

Deliverable D3.1

Analysis of sensors and identification of technical solutions

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Table of contents

Acronyms and abbreviations 5
References 6
Executive Summary 7
1. Introduction 8
2. Status on concerned pilot lines 9
3. Defects on laser technologies processes 11
3.1. Gas pores 11
3.2. Lack of fusion 12
3.3. Cracks 12
3.4. Thermal distorsion and support failure 13
3.5. Roughness & waviness 13
3.6. Lack of recoating 14
3.7. Layer shift 15
4. Monitoring of laser processes 16
4.1. Process signals 16
4.2. Process monitoring – integration of sensors 16
4.3. Surface and geometric inspection 17
4.4. Volumetric inspection 17
5. Sensors for laser technologies 18
5.1. Sensors for LPBF process monitoring 18
5.2. Sensors for DED and laser texturing process monitoring 18
5.3. Sensors for part quality control 19
5.3.1. Existing off-line NDI quality control 19
5.3.2. Existing in-line NDI quality control 19
6. Commercially available sensors 23
6.1. Eddy current sensor for in-situ defects for LPBF 23
6.1.1. Eddy Current DILAPRO test 24

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6.2. Project Fringe for powder bed monitoring for LPBF 26
6.3. AMiRIS for detection of defects for LPBF 27
6.4. SLM.Quality for SLM process monitoring for LPBF 28
6.5. Process Monitoring by Aconity for LPBF 28
6.6. AMSENSE® process monitoring for LBPF 29
6.7. Acoustic sensor for laser texturing and LPBF 30
6.8. Pyrometer for laser technologies 30
6.8.1. KLEIBER KG 740-LO 31
6.8.2. Dr Mergenthaler GmbH 31
6.9. Thermal camera for heat monitoring in DED 31
6.9.1. Optris 31
6.9.2. Xiris Automation GmbH 32
6.9.3. FLIR 32
6.9.4. Infrared camera DILAPRO test 32
6.9.5. Clamir / NIT 35
6.10. Profile sensors for DED 36
6.10.1. µepsilon scanCONTROL 36
6.10.2. LMI tecnnologies Gocator 36
6.10.3. Wenglor MLZL131 37
6.10.4. Falldorf Sensor 37
6.11. NLIGHT plasmo - Multi sensor system for DED 37
6.12. LIsec powder nozzle control 38
6.13. Primes – laser power and quality control 39
7. Sensor solutions for DILAPRO pilot lines 41
7.1. Pilot line 1: Hymax (CRM) 41
7.2. Pilot line 2: Ianus cell (P.ADD) 41
7.3. Pilot line 3: SLM (DTI) 41
7.4. Pilot line 4: NOMAD®03 (Fieldmade) 42
7.5. Pilot line 5: Aconity machine (DCU) 42

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7.6. Pilot line 6: Laser texturing (DCU) 43
8. Real-time process monitoring for automatic control 44
8.1. Overview of the plan for automatic control 44
8.2. Real-time feedback control using IR imaging 45
8.3. Quasi-real time feedback control using profilometry or acoustic emission 46
8.4. Quasi-real time feedback control using eddy current monitoring 47
9. Conclusion 48

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Acronyms and abbreviations

AM	Additive Manufacturing
CRM	Center of Research in Metallurgy
CMOS	Complementary Metal-Oxide-Semiconductor
CT	Computed Tomography
DCU	Dublin Center University
DED	Direct Energy Deposition
DTI	Danish Technological Institute
ET	Eddy current Test
Hymax	Hybrid and Manufacturing XI
IR	Infrared
IRT	InfraRed Thermography
LMD	Laser Metal Deposition
LPBF	Laser Powder Bed Fusion
MET	Optical metrology
NDI	Non-Destructive Inspection
PCRT	Process Compensated Resonance Testing
PT	Penetrant testing
UT	Ultrasonic testing
WAAM	Wire Arc Additive Manufacturing
WLAM	Wire Laser Additive Manufacturing

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Executive Summary

In this report, the most common defects observed on laser processes have been shortly described, followed by a state-of-the-art analysis of the non-destructive inspection techniques that can be used for DED, L-PBF and laser texturing processes. Trials have been performed with some sensors, to test their applicability for the DILAPRO project. An infrared camera has been tested in DED on Inconel 718 material. The camera was used as inline control system to detect over thicknesses and overheating areas. Other trials have been performed with eddy current sensors, where first results are presented in this deliverable.
Depending on the current pilot lines status and requirements, each pilot line has a focus on specific sensors. Some pilot lines need to focus on the process monitoring itself, while others are already equipped with process monitoring sensors, and will instead focus on sensors for the build part health. The solutions for each pilot line are described in detail below.

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1. Introduction

The DILAPRO project will improve additive manufacturing and laser production of complex products by creating a Digital Twin software which will be a key point for the digital certification of the produced part. To make the digital twin useable and reliable data should be measured, recorded and treated. This data will be measured with a combination of sensors.

This deliverable deals with **work package 3 "Monitoring and quality control"**. This work package aims to develop and build a hyperspectral sensor-based feedback control system to achieve *in-situ* quality control and in-process part certification for the laser technologies included in DILAPRO. The quality control will be done by monitoring the process parameters (laser power, laser speed, robot trajectory, wiper and elevator position, powder flow, melt pool size, machine status and process logs), the environment (O2 concentration, gas pressure and gas flow, temperatures).

In the report, the best available technologies and commercially available products will be identified. A reflection to find the optimal solutions, by the usage of a single type of technology or a combination of various technologies has been done.

In this study, the focus is on DED, LPBF and laser texturing. Other laser technologies will not be taken into account.

More specifically, the equipment which is concerned by this study are listed in the table below:

Table 1 Pilot lines that are used in DILAPRO project

Laser technology	Pilot line	Pilot line owner
DED	Ianus cell	Prima Additive
DED	Hymax	CRM
LPBF	SLM 280	DTI
LPBF	NOMAD03	Fieldmade
LPBF	Aconity Mini	DCU
Laser texturing	NKT Origami XP 4W femto-second laser IPG Photonics fibre laser 1.5 kW	DCU

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2. Status on concerned pilot lines

The detailed status of each pilot line can be found in the deliverable "D1.2 Identification and description of production lines available for use cases including boundary conditions and requirements for Digital Twin integration" [1]. The paragraph hereafter shows a brief overview of the pilot lines and their status on installed sensors.

There are two DED pilot lines:

- Hymax at CRM which is a tailor made and unique line in Europe with a 6-axis robot and 5 different printing heads. Currently, a camera monitors the melt pool size, and this camera is able to control the laser power to keep a constant melt pool size. However, this functionality has yet to be implemented and will require further experimentation. The Hymax also has access to a thermal camera. This camera is off-line, meaning that it is on a tripod right next to the external manipulator. We cannot measure the temperature of the melt pool, but it is used to observe the heating distribution within the build part.
- The IANUS multi-process robotic cell is based on a system consisting of an Autonox robotic arm and a laser source, inserted inside a cell with a working volume of 1600 x 1200 x 700 mm. Currently, the Ianus cell is equipped with a melt pool monitoring system.

There are three LBPF pilot lines:

- DTI is equipped with 3 SLM 280 machines. SLM 280 is a metal 3D printer with two twin IPG lasers (either 2X400W or 2X700W) and a 3D scan optic that allows build rates 80% faster than single laser machines. Currently, SLM 280 is equipped with sensors for the O2 concentration, for the temperature, and for the gas flow pressures.
- The pilot production line facilitated by Fieldmade is a NOMAD®03 microfactory. This mobile unit contains a modified DMG MORI LASERTEC 30 SLM unit for producing metal parts. At the beginning of the project, this equipment was limited to simple sensors integrated by default in the DMG MORI LASERTEC 30 SLM machine. These include oxygen sensors, temperature sensors and a low-resolution off-axis camera for process monitoring. Other sensors check the operating status of various components in the machine, such as laser power, elevator position etc.
- The AM pilot production line facilitated by DCU is Aconity 3D Printing Lab. This facility primarily contains an AconityMINI SLM machine to build complex 3D metallic components, and is currently installed with pyrometric sensors for IR data capture to interpret the melt pool temperatures of samples along each build layer.

Last, one laser texturing pilot line is used in the project:

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- A second pilot production line facilitated by DCU is Laser Processing Lab, which is the only pilot line in the consortium used for Laser Texturing. This unit contains an in-house constructed laser-based texturing and surface hardening equipment. The system combines two laser systems with a 5-axis stage. There is currently no *in-situ* sensor data collection from the laser texturing process. The system is digitalized in the control of the lasers, beam scanner, and stage.

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3. Defects on laser technologies processes

Prior to printing parts in additive manufacturing, there is an iterative process of parameter optimization for each material and each printing process. This is done to ensure process stability, metallurgical and mechanical integrity and dimensional accuracy of the printed material. Deviations from this optimized set of parameters, can lead to unacceptable defects in the final product. This optimized set of parameters does not necessarily lead to successful printing of parts due to their added level of geometrical complexity in some cases; sudden deviation in printing area, overhang, thin walls, bulky sections, etc.

The following sections describe common printing defects caused by process parameter deviations and their main characteristics: origin/cause, form, size and location relative to the build direction.

The most common defects that can be observed in AM and laser texturing are listed in the table below (the list in non-exhaustive):

Table 2 typical defect found in AM and laser texturing

Type of defect	DED	LPBF	Laser texturing
Gas pores	x	x	x
Lack of fusion	x	x	
Cracks	x	x	x
Thermal distorsion	x	x	x
Support failure		x	
Roughness & waviness	x	x	x
Lack of recoating		x	
Layer shift		x	

Those defects are detailed hereafter.

