Additive Metals: State of the Art in Process Monitoring and Safety Assurance
Safety Assurance in Metal AM

- Metal Additive has two significant hazards:
  - **Radiation Source**
    - Generally mitigated through interlocks, machine controls
    - Class 1 laser
  - **Powdered Material**
    - Powder is flammable, often reactive
    - Necessitates inert atmosphere
    - Passivation for open atmosphere handling
Safety Assurance in for Powdered Materials

- Machine design for ATEX II compliance
  - Design to protect from potential ignition sources

- Operator powder handling in separate glovebox
  - **NOT IN PROCESS CHAMBER**
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Safety Assurance in for Powdered Materials

- **Filter Considerations:**

- **Reduce Operator exposure through fewer filter changes**
  - Increase in filter area from 4m$^2$ to 20m$^2$
  - Automated filter clean

- **Filter exchange is done **without** touching a reactive filter cartridge**
  - Cartridge water-flood passivated in sealed filter housing
  - Passivation under inert atmosphere
Quality Demands for Certifications

- Standards: General (e.g. ISO 9001, ISO 13485) and application specific (e.g. DIN EN ISO 22674)
- Every industry has its own specific certifications
  - FAA certification and MMPDS listing for Aerospace
  - API and NACE certification for oil and gas
  - Etc.
- Medical and aerospace applications have high quality demands due to a high level of safety requirements
- Certifications and standards require high confidence in material properties of *each part built*
Quality escapes often sum of several influencing factors:

- Build atmosphere: Gas composition, O₂ content
- Process chamber and build plate temperature
- Laser power, beam quality
- Powder chemical composition, particle size distribution, flowability

Highly dynamic LM process

Stringent requirements for high-fidelity process monitoring

- High spatial- and temporal-resolution
- High dynamic range for sensors
Options for Process Monitoring

LM process consists of two basic steps:

- Coating
  - Uniform coating is required for every layer
  - Short-feeds or "overdosing" cause process failures or inefficient operation

Coating control system

- Meltpool
  - Decisive factor of the LM process
  - Incorrect energy input causes pores, stresses etc.

Meltpool monitoring system
Setup of the Coating Control

- Flashing light source
- Analyzing software
- High resolution camera
- Analysis of image before & after coating
Advantages of Coating Control

- Detection of areas with insufficient powder feed
- Real time control of the powder dose factor is possible
- Optimal coating for every slice
- Setup-time and powder saving
- Possibility to realize bigger build parts without refilling of powder

Outlook:

- Potential automated removal of curled up build parts
QM\textsubscript{coating}^{RT} – Application

- The melted area of many parts varies from layer to layer
- The powder amount that is necessary for a fully coated layer proportional to area of the part
- To reduce the risk of insufficient powder feed, machine operators typically use a high feed factor (200%)

► QM\textsubscript{coating}^{RT} can automatically adapt the feed factor to the build part size and can avoid high powder usage
$QM_{coating}^{RT}$ – Demonstration Build Job

- Cone experiment: Dimensions of build part increases layer by layer
- $QM_{coating}^{RT}$ was switched off until layer 1780 and powder dose factor was set to 100%
- $QM_{coating}^{RT}$ was switched on at layer 1780 and the system began to control the coating
$QM_{coating}^{RT}$ – Demonstration Build Job

- Feed factor 100% causes lack of powder behind the part
- Activation of $QM_{coating}^{RT}$ increases the feed factor to 137% at layer 1810
- Error Area of 1% at layer 2656, which is set in the $QM_{coating}^{RT}$ parameters

➤ Mean feed factor could be reduced by 50% - 25% of powder was saved
Process Defects

Influencing factors on the process (laser power, scanning speed, hatches etc.)

Examples:

- Scanning speed too high
  Unmelted Powder (1)
- Scanning speed too low
  Gas inclusion (2)
- Hatch distance too big
  Linear pore line (3)
- Hatch distance too small
  Too much energy (4)
Setup of Meltpool Monitoring – OFF Axis

Approach 1: Infrared sensitive camera OFF-Axis

- Angle induced detection error
- Low resolution – detection by single pixel
- Low Sample rates
- Easy to integrate
Approach 2: Infared sensitive camera ON-Axis

- Directly through the scanning optic
- High resolution
  - Small Region of Interest
  - 1 pixel $\approx$ 10-12µm
- High sample rates
  - Scanning speed 3500mm/s
  - Sample rate >10kHz
  - Sample every 100µm-200µm
Meltpool Monitoring

- Characteristics which can be detected with meltpool monitoring (e.g.)
  - Meltpool Intensity & Meltpool Size

- Process anomalies and possible correlation to meltpool characteristics
  - Contamination of optics
  - Increasing of \( \text{O}_2 \)
  - Coating errors
  - Scanning speed
  - Etc.
  - Lower meltpool intensity
  - Increase in meltpool size
  - High variation of meltpool size
  - Differences in meltpool intensity
• Variation of laser power causes clear deviation of meltpool intensity
• No differences on visual inspection
• Variation of dose factor causes deviation in heat conduction and melt pool area
• No differences on visual inspection
QM_{\text{meltpool}}^{RT} – Demonstration Build Job - Micro Sections

- Micro sections of reference job
  - low porosity
- Micro sections of job with laser power reduction
  - high porosity
QM system: $QM_{\text{meltpool}}$

Part no. 1: NOT OK.

Part no. 30: OK.
Advantages of ON-Axis Meltpool Monitoring

- Realtime analysis
- High resolution, small region of interest (1 pixel ≈ e.g. 10-12µm)
- High sample rate (>10kHz)
- Data available immediately after build process
- Can infer cause of process anomalies
- Possible to reduce post-process quality control
- Important for various industries to guarantee reliable part quality
New Developments

- Correlation of melt pool emissions to corresponding coordinates on the build platform
- High sample rates enable correlation within the dynamic process
- 3D visualization of the build parts directly after build process - comparable with CT Scan
Outlook – What’s next?
# Conclusion - More Detailed Process Monitoring

## Machine Status Monitoring

- Not all influencing variables are covered
- Difficult to interpret influences on part quality
- Less expensive
- Cheap solution
- Easy to integrate

## Process Monitoring

- Calibration on material/process required
- Covers more influencing variables
- Detailed in-situ inspection
- Reduce post process quality measurements
- Necessity, material and process certification
Thank you for your kind attention!

I am happy to answer your questions now!

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