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

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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
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
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
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
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**
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
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

InfiniAM Spectral data collection
Captures wavelengths from 700 to 1700 nm for analysis of plasma, thermal and laser emissions
• All sensors are passive and do not impinge on optical delivery path

• Processing parameters unaffected
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
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

Laser intensity

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| 10% | 20% | 30% | 40% | 50% | 60% | 70% | 80% | 90% | 100% |
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Melt pool intensity
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
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
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
Thank you

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