3.1. Gas pores

Description: Gas pores are spherical voids that contain gas within the printed solid material.

Typical size: 0 – 500µm

Common root cause: pores in the powder itself, pores from keyhole (LPBF), pores from melt pool surface fluctuation, dissolved gas precipitation, impurities on the substrate (DED and laser texturing), in aluminum alloys due to hydrogen in-take (humidity) (DED and laser texturing), low melting alloying elements can outgas during the DED process and lead to porosity (DED)

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Example of defect:

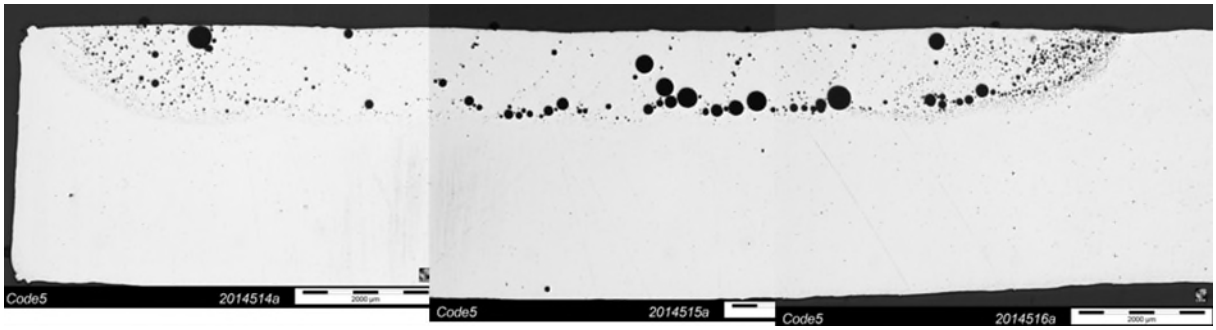


Figure 1 Cross-cut after laser texturing of an Al-based part

3.2. Lack of fusion

Description: Lack of fusion leads to irregular shaped pores, in LPBF they are partially filled with unmolten powder.

Typical size: in LPBF between 0 – 100 µm, in DED between 100 – 2000 µm

Common root cause: low energy density, incorrect overlap applied during path planning, too high speed and too high layer thickness (LPBF), contaminations

Example of defect:



Figure 2 Lack of fusion observed on a 316L LMD part

3.3. Cracks

Description: flat and sharp defects quite detrimental for mechanical properties

Typical size: 0 up to > 10µm, for

Orientation of the cracks: DED: perpendicular to stress direction (often perpendicular to the building direction), LPBF: various directions in places with high constrains: joining and/or splitting of geometries, sudden and harsh changes in section, sudden changes in thermal behavior.

Common root cause: Materials prone to solidification cracking, thermal stresses, hot cracking due to weld metal or HAZ embrittlement, Cold cracking with residual stresses.

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Example of defect:

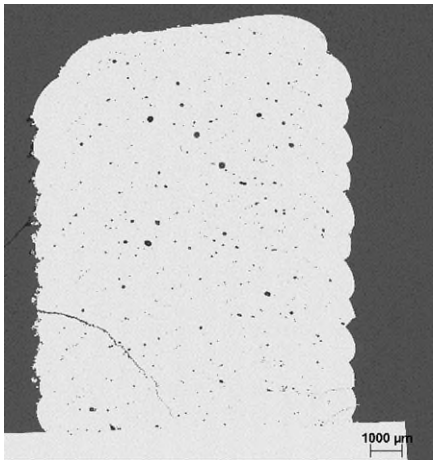


Figure 3 Example of solidifications cracks observed in a DED samples.

3.4. Thermal distorsion and support failure

Description: The thermal gradients during the printing process induce stresses and these stresses can lead to substantial distortions, depending on the part geometry

Typical size: 10 – 400mm

Common root cause: Thermal stresses, support failure (LPBF), base plate too compliant (DED), Insufficient support (LPBF), layer shift, poorly balanced residual stresses resulting from inhomogeneous thermal field.

Example of defect:

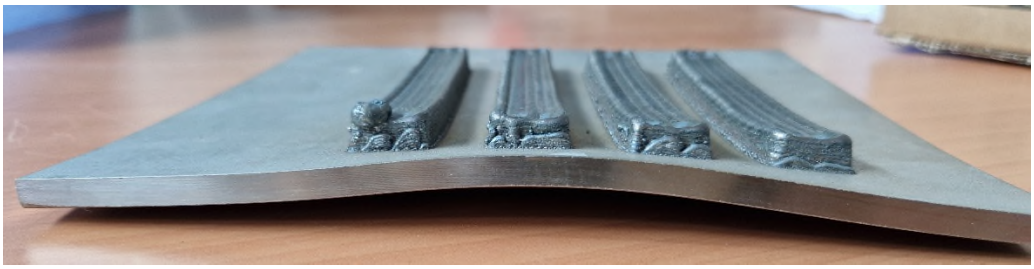


Figure 4 Build support deformation which induced defects on the geometry of the parts

3.5. Roughness & waviness

Description: The surface of AM parts varies strongly with orientation of the surface area; If it cannot be compensated by assigning specific parameters, the roughness varies. There is also a waviness with a size in the order of the layer thickness. For DED it can have an impact in the definition of the machining allowance.

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Common root cause: Imperfect parameters. Or that is a characteristic of the process, if the roughness or waviness don't match the specification, machining will be required.

Example of defect: In the graph below, a significant roughness variation can be observed depending on the printing trajectory.

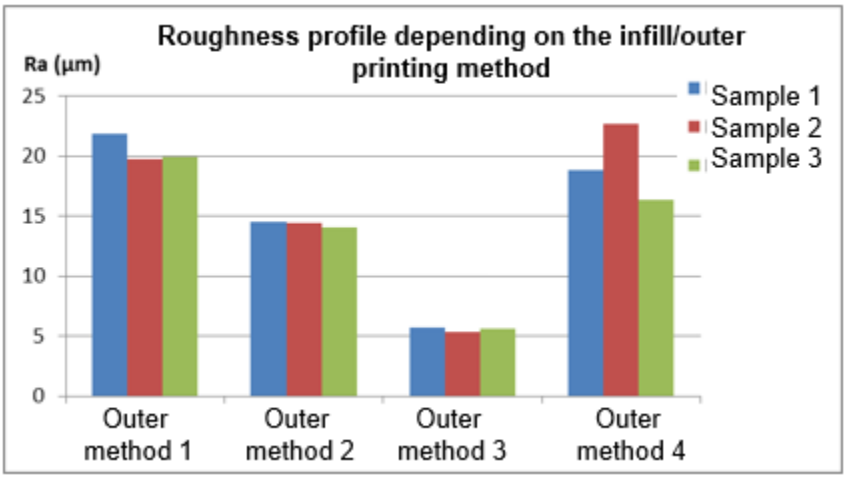


Figure 5 Graph of roughness of LPBF samples depending on the printing trajectory method

3.6. Lack of recoating

Description: The recoating between exposure of layers is not sufficient and the complete printing area is not covered with powder

Typical size: 10 – up to the length of the chamber

Common root cause: wrong settings on the machine, insufficient flowability of powder, algorithms for exposure area compensation not working.

Example of defect:

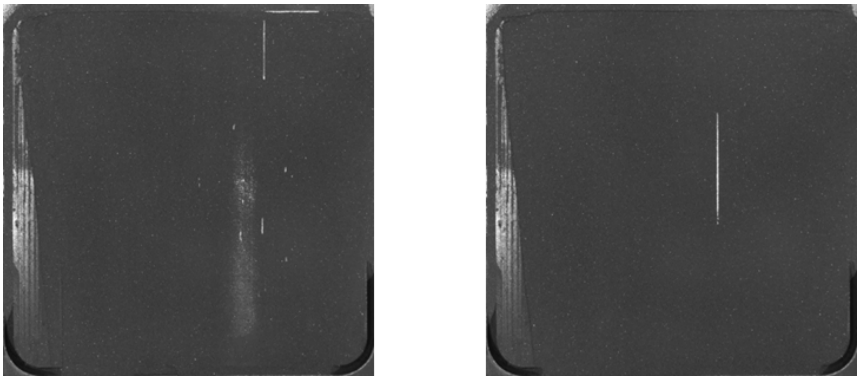


Figure 6 LPBF process - Some streaking observed during recoating

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3.7. Layer shift

Description: layer shifting occurs any time a layer is printed with a horizontal offset from where it should have been printed.

Common root cause: a layer shift can append in case of bad calibration, stop and start during the production, collision of the robot which could induce a shift (DED)

Example of defect:



Figure 7 LBPF process - Example of layer shifts

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4. Monitoring of laser processes

The monitoring of laser processes can be divided into four categories:

1) Process signals
2) Process monitoring
3) Surface and geometric inspection
4) Volumetric inspection

4.1. Process signals

The evaluation of process signals can be used to detect instabilities during the process. The readout of the pose of the handling system (robot or CNC-System) linked to the process signals allows to clearly locate a potential defect.

Indeed, the process signals allow to check that the process ran as planned with no deviation in terms of input of laser power, powder flow speed, robot speed and gas flow. The evaluation of powder flow speed is important, since an insufficient deposition of material will lead to different kind of defects. Irregularities within these parameters can be linked to the pose and therefore to a specific part section with potential defects.

4.2. Process monitoring – integration of sensors

The next step after verifying that the process parameters run acceptably, is to perform measurements during the process to confirm that everything is happening within the expected ranges. As first step the process log can confirm that the input is correctly set and as a second step, we can measure the actual value to check that it matches the input value.

