This project has received funding from the European Community's
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**MANUELA**
Additive Manufacturing
using Metal Pilot Line

# Deliverable No. 4.6

# Title of the deliverable: On-line system calibrated and tested

# WP No. 4

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# Contents



# List of figures and tables



# Terms and definitions

| Acronym | Description |
|---|---|
| AM | Additive Manufacturing |
| EBM | Electron Beam Melting |
| LPBF | Laser Powder Bed Fusion |
| OT | Optical Tomography |
| MPM | Melt Pool Monitoring |

# Executive Summary

This report summarises the actions with repect to the installation, calibration and developed cope for the core on-line process monitoring facility established at Chalmers University Technology to enable future on-line process monitoring control when fabrication demontrators connected to pre-defined and open call use cases. The report demonstrates the capabilities and application of latest on-line process monitoring technology enabling future first part righ capacitity and repeatability. With the completition of this Deliverable, the Miletone MS7 "On-line monitoring system for improved processing" is achieved. This has been verified by the manufacturing of defect free test samples of two materials, Ni-base alloy HX and stainless steel 316L, with strongly improved productivity without compromising material quality. Both cases are realised with small spread in as-printed relative density and the for the latter demonstration of mechanical properties better than standard is also shown.

# 1 Introduction

## 1.1 Process monitoring in laser powder bed fusion

Although extensive development has been done over the years by machine manufacturers and researchers in scientific community to optimise the processing conditions for Laser Powder Bed fusion (LPBF) of specific materials, the quality assurance of the part for mission-critical applications remains a challenge. Physical phenomenon such as uneven distribution/packing of stochastic powder, hydro-dynamic instability of melt pool, generation of spatter and welding plume (smoke), thermal distortion, heat accumulation in local scan areas, etc, can generate defects of different nature and variable microstructure in the LPBF products. Process monitoring is used as tool to track the critical events that can lead to quality issues in the LPBF produced parts. This activity hance has been aimed at addressing the correlation between monitoring data and the defects (porosity and cracking), geometrical compliance, microstructure and properties of the LPBF products.

# 2 Process monitoring capabilities at Chalmers

## 2.1 Theory and hardware

In terms of monitoring of LPBFs key process properties, Chalmers has the following capabilities:

- Laser power monitoring during build process and comparison with its target value
- Duration of laser exposure per layer
- Oxygen concentration in the build chamber
- Platform temperature

Powder bed monitoring registers an image of the building area after recoating and after exposure for each layer. This system is capable of detecting recoating issues, as exemplified in Figure 1.

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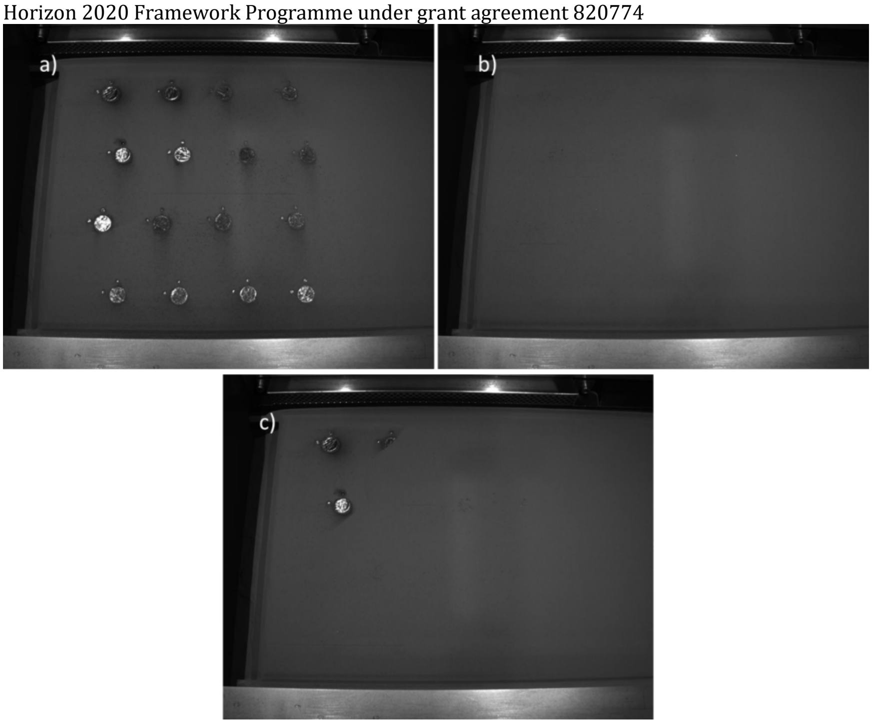


