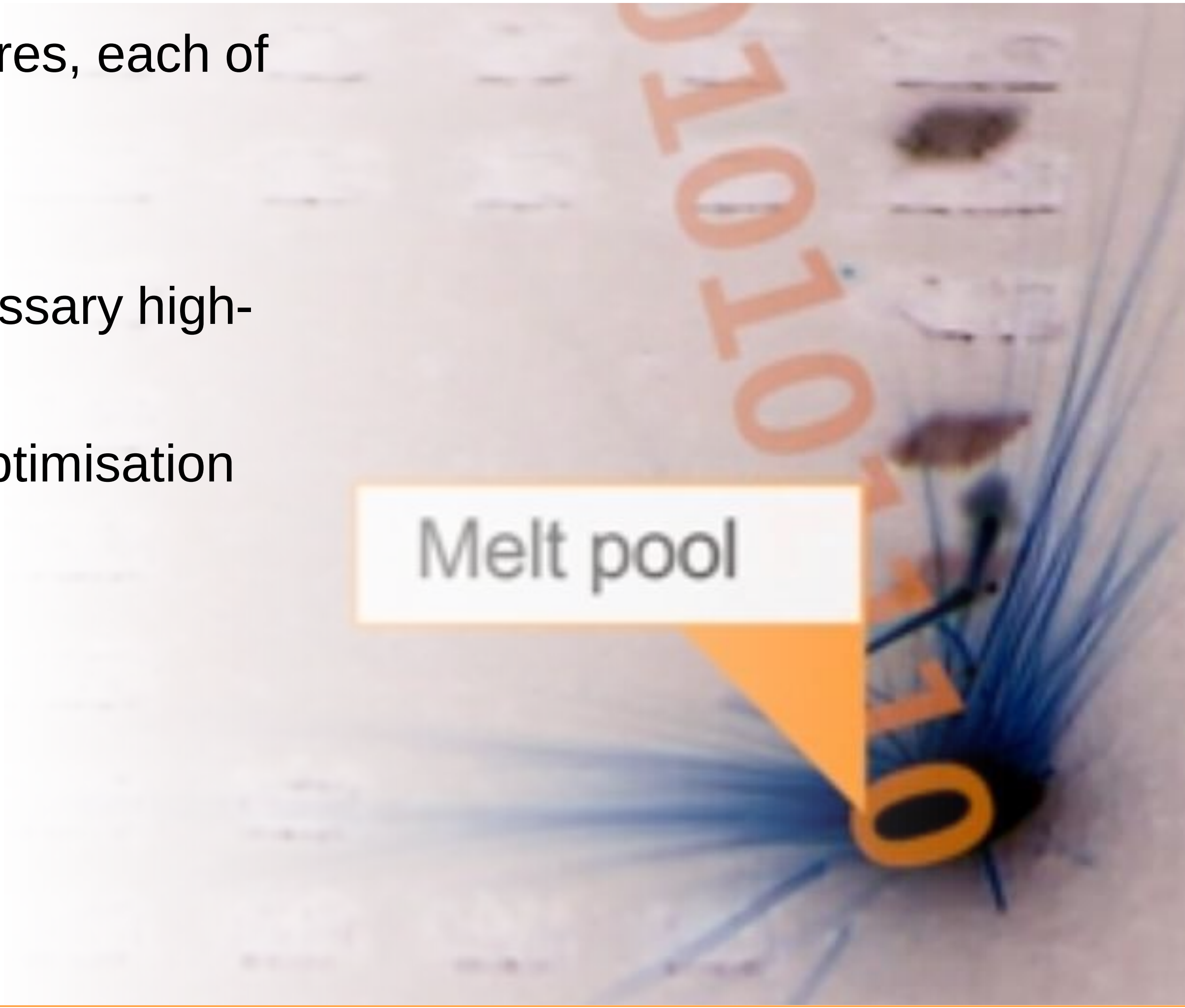
Conclusions

- LPBF builds up parts from millions of laser exposures, each of which contribute to component quality
- Melting process exhibits inherent, rapid variation
- New real-time monitoring techniques provide necessary high-speed, high-resolution process data
- Enables traceable production and rapid process optimisation
- New process control possibilities
  - Detecting defects as they arise
  - Correcting errors in process
- Closer to the ideal of defect-free AM parts



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