For example, optical methods can be used to measure the actual powder flow speed, and the melt pool can be monitored to ensure a stability of the melt pool all along the building. Cameras can be installed on-axis (laser-based DED) and off-axis and additional optical filters, or illumination devices are suitable to increase the quality of the picture. The on-axis option in laser-based DED is advanced in determining 2D geometrical characteristics of the melt pool. Off-axis installations can also provide a view of the molten pool and the interaction with the feedstock.

Or infrared method can also be used to monitor the melt pool. Similar to the previous cameras, they can be installed on-axis and off-axis. The simplest example of infrared-sensors are pyrometers that are able to measure the temperature of the molten pool or any other part of the print and show the temperature prior calibration of the emissivity. There are already infrared cameras dedicated to the observation of the molten pool in on-line and off-line configurations.

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There are other methods that allow to obtain a picture of what is happening in terms of processing. Acoustic emissions during the print allows to detect deviations in the process as shown by Hauser et al. [2]. In their work, the measurement of the acoustic waves emitted during the process allowed to observe geometrical fluctuation during processing. Atomic emission spectra have also been used to perform a monitoring of the process by measuring the composition of the fumes released during printing.

4.3. Surface and geometric inspection

The in-line surface and geometry inspection aids in the detection of defects, assessment of surface roughness, validation of dimensional accuracy, and overall assurance of process quality. The inspection can be performed during the process or after the deposition of a complete layer or part section.

Suitable methods and systems to perform a geometrical or surface inspection are Profilometer, Optical coherence Tomography (OCT), Laser Triangulation and displacement sensors.

4.4. Volumetric inspection

The in-line application of sub-surface NDT inspection techniques in DED and LPBF technologies is not yet sufficiently robust and mature to be industrialised. Given the elevated temperatures involved, the use of conventional coupling agents is not possible; which implies that only contactless methods such as, thermography, laser ultrasonics, laser vibrometry, EMAT or Eddy-Current could be considered. None of these technologies however is today considered to be at TRL 4 or 5 when applied to in-line NDI.

Categories 4.2, 4.3 and 4.4 deal with sensors that are useful for the development of the digital twin and part qualification in the frame of the DILAPRO project.

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5. Sensors for laser technologies

5.1. Sensors for LPBF process monitoring

In LPBF, established processes include optical powder bed and melt pool monitoring. Optical powder bed monitoring uses cameras to record the build level before and after powder coating. Anomalies in the height profile of the powder bed and the exposed areas can be detected by image-processing reconstruction. In melt pool monitoring, photodiodes detect the emitted light of the melt pool during the exposure process. In addition to detecting the process light, different emission spectra allow the relative melt pool temperature to be determined. The data are mapped in the build level via the scan paths of the laser and generate a heat map of the exposure areas. Local deviations are used to draw conclusions about process instabilities and internal component defects (cracks, pores) in the generated layers.

5.2. Sensors for DED and laser texturing process monitoring

In DED, monitoring the welding data can provide valuable information about process instabilities and potential defects. The readout of the pose of the handling system (robot or CNC-System) is necessary to clearly locate a potential defect. The evaluation of powder flow is important, since an insufficient deposition of material will lead to different kind of defects. Irregularities within these parameters can be linked to the pose and therefore to a specific part section with potential defects.

Several methods can be suitable for the monitoring of the process parameters and the build. Optical methods, with image signals with a visible spectrum can be used to obtain pictures of the molten pool, depositing layers and feedstocks. Commonly CCD and CMOS cameras are used for monitoring in DED. Cameras can be installed on-axis and off-axis.

Off-axis installations can also provide a view of the molten pool and the interaction with the feedstock. As an example, the commercially available cameras proposed by Cavitar [3] or XIRIS [4] use machine learning to determine the geometry of the molten pool from optical video and can work in high luminosity environments such as LMD. They also enable a height measurement between process head and process zone with a respective evaluation of the recorded picture.

There are also infrared methods, these cameras are based on the intensity emitted by the hot processed part in the infra-red region of the spectrum. Similar to the previous cameras, they can be installed on-axis and off-axis. There are already infrared cameras dedicated to the observation of the molten pool in on-line and off-line configurations. One example is the CLAMIR [5] camera from NIT Technologies that is able to measure the area of the molten

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pool. It integrates a closed control loop to the power source to maintain the molten pool size.

There are other methods that allow to obtain a picture of what is happening in terms of processing. Acoustic emissions during WAAM allows to detect deviations in the WAAM process as shown by Hauser et al. [2]. In their work, the measurement of the acoustic waves emitted during the process allowed to observe geometrical fluctuation during processing. Atomic emission spectra have also been used to perform a monitoring of the process by measuring the composition of the fumes released during printing. These can be used to determine, for example, if an element is being evaporated in a higher rate than expected. Montazeri et al. [6] observed that this atomic emission information can be related to the amount of porosity in a layer-by-layer basis for L-PBF but could be extrapolated to DED.

5.3. Sensors for part quality control

Non-destructive Inspection (NDI) involves various inspection methods that do not cause harm or alter the properties of the tested materials. These techniques enable manufacturers to detect the previously listed surface irregularities, internal defects, and dimensional accuracy issues in the printed metal parts. These techniques are necessary for manufacturers and users to assess the overall quality of the printed components, ensure adherence to design specifications, and verify the structural integrity of the parts.

5.3.1. Existing off-line NDI quality control

A wide range of offline NDI technologies exists which can allow to detect the defects in an AM part, such as Computed Tomography (CT), Eddy current Testing (ET), Optical Metrology (MET), Penetrant Testing (PT), Process Compensated Resonance Testing (PCRT), Acoustic Emission (AE), Radiographic Testing (RT), InfraRed Thermography (IRT) and Ultrasonic Testing (UT). Those methods need to be performed off-line at the end of the process as an additional step.

5.3.2. Existing in-line NDI quality control

The topic of NDI in additive manufacturing is vast since there is not a single solution to detect all potential defects. Therefore, the choice of NDI for a printed part is usually made based on the defects of interest within the budget. Therefore, this becomes a costly process in terms of time allocation since, in most of the cases and for small batches, the control is usually discontinuous and difficult to fully automatize.

The role of in-line NDI techniques is somewhat to overcome this drawback by performing this task during printing, thus removing a costly operation in the manufacturing flow. A correctly selected and implemented in-line NDI process can have the following advantages:

- Early detection of process instabilities and defects: As some printing jobs can last for several days, it is important to detect any anomaly and make the decision on whether to stop the job, take corrective actions or continue the job.

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- Global analysis of the printed component: For some cases, it would be possible to NDI the whole component, large sections or locations of interest layer-by-layer. This will bring access to sections that are inaccessible once the whole component is printed.
- Pinpoint the location of observed deviations: in-line monitoring, in combination with process signals, can be used to determine the location within the component of a potential defect site. This would increase the performance of off-line NDI by limiting the number and scope of testing and increasing the success rate to find defects.
- Qualification: NDI results can be used to certify the respect of the requirements in terms of tolerances and health.

However, the use of only one sensor does not allow a reliable and comprehensive prediction regarding class, location, shape and criticality of the defect. Only the simultaneous consideration of the process characteristics central to the defect formation can guarantee a conclusion about the resulting part quality. For this purpose, the fused measurement data from multiple sensors must be analyzed.

In the LPBF process, in addition to the optical systems already available for geometry and melt pool monitoring, other non-destructive testing methods offer high potential for in-line NDI, most of which are still under development. Ultrasonic testing (UT) can be integrated into the build plate, allowing the volume of manufactured components to be inspected (but only applicable for very simple geometries). Thermographic testing (TT) is suitable because of the heat introduced into the component by the process laser during printing. Camera systems can be mounted outside the build chamber and thermograms of the surface can be taken and analyzed during manufacturing. Another very smart application is acoustic emission (AE) analysis. Here, the sound generated in the melt pool is detected and evaluated. Changes in the frequency spectrum can indicate faulty production. For electrically conductive materials (metals), eddy current testing (ET) is a common method for near-surface testing. The testable depth depends on the material properties and the test frequency. The testing technique itself must be brought close to the surface to be tested. For this purpose, the powder recoater is the obvious choice for all powder bed-based processes. In this way, during the powder coating process, both the printed surface and, for the first time, due to the depth effect of the eddy current test, the integrity of the layers produced last can be inspected. In this way, a three-dimensional electromagnetic tomogram is created layer by layer without the need for additional inspection time in the process sequence.

In-line NDI techniques are widely used in DED processes, since early machine setups were equipped with open controls. This allowed a flexible integration of monitoring systems and sensors.

The Table 3 and Table 4 below show the capabilities of in-line NDI techniques that are available on the market or on development for LPBF and DED/Laser texturing process respectively.