**Figure 4: Sample of powder bed monitoring system output; a) post exposure; b) post recoating with no issues; c) post recoating with uneven powder distribution**

EOSTATE Exposure OT system uses a high resolution camera that captures radiation in the near-infrared range. The system is set to register a long exposure image every 0.1 second and generate two different outputs:

a) By combining all images generated in a layer by integration
b) By registering the maximum value a pixel has achieved during exposure of a layer

These outputs are treated by image processing algorithms to detect deviations and establish indications, as exemplified in Figure 3.

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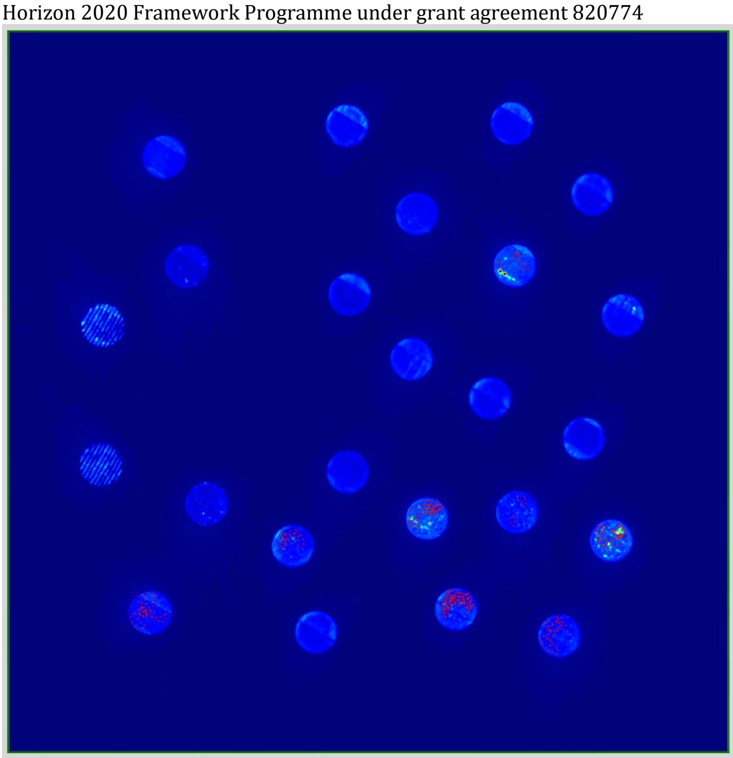

**Figure 5: Sample of exposure OT system output. Indications are marked in red.**

EOSTATE MeltPool system uses two photodiodes to register the melt pool radiation emissions. The signals are then processed by algorithms to identify different types of deviation and therefore establish indications.