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Table 3 Capabilities of in-line NDI techniques for LPBF processes

SENSOR TECHNOLOGY	SENSOR SET-UP		PROCESS - IRREGULARITIES & DEFECTS FOR PROCESS MONITORING				PROCESS - IRREGULARITIES & DEFECTS FOR PART QUALITY CONTROL			
	On-axis	Off-axis	Deformation & Lack of powder	Emissions of melt pool	Size and shape of melt pool	Topography of powder	Geometry / contour of part	Topography of part	Porosity	Cracks
Event-based camera	✓	X	-	++	++	--	--	--	--	-
Event-based camera (scanning)	✓	X	+	--	--	--	++	--	--	--
Event-based camera	X	✓	+	++	--	--	0	--	-	--
Laser triangulation	/	✓	++	--	--	++	+	++	-	--
Conventional Camera	X	✓	+	-	--	-	++	-	--	--
Light Field Camera	✓	X	-	0	+	--	--	--	-	-
Light Field Camera (scanning)	✓	X	++	--	--	++	++	++	--	-
Light Field Camera	X	✓	+	-	--	+	+	+	-	--
Contact image sensor (CIS)	/	✓	++	--	--	+	++	+	-	--
Line-Scanner	/	✓	++	--	--	+	++	+	-	--
Photodiode	X	✓	--	+	--	--	--	--	-	-
Photodiode	✓	X	--	++	--	--	--	--	--	-
Pyrometry	✓	X	--	++	--	--	--	--	--	-
Fringe projection	X	✓	++	--	--	++	++	++	--	-
Thermal Camera	X	✓	-	+	--	--	-	--	-	-
Thermal Camera	✓	X	-	++	+	--	--	--	--	-
Acoustic sensor	X	✓	--	--	--	--	--	--	-	+
Eddy current	/	✓	--	--	--	--	++	--	+	+

Table 4 Capabilities of in-line NDI techniques for DED and laser texturing processes

SENSOR TECHNOLOGY	Sensor Set-Up		Process - IRREGULARITIES & DEFECTS For process monitoring			Process - IRREGULARITIES & DEFECTS For part quality control			
	On-axis	Off-axis	Distance between process head and part	Emissions of melt pool	Size and shape of melt pool	Geometry / contour of part	Topography of part	Porosity	Cracks
Welding camera	✓	X	--	-	++	-	-	--	--
Welding camera	X	✓	+	-	+	+	-	--	--
Structured light	X	✓	++	++	--	++	++	--	--
3D camera	X	✓	++	++	--	++	++	--	--
Pyrometry	✓	✓	--	++	--	--	--	-	-
Thermal Camera	X	✓	++	+	+	-	--	-	-
Thermal Camera	✓	X	-	++	+	--	--	-	-
Acoustic sensor	X	✓	--	--	--	--	--	-	+
OCT	✓	X	++	--	--	0	++	--	--
Laser triangulation	X	✓	++	++	--	++	++	--	--
Fringe projection profilometry	X	✓	++	++	--	++	++	--	--
Thermography	X	✓	--	--	--	--	+	-	+
Eddy current	X	✓	--	--	--	--	+	+	++
Laser ultrasonic	X	✓	--	--	--	--	--	+	++

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Electromagnetic acoustic transductor	X	✓	--	--	--	--	--	+	++

Legend

++	+	0	-	--
Very efficient	→			Not capable of measuring

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6. Commercially available sensors

In this section, the already commercially available sensors will be described, to give an overview of what is currently possible. The sensors that will be employed in the DILAPRO project are the Eddy current sensor for *in-situ* defect detection, acoustics sensors, thermal monitoring, melt pool temperature monitoring, laser power and layer thickness monitoring. These will be described for each pilot line in section 7.

6.1. Eddy current sensor for in-situ defects for LPBF

https://amiquam.net/

Description:
The eddy current technique is used to test the surfaces of conductive materials. Via electromagnetic coils the eddy currents are excited in the surface. If there is an inhomogeneity in the path of the current, it is deflected. This changes the magnetic field at the location of the sensor and topographic defects in the surface can be detected. Depending on the material and frequency used, internal defects in the material density (such as cavities, pores, e.g.) can also be detected. However, sensitivity decreases with increasing depth of penetration.
Currently, it is well developed for LPBF application, where the sensor is located at the recoater, being moved continuously across the build plate. Current versions (W1) only measure 1 or 2 specific lines on the build plate (which becomes a cross-section when layers are added on top of each other), and it is therefore not covering the entire build volume.
Within the DILAPRO project, it will be further developed on LPBF machines to cover the entire build plate (W2), and it will be implemented on DED equipment for the first time.

Test method / sensor technology: electromagnetic testing / eddy current sensor

Applicability to standards and industrialization potential:

- Normalised technique (ASNT, ISO15548, ASTM E1004-17, ASTM 3166:20, BS EN)
- Approved for AM in situ inspection ASTM 3166
- Compatible with AM QC standards ASTM 52930
- Technique of choice for surface breaking crack detection in metallic components

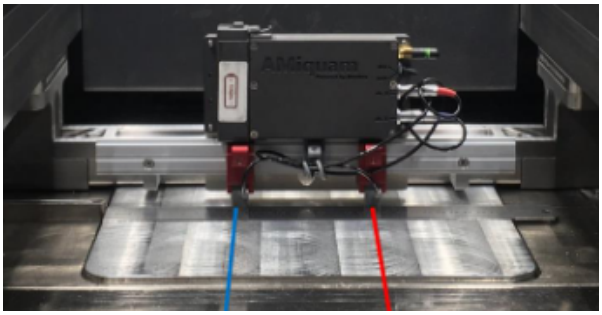


Figure 8 Image of wireless and retrofittable AMiquam W1 eddy current sensor on powder recoater of a EOS machine

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The table below show the type of defects which can be detected by the eddy current sensor (column ET of Table 5).

Table 5 Extract from ASTM E3166-20 [7]

TABLE 3 Application of NDT to Detect Additive Manufacturing Discontinuity Classes[A]

	Covered in this Guide							Not Covered in this Guide				
Discontinuity Class	CT/RT/ CR/DR	ET	MET[B]	PCRT	PT	IRT	UT	AE	LT	NR	MT	VT
Surface	X[C]	X[D]	X	–	X[D]	–	–	–	–	–	–	X
Porosity	X	X[D]	–	X	X[D]	–	X	–	–	–	–	X
Cracking	X[E]	X[D]	–	X	X[D]	X	X	X	X[F]	–	X	X[G]
Lack of Fusion	X[E]	X[D]	–	X	X[D]	X	X	X	–	–	X	–
Part Dimensions	X	–	X	–	–	–	–	–	–	X[H]	–	–
Density[I]	X[J]	–	–	X	–	–	–	–	–	–	–	–
Inclusions	X[K]	X[D]	–	X	–	X	X	–	–	–	–	–
Discoloration	–	–	–	–	–	–	–	–	–	–	–	X
Residual Stress	–	X[D,L]	X	X	–	–	–	–	–	X	–	–
Hermetic Sealing	–	–	–	–	–	–	–	–	X[F]	–	–	–

[A] Abbreviations used: – = not applicable, AE = Acoustic Emission, CR = Computed Radiography, CT = Computed Tomography, DR = Digital Radiology, ET = Eddy Current Testing, IRT = Infrared Thermography, LT = Leak Testing , MET = Metrology, MT = Magnetic Particle Testing, NR = Neutron Radiography, PCRT = Process Compensated Resonance Testing, PT = Penetrant Testing, RT = Radiographic Testing, UT = Ultrasonic Testing, and VT = Visual Testing.
[B] Includes Digital Imaging.
[C] Especially helpful when characterizing internal passageways or cavities (complex geometry parts) for underfill and overfill, or other internal features not accessible to MET, PT, or VT (including borescopy).
[D] Applicable if on surface.
[E] Radiographic methods are not optimal for detecting tight laminar features like cracking and LOF, which typically do not exhibit enough density change.
[F] If large enough to cause a leak or pressure drop across the part.
[G] Macroscopic cracks only.
[H] Conventional neutron radiography (NR) allows determination of internal and external dimensions.
[I] Pycnometry (Archimedes principle).
[J] Density variations will only show up in imaged regions having equivalent thickness.
[K] If inclusions are large enough and sufficient scattering contrast exists.
[L] Residual stress can be assessed if resulting from surface post-processing (for example, peening).

6.1.1. Eddy Current DILAPRO test

A sensor trial run was performed at DCU, where the Eddy Current sensor W1 from Amiquam has been installed on the Aconity Mini.
Below is a report from Medad Monu, Josiah Chekotu, Eanna McCarthy and Dermot Brabazon.

PBF-LB equipment: AconityMINI® 3D with a 200 W– 1068nm Yb fibre laser

Parameters: Full factorial (FF) DoE of 4 factors in 4 levels (4^4) = 256 samples
Laser power = [80, 120, 160, 200] W ; Scan speed = [600, 800, 1000, 1200] mm/s; Hatch spacing = [60, 90, 120, 150] µm; Spot size = [80, 90, 100, 110] µm; Layer thickness = 50 µm (constant)
Metal powder type: 316L stainless steel
Particle Size Distribution = 15 – 45 µm

For the sensor trial run, we printed only 84 samples, from the lot of 256 samples

Sample geometry: The experiment involved 70 samples with dimensions of 7 x 7 x 7 mm and 14 larger samples measuring 11.5 x 11.5 x 5 mm. Pyrometry and acoustics sensors were used to monitor the entire build, covering all 84 samples. However, eddy current sensors were used exclusively to monitor the 14 larger samples (11.5 x 11.5 x 5 mm).

Print Layout: Samples were printed according to sample number in the image below. That is, from left to right, starting from the top to bottom.

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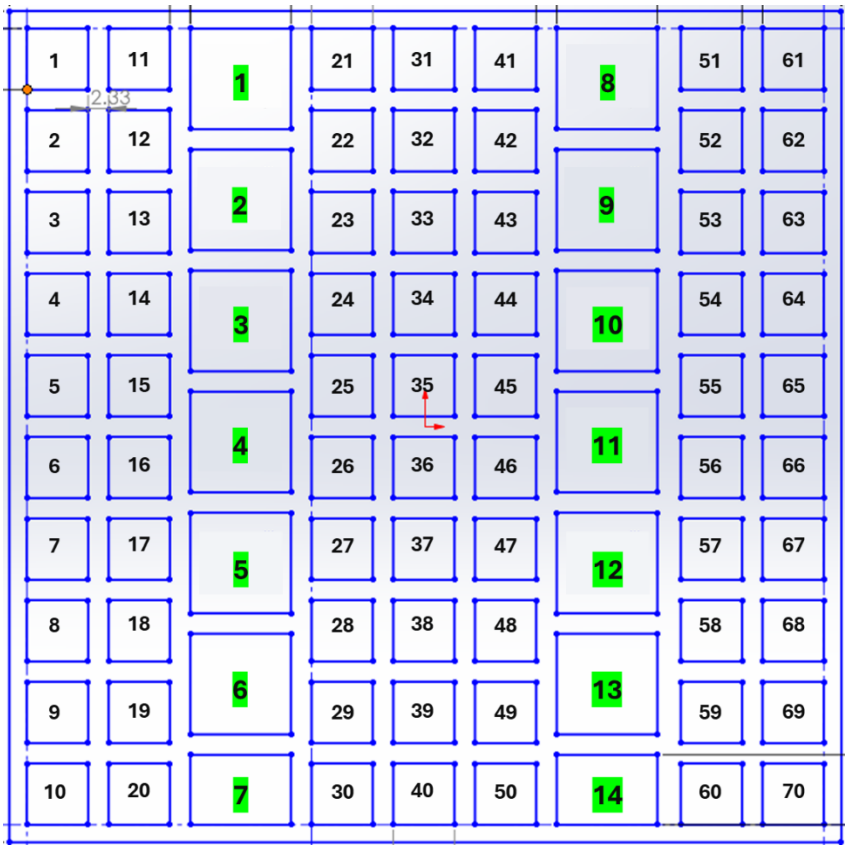


Figure 9 Samples layout

Sensor information:

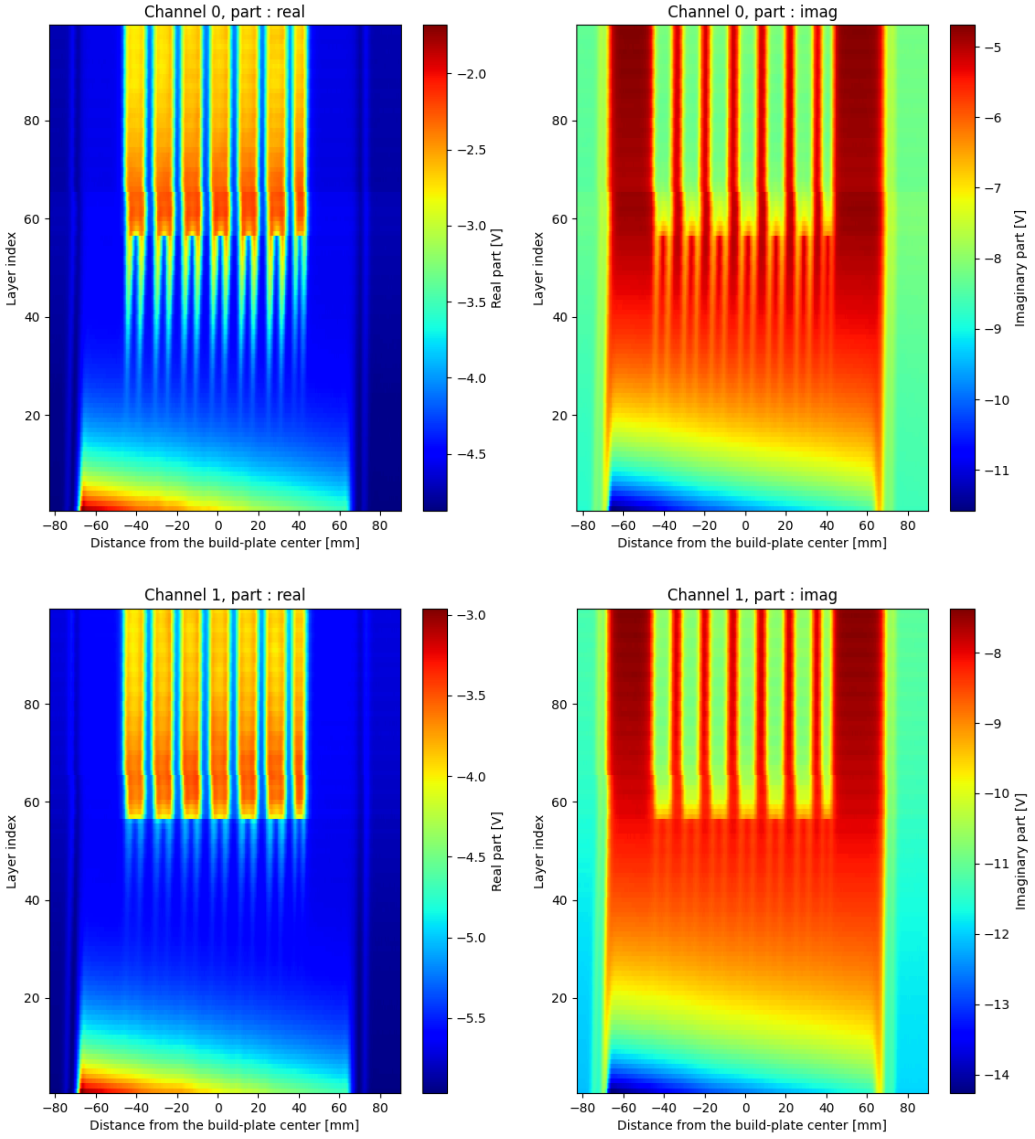
Sensor	Make/Model	No. of Channels	Acquisition rate	Measure property	Data range and state	format
Pyrometer	Kleiber® KG 740 - LO pyrometers	2	100kHz	Melt pool thermal infrared emission (.e., melt pool temperature)	Only 2.85pcd to 5.pcd (raw data)	Structured data (.pcd) X, Y, Temp, Temp
Eddy Current	AMiquam	2	380Hz	Thermal conductivity	Full raw data	mySQL database format
Acoustics	Avisoft-Bioacoustics CM16/CMPA	1	100kHz	Laser-powder noise interference	Full raw data	Audio (.wav)

Every **.pcd** file in the Pyrometer data folder represents one layer. Thus, file 2.85.pcd refers to sample build layer height of 2.85 mm, and 5.pcd is 5mm

Eddy current data: We sent the data from the eddy current sensor to AMiquam for post-processing. The resulting image as shown below is what we received. It illustrates the thermal conductivity variations in the build part along the building direction (i.e., the height of the sample). The image displays samples 1 to 7 from left to right, within each eddy current

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channels (i.e., Channel 0 is for samples 1 to 7 (left to right), and Channel 1 is for samples 8 to 14). This corresponds to samples 1 to 7, and 8 to 14 from the print layout.



At present, we are still trying to figure out how to extract insights from the audio file recording given the amount of noise in the data. What we know from literature is that the relevant audio frequency to PBF-LB process is in the range of 0.5 to 50 kHz.

6.2. Project Fringe for powder bed monitoring for LPBF

https://www.additivemonitoring.com/

Description:
The Fringe in-situ monitoring technology measures the full-field height of every powder and melted layer surface and performs a 3D-topographic powder bed inspection. The

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technology records objective data using a repeatable process to produce quantifiable units of the powder bed surface.
The scan area is 280 x 280 mm with spatial resolution of 100 µm in X,Y with a height resolution of 10 µm in Z.

Test method / sensor technology: optical inspection / fringe projection

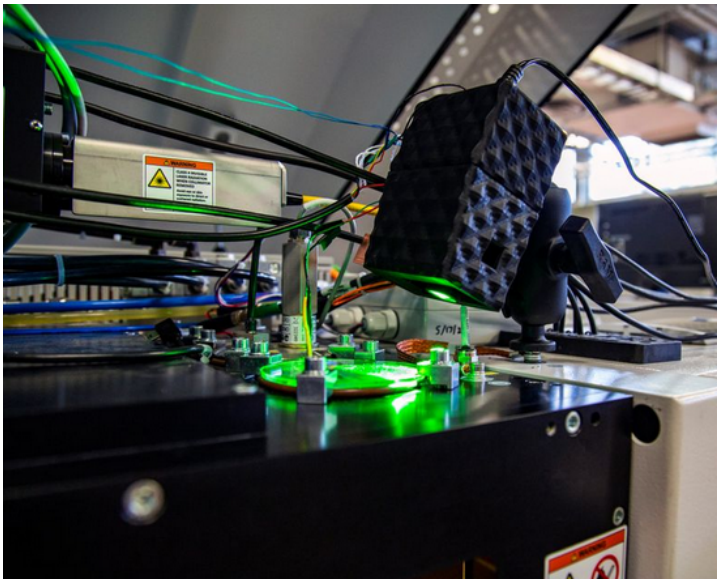


Figure 10 View of the fringe 3D sensor - www.phase-3d.com

6.3. AMiRIS for detection of defects for LPBF

www.additiveassurance.com

Description:
The patent pending technology combines a suite of optical sensors to gather micron-level detail, and through machine learning provide rich insight into the process. This equipment gives an indicative detection of anomalies in melted surfaces but only from a size of 300 µm and of bigger size stated as detectable.
Multiple CMOS Sensors (Off Axis) with NIR-spectrum (720 – 850 nm) in long exposure mode (several working in parallel)

Measurement characteristics:

- High-resolution images down to 10 µm per pixel for a 250 x250 mm2 build platform

Test method / sensor technology: optical inspection / CMOS sensors

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6.4. SLM.Quality for SLM process monitoring for LPBF

www.nikon-slm-solutions.com

Description:
The package sensor and software offers the following capabilities:

- Melt Pool Monitoring: 2 Photodiodes (Visible Light and IR) for each laser
- Layer Control System: one or two visual camera(s) (off-axis) depending on machine size
- Laser Power Monitoring
- Additive.Quality software
    - Thermal emissions for each scan vector
    - Material independent
    - Real-time 2D layer visualization