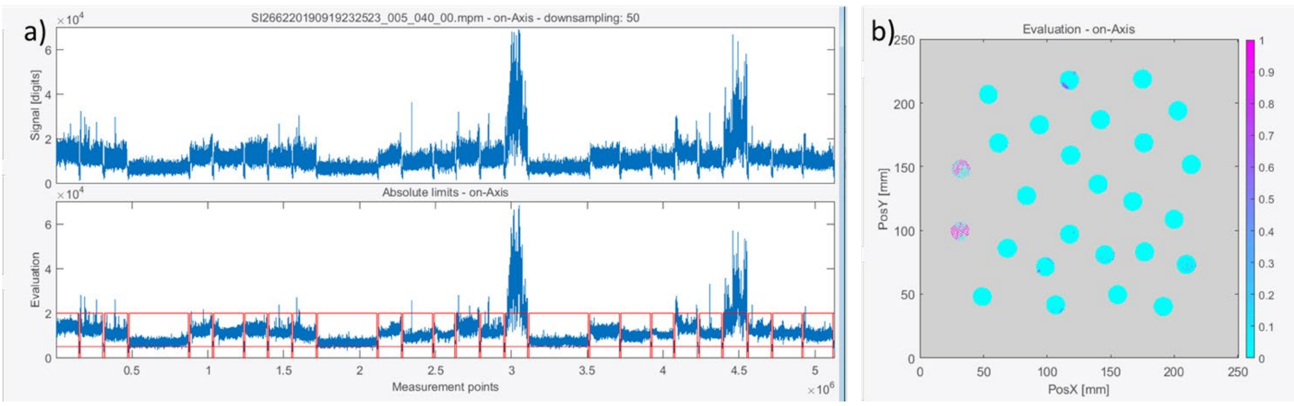


**Figure 6: Sample of MeltPool system output; a) signal output in the raw condition and processed by an algorithm; b) the resulting indications**

## 2.2 Calibration and validation procedure

In the MPM system, the output signal needs to be corrected to compensate for its variations over the building platform caused by aberrations in the optical path. Since these deviations are process dependent, calibration is needed for each material and parameter set used. This calibration has been performed as per user manual.

## 2.3 Strategies

To make sense of the monitoring data, experiments are designed to introduce some process variations through manipulation of pre-defined processing conditions including laser power, scan speed, layer thickness, hatch distance, scan strategy, inert gas flow rate. Monitoring data are gathered while building the parts or specimens with some designed perturbation to the processing conditions. The monitoring data are then compared to the experimental observations of defects and microstructure to build an empirical relationship between the two and to better understand physical mechanisms in LPBF process.

During optimization of processing parameters, the monitoring data is used to identify the potential cause (overheating or lack of fusion) and locations of the defects in the produced part. Through evaluation of the monitoring signal, the trial-and-error experimental procedure can be shortened by eliminating the need to conduct metallographic analysis of many specimens.

While building engineering components (use cases) with complex geometry, monitoring data can be used to identify potential areas of quality issues with prior knowledge of monitoring data-defect relationship for a given material. The monitoring process helps to explain the problems encountered and thus accelerate the feedback from manufacturing sites to the designers and customers to improve the design and manufacturing strategy of the components.

# 3 Applications

## 3.1 Product design

Research on part quality regarding different geometries provides the design rules for AM product. On one hand, AM offers more freedom for design. On the other hand, due to the influence of geometry on LPBF process there are variations in part qualities that are of concern to the applications.

Typical cases of quality issues in LPBF parts include overheating in areas built on support structure, warpage of overhangs (see Figure 4) and discontinuity in powder bed due to recoating errors.

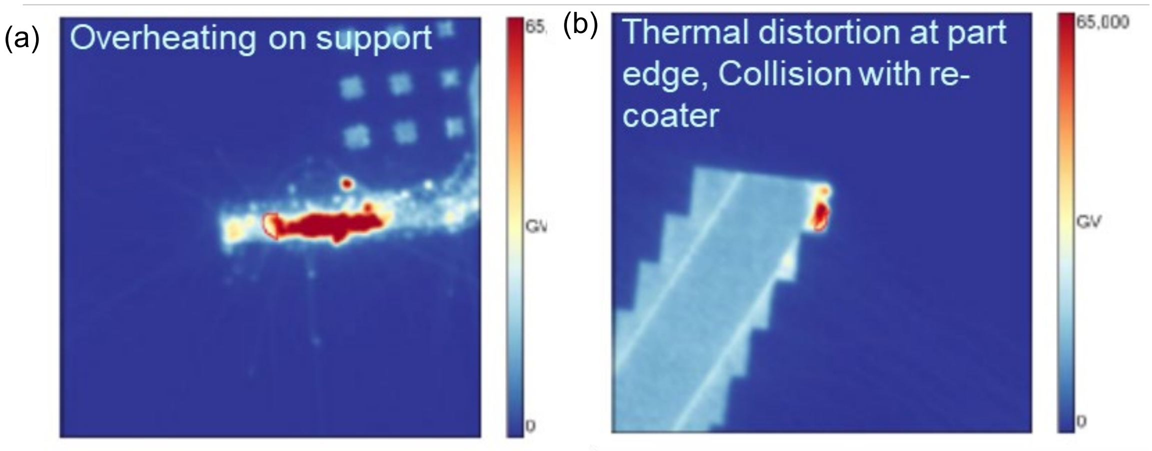


**Figure 4. OT images of (a) overheated area built on support structure and (b) an overhanging surface with flaws on the edge.**