Measurement characteristics:

- Indication for process instabilities and internal part defects, direct defect detection measurement in powder bed for:
    - Part deformation
    - Geometry and contour of part
- Inhomogeneities in powder recoating
- Investigated layerwise emission profile gives an indication for detection of process instabilities and part defects like:
    - Anomalies in melt pool emission indicatively linked to heat transfer and melt pool temperature

Test method / sensor technology: optical inspection

6.5. Process Monitoring by Aconity for LPBF

www.aconity3d.com

Description:

- Pyrometer (single / dual)
    - Spectral range: 2 / 1,5 - 2,2 µm
    - Measuring range: 500 - 2500 °C
    - Measurement area: ca. Ø 400 µm, lateral adjustable
    - Frame rate: 100 kHz
- Coaxial Highspeed camera (CMOS)
    - Image section: ca. 3 x 3 mm^2
    - Resolution: 320 x 320 px
    - Frame rate: 5 kHz

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- Thermal imaging
  - Spectral range: 7.5 - 14 µm
  - Temperature range: - 40 - 2000 °C
  - Detector type: Microbolometer
  - Image format: 2,048 x 1,536 pixels
  - Repetition rate: 30 Hz at 1.024 x 768 Pixel, 240 Hz at 1.024 x 96 Pixel

Measurement characteristics:
Investigated layer wise emission profile gives an indication for detection of process instabilities and part defects like anomalies in melt pool emission indicatively linked to heat transfer / melt pool temperature.

Test method / sensor technology: Optical inspection

6.6. AMSENSE® process monitoring for LBPF

www.arctos-us.com/additive-manufacturing/

Description:
Arctos propose a global solution composed with several sensors to cover the process monitoring and defect detection:

- AMS-RECOAT for powder bed monitoring (CMOS Camera) (off axis)
  - Layer and recoating monitoring
  - 12 MP CMOS Camera (off axis)
- AMS-TOMO Thermal tomography sensor (NIR-spectrum) (off-axis)
  - Resolution 100 µm/pixel
  - Data can be plotted in xy and xz plane
- AMS-heatCAM Long-Wave IR camera to track solid state heat flow
- AMS-SPAT Spatter Tracking sensor
  - Automated identification and tagging of multiple spatter events
  - Resolution 200 – 250 µm/pixel
- AMS-MVIEV high-speed co-axial camera to track melt-pool size and shape

Measurement characteristics:
- AMS-RECOAT:
  - Detection of part deformation and inhomogeneities in powder bed (lack of powder, powder trenches, ...)
- AMS-TOMO:
  - Tracking and mapping of emissions of melt pool as indication for process instabilities and part defects
- AMS-heatCAM:
  - Tracking and mapping of cooling behaviour within the build plane as indication for part defects

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- AMS-SPAT:
  - Tracking of process spatter behaviour within the build plane as indication for process instabilities (overheating, keyhole welding)
- AMS-MVIEV:
  - Tracking and mapping of emissions of melt pool as indication for process instabilities and part defects
  - Tracking of melt pool dynamics (size and shape) as indication for process instabilities and part defects

Test method / sensor technology: optical inspection / various sensors (TT, high-speed imaging, long-wave IR imaging)

6.7. Acoustic sensor for laser texturing and LPBF

https://avisoft.com/ultrasound-microphones/cm16-cmpa/

Description:
Avisoft condenser ultrasound sensors combined with the software Avisoft-SASLab Pro allow to detect some defects in the bulk material (porosity, crack, etc).

Measurement characteristics:
- Frequency range of 2 kHz – 200 kHz
- Approximate input-referred self-noise Level (bandwidth: 30-50 kHz): 18 dB SPL
- Approximate sensitivity: 500 mV/Pa
- Software: Avisoft-SASLab Pro
-

Test method / sensor technology: Ultrasound microphone

LPBF Aconity machine at DCU has just been equipped with this sensor. The filtered Acoustic data will be used as is, for Machine learning. The same acoustic sensor, generating the same form of data, are being fitted to the Laser Texturing system at DCU where they will also be used for Machine learning.

6.8. Pyrometer for laser technologies

Description: Pyrometer allows to monitor the melt-pool temperature to achieve a constant and homogeneous track width. And thus to identify any deviation during the printing process. Pyrometer can be placed on-axis, and coaxial. They are equiped with a LED-pilot light to enables quick and accurate focus.

Test method / sensor technology: Infrared radiation and fibre optics

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6.8.1. KLEIBER KG 740-LO

https://www.kleiberinfrared.com

The KLEIBER 740 - LO with fibre optics is a high speed pyrometer for very fast temperature measurements. The emissivity correction is adjustable between 0.1 and 1.0.

Main characteristics:
- Measures in the range 500-2500°C
- Spot sizes from 0.3 mm to 11mm
- Response time 6 μs

6.8.2. Dr Mergenthaler GmbH

https://www.mergenthaler-laser.com

The digital Mergenthaler infrared 2 color pyrometers is independent of the emissivity of the material and the spot size. And can work in a closed loop controlled process. Indeed the slow heating of the workpiece during the process gradually creates an ever widening welding seam and this undesirable process is counteracted by the closed loop temperature control.

Main characteristics:
- High Speed fiber coupled 2 Color Pyrometer
- Temperature is independent of the emissivity of the surface
- Measures in the range 800-2200°C
- Measurement period: From 0,1 ms
- Spot diameter from 100 µm
- Closed loop controlled process is possible
- software LASCON Process Manager

6.9. Thermal camera for heat monitoring in DED

Description:
The thermal camera allows to monitor the thermal history during the building of the part. Depending on the temperature range, this sensor is usefull to identify the interpass temperature, to detect overheating areas, to monitor the melt pool (size and temperature), to monitor the deposited material temperature, etc.The camera can be installed off or on-axis.

Test method / sensor technology: Optical inspection / thermal camera

6.9.1. Optris

www.optris.com

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This camera is only partially suitable for process monitoring due to its limited temperature range. It is interesting to measure the interpass temperature, the overheating areas and deposited material temprature.

Main characteristics:
- The thermal camera measures within LWIR range (8 µm - 14 µm)
- Software: optris PIX Connect
- Various options for optical settings or temperature ranges
- Resolution: 80 x 80 (Xi 80); 382 x 288 (Xi 400)
- Framerate: 50 fps (Xi 80); 80 fps (Xi 400)
- Temperature (variable ranges possible): 150… 900°C (Xi 80); 200… 1500°C (optional for Xi 400)
- Spectral range: 8 –14 µm

6.9.2. Xiris Automation GmbH

www.xiris.com

Due to its large temperature range, this camera allow to monitor the melt pool size and temperature but also to measure the interpass temperature and the deposited material temperature.

Main characteristics:
- Resolution: 640 x 512
- Framerate: 180 fps
- Temperature: 350 - 1500°C (extension to 400 – 1850 °C possible)
- Spectral range: 900 –1700 nm

6.9.3. FLIR

https://www.flir.eu/

Main characteristics:
- Resolution: 640x512
- Framerate: Programmable; Up to ~45 Hz (GigE), 60 Hz (CXP)
- Temperature: (extension to 400 – 1850 °C possible)
- Spectral range: 3.0–5.0 µm

6.9.4. Infrared camera DILAPRO test

Two trials were performed with a FLIR camera. The FLIR infrared camera was used to monitor WAAM and WLAM tests. The camera was used as inline control system to detect over thicknesses and overheating areas and to analyse the thermal history during the construction of the part.

First test:
Equipment: WAAM torch from Lorch installed on Hymax at CRM.

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Material: Inconel 718 1mm wire diameter.
Some of the results are shown hereafter:

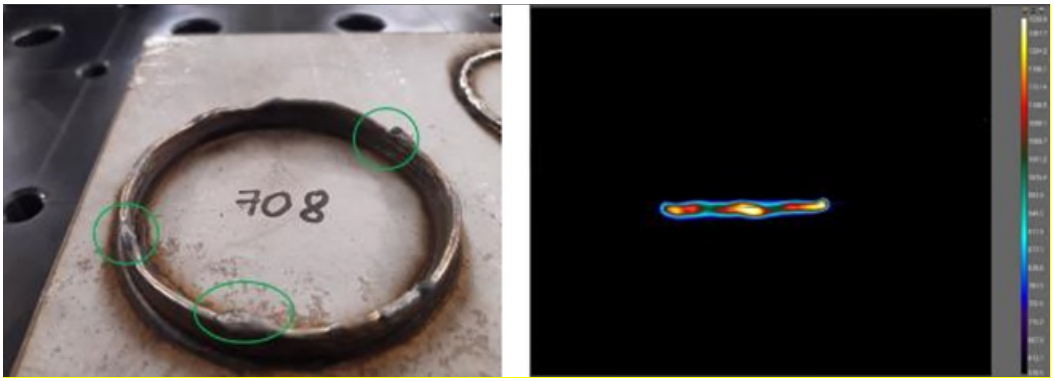


Figure 11 (left) over thicknesses and (right) corresponding hot spots

The corresponding temperature profiles for over thicknesses and sound areas are shown here under.