## 3.2 Process parameter optimization

Process parameter optimization for Hastelloy X is relevant for use cases 4 (gas turbine combustor liner and injector) and 6 (gas turbine fuel nozzle). The optimization was performed with focus on increased productivity. Verification was performed by metallographic analysis of a minimal area of 200 mm$^2$ and has two success criteria: amount of discontinuities inferior to 0.1% and no discontinuities larger than 100µm in the cross-section analysed.

For the target layer thickness, 100 µm, it was found that the set of parameters on  produce parts that meet the success criteria established above.

**Table 4: Optimized Process parameters for Hastelloy X**

| Laser power (W) | Scan speed (mm/s) | Hatch distance (mm) | Layer thickness (µm) |
|---|---|---|---|
| 370 | 750 | 0,11 | 100 |

An analysis of impact of selected build variables on the productivity was performed. Each of the variables laser power, scan speed, hatch distance and layer thickness was varied separately by halving and doubling it from its default value and the time to build a standard component was simulated. Part quality is not considered in this analysis. Table 2 presents the variation in building time in relation to the default set of parameters, where the index 0 represents the default value of the variable.

**Table 5: Influence of selected process parameters on building time**

| Variable | $h/h_0$ (hatch distance) | | $v/v_0$ (scan speed) | | $t/t_0$ (layer thickness) | | $P/P_0$ (laser power) | |
|---|---|---|---|---|---|---|---|---|
| Ratio | 0.5 | 2 | 0.5 | 2 | 0.5 | 2 | 0.5 | 2 |
| Variation in build time | +14% | -7% | +12% | -6% | +109% | -50% | 0% | 0% |

A variation in layer thickness causes therefore the most impact in building time, while variation in hatch distance and scan speed have a moderate impact.

The process productivity using the optimized parameters in Table 1 was compared with that obtained using standard build parameters. The result is summarized on Table 3.

**Table 6 Productivity increase for use case 6**

| Parameter set | Total time (hh:mm) | Productivity ($cm^3/h$) | Productivity increase (%) |
|---|---|---|---|
| Default | 17:44 | 4.62 | - |
| Optimized 100 µm | 7:38 | 10.68 | 131% |

## 3.3 Manufacturing repeatability

Manufacturing repeatability refers to the consistency in quality across different batches with the same design and predefined process. Environmental factors such as humidity and gas supply can disturb the build process and cause issues. In addition, the degradation of powder feedstock over time can also lead to deterioration of part quality. Monitoring data provides traceability of the products by storing the information of melt pool intensity for each layer of deposition and giving suggestions for critical quality issues.

## 3.4 Manufacturing quality

In addition to the variation in quality over time/batches, there is a certain level of variation in part quality across the same build. The variation originates from the uneven powder size/shape over the build plate, the change in protection gas flow rate from gas inlet to outlet and the heat accumulation with increasing build height. The monitoring data is used to evaluate both local fluctuation and global change in melt pool intensity (Grey value), thus providing implications for quality variation in products.

# 4 Conclusions

This report summarises the actions with repect to the installation, calibration and developed cope for the core on-line process monitoring facility established at Chalmers University Technology to enable future on-line process monitoring control when fabrication demontrators connected to pre-defined and open call use cases. The report demonstrates the capabilities and application of latest on-line process monitoring technology enabling future first part righ capacitity and repeatability. With the completition of this deliverable, the Miletone MS7 “On-line monitoring system for improved processing” is acheived. This has been verified by the manufacturing of defect free test samples of two materials, Ni-base alloy HX and stainless steel 316L, with strongly improved productivity without compromising material quality. Both cases are realised with small spread in as-printed relative density and the for the latter demonstration of mechanical properties better than standard is also shown.