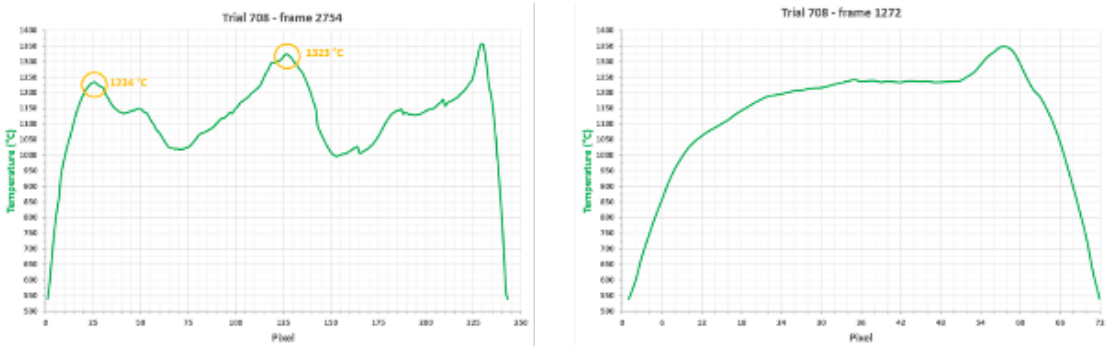


Figure 12 (left) temperature profile when over thicknesses are faced and (right), temperature profile without over thicknesses

This camera was also used to detect the appearance of oxidation areas, as shown in the following figure.



Figure 13: (left) oxidation areas during WAAM manufacturing and (right) temperature profile of different areas

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The oxidized areas are induced by overheating during the manufacturing process.

Second test:

Equipment: Precitec WLAM head installed on Hymax at CRM.
Material: Inconel 718 1mm wire diameter.
Parameters: The length of the sample is 150mm, each layer measure 0.67mm heigh and ten layers were done. The wire head speed was 1.2m/min and the wire speed was 2.2m/min
Some of the results are shown hereafter:

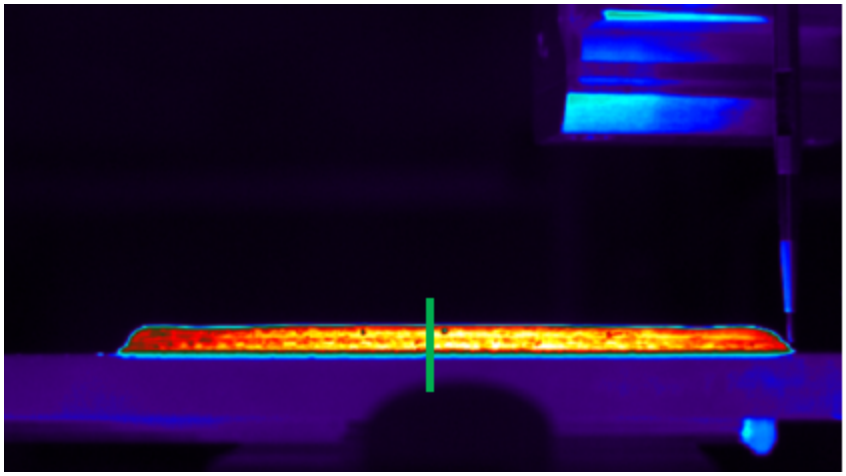


Figure 14 IR camera side view after 10 layers

The data were registered at 50Hz which means one measure each 20ms. Then a column was selected on the middle of the wall and the temperature history was analysed (see green line on Figure 14).

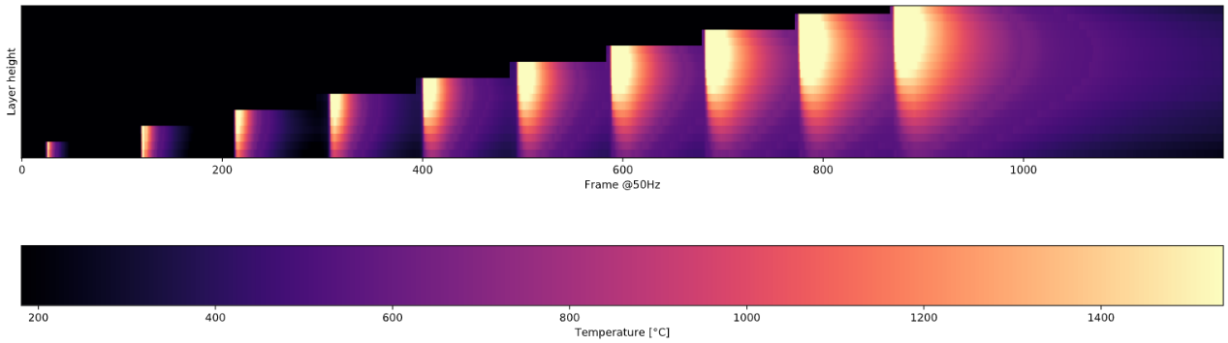


Figure 15 Temperature behaviour between the first layer and the final layer

The Figure 15 gives an overview of the temperature behaviour all along the column. We can observe that the temperature increases gradually during the build.

Another observation is the temperature evolution on one point, see Figure 16. It can be observed that at each pass of the head, the temperature increases but this temperature rise decreases gradually with the number of layers.

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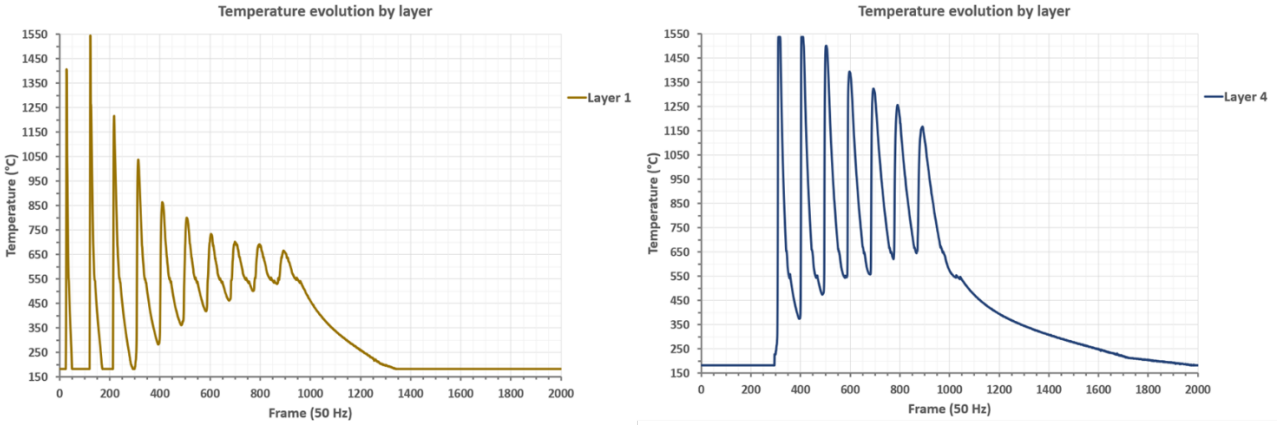


Figure 16 Temperature evolution on one layer (layer 1 on the left and layer 4 on the right)

These tests have shown that the thermal camera installed can give valuable input to the DILAPRO pilot line and it will be used throughout the project.

6.9.5. Clamir / NIT

www.niteurope.com

This camera is useful to monitor the melt pool geometry and it can be used for closed-loop process control. The laser power can be automatically adjusted by the Clamir software to keep a constant melt pool size.

Main characteristics:

- Thermal camera measures the melt pool and deposited material with MWIR range (1 µm - 5 µm)
- Software: NIT Visualization SW v.2.1
- Resolution: 128 x128
- Framerate: 2000 fps – 4000 fps
- Spectral range: 1 µm - 5 m
- On or off-axis

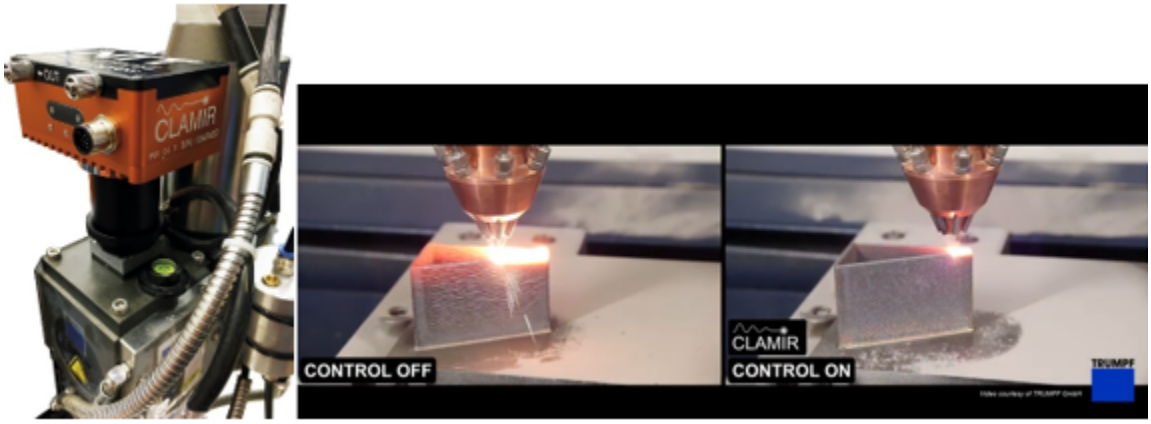


Figure 17 Clamir on Hymax pilot line and effect of close loop control on the melt pool

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6.10. Profile sensors for DED

Description:
The profile sensors work with the laser triangulation technology. Depending on the brand and the series, there are different working distance which affects the size of the scanning field and the resolution.
With this type of sensor, the following aspects can be checked during the printing:

- Weld track height
- Weld track width
- Seam offset
- Shape deviations, distortion

Test method / sensor technology: Optical inspection / Laser triangulation sensor

6.10.1. µepsilon scanCONTROL

https://www.micro-epsilon.fr/

Micro Epsilons Laser profile sensor from the scanCONTROL series are high performing profile sensors. It is available with a red laser diode (658nm) or with a blue laser diode (405nm) suits for hot object surface exceeding 700°C).
Two options are available: compact and smart

- Compact: provide calibrated profile data that can be further processed with own software evaluation on a PC.
- Smart: provide selected measurement values. The configuration of the sensors and measurement programs is stored in the internal controller.

Measurement characteristics:

- Measurement range: 100 mm (x-axis) and 265 mm (z-axis)
- Resolution: 1280 points (x-axis) and 12 µm (z-axis)
- Frame rate:
- Standard up to 300 Hz
- Highspeed up to 2000 Hz

6.10.2. LMI tecnnologies Gocator

https://lmi3d.com/

Depending on the model, the resolution, field of view, clearance distance and measurement range are differents.

Measurement characteristics:

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Model	2320	2330	2340	2350	2370	2375	2380
Resolution X (mm)	0.014	0.044	0.095	0.150	0.275	0.255	0.375
Resolution Z (mm)	0.0018	0.006	0.013	0.019	0.055	0.175	0.092
Field of View(mm)	18 - 26	47 - 85	96 - 194	158 - 365	308 - 687	324 - 1010	390 - 1260
Clearance Distance (mm)	40	90	190	300	400	650	350
Measurement Range (mm)	25	80	210	400	500	1350	800

6.10.3. Wenglor MLZL131

www.wenglor.com

Laser triangulation scanners using blue laser (450 nm) with integrated protective housing. And integrated data evaluation for tracking point determination is possible as an option.

Measurement characteristics:

- Measurement range: 38 – 62 mm (x-axis) and 84 mm (z-axis)
- Resolution: 32 –64 µm (x-axis) and 8.3 - 32.5 µm (z-axis)
- Frame rate:
- Standard up to 200 Hz
- Highspeed up to 4000 Hz

6.10.4. Falldorf Sensor

www.falldorfsensor.de

Laser triangulation sensor with integrated protective housing and cooling.

Measurement characteristics:

- Measurement range: 80 mm (x-axis) and 60 mm (z-axis)
- Resolution: 30 µm (x-axis) and 77 µm (z-axis)

6.11. NLIGHT plasmo – Multi sensor system for DED

https://www.plasmo.eu/en

Description:
Plasmo systems enable the detection of process irregularities through sensor and camera based technologies (processobserver, plasmoeye, profileobserver). Furthermore, processing positions as well as process parameters are recorded. Close-loop process control work in progress.

- Multi-sensor system:
    - Processobserver (Diode)

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  - Plasmoeye (NIR camera)
  - Profileobserver (Laser triangulation)
  - Integration of additional sensors possible
- Software package provides various algorithms, statistical models and graphical data analysis:
  - Processobserver 6.0
  - Plasmoeye NIR
  - Offline Reader V5

Measurement characteristics:
- Processobserver:
  - Framerate: 250 Hz
  - Range: 400 – 1800 nm

Test method / sensor technology:
Applicability to standards ans industrialization potential:

6.12. Llsec powder nozzle control

www.iws.fraunhofer.de

Description:
As a significantly process-influencing piece of hardware, the condition of the powder nozzle must be checked and evaluated regularly in order to carry out reproducible processes. This device is off-axis but a semi-automatic measurement can be put in place between every x layers for example.

Measurement characteristics:
Analysis of the powder cone, detection of irregularities within the cone

Test method / sensor technology: high speed camera / image analysis

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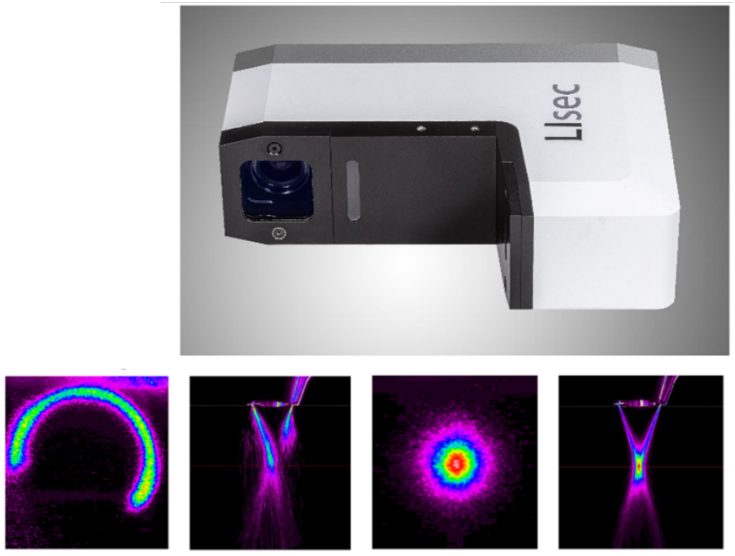


Figure 18 LIsec machine and examples of image analysis

6.13. Primes – laser power and quality control

https://www.primes.de/en

Description:
Laser power and beam quality are both essential aspects for a stable process. Depending on the raw material the initial power and the building power can be critical point. Moreover having a stable laser profil is important especially in case of process deviation regarding the working distance.
The cube is short time measurement devices and gives only the laser power. This allows to check the input laser power and the real output laser power.
The combination of the PowerMonitor PM48 and the FocusMonitor FM+ allows to measure the laser power and the profil.

Measurement characteristics:
Accuracy of +/- 3 %. With a reproducibility of +/- 1 %



Figure 19 Primes power monitor and focus monitor

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Within Dilapro project, several sensors will be installed on the different pilot lines : Pyrometer, acoustic emission sensor, eddy current sensor, thermal camera, laser power monitoring and laser triangulation sensor.

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7. Sensor solutions for DILAPRO pilot lines

In this section, the sensors that will be (or have already been) implemented in the project on the DILAPRO pilot lines are described.

7.1. Pilot line 1: Hymax (CRM)

What is missing on the Hymax pilot line is the history of printing. Thus, the effort is put on the implementation of recording systems to be able to record the process logs, robot trajectory etc. And few sensors to be able to monitor the essentials parameters like laser power, gas flow rate, melt pool temperature, layer thickness and thermal history.

Table 6 Sensors solution for pilot line 1

Parameter	Device	Comments	Status
Melt pool temperature	Dr Mergenthaler GmbH and laserline	To monitor the melt pool temperature all along the process, identification of hotspots	To be installed
Laser power	Primes "The cube"	To check the real laser power	Installed
Layer thickness	LMI technologies or µEpsilon	To scan the whole surface between each deposited layer and be able to detect any dimensional deviation and to check the layer height.	To be installed

7.2. Pilot line 2: Ianus cell (P.ADD)

The pilot line of Prima Additive already has solutions to monitor the melt pool and basic process parameters like temperature, gas flow rate etc. So they will focus towards the direct defect analysis by implementing the eddy current sensor of AMIQUAM.

Table 7 Sensors solution for pilot line 2

Parameter	Device	Comments	Status
Subsurface defects detection	AMIQUAM – Eddy current sensors	Identification of near-surface instability in melt-pool (crack formations); pore formations - location and depth; residual stress	To be installed

7.3. Pilot line 3: SLM (DTI)

Currently, SLM 280 have sensors for O2, temperature and gas flow rate measurement. The process parameters are already covered, so the focus will be on the build part health. Therefore, an Eddy current sensor from Amiquam and a thermal camera that can enable thermal imaging will be installed on this pilot line.

Table 8 Sensors solution for piot line 3

Parameter	Device	Comments	Status

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Subsurface defects detection	AMIQUAM – Eddy current sensors	Identification of near-surface instability in melt-pool (crack formations); pore formations - location and depth; residual stress	To be installed
Thermal monitoring	Thermal camera to be determined	Identification of hotspots, thermal concentration, and thermal dispersion in the part	To be installed

7.4. Pilot line 4: NOMAD®03 (Fieldmade)

At the moment, the level of sensor integration in the NOMAD®03 microfactory was limited to simple sensors integrated by default in the DMG MORI LASERTEC 30 SLM machine. Meaning that the pilot line is already equipped with sensors to monitor the process itself (laser, power, gas flow rate, temperature, off-axis camera for thermal analysis). And within the DILAPRO project they will focus towards the direct defect analysis by implementing the eddy current sensor of AMIQUAM.

Table 9 Sensors solution for pilot line 4

Parameter	Device	Comments	Status
Subsurface defects detection	AMIQUAM – Eddy current sensors	Identification of near-surface instability in melt-pool (crack formations); pore formations - location and depth; residual stress	System installed

7.5. Pilot line 5: Aconity machine (DCU)

This LPBF pilot line already contains pyrometers for melt pool monitoring and sensors for gas flow rate and temperature of the chamber and substrate measurement. The machine is being retrofitted with eddy current sensors and acoustic emission sensors. These two different technologies along with pyrometric sensors will be used to capture in-situ data and prevent any defects or deviation during the printing process.

Table 10 Sensors solution for pilot line 5

Parameter	Device	Comments	Status
Subsurface defects detection	AMIQUAM – Eddy current sensors	Identification of near-surface instability in melt-pool (crack formations); pore formations - location and depth; residual stress	Installed
Pore and defects formation	Acoustic emission sensors - Avisoft Bioacoustics	To scan the whole surface between each deposited layer and be able to detect any dimensional deviation and to check the layer height.	Installed

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7.6. Pilot line 6: Laser texturing (DCU)

The laser texturing pilot line, the system is digitalized in the control of the lasers and beam scanner but there is currently no in-situ sensor data collection. With these sensors, the defect formation could be prevented.

Table 11 Sensors solution for pilot line 6

Parameter	Device	Comments	Status
Melt pool temperature	KLEIBER KG 740-LO Measures in the range 500-2500°C	Identification of hotspots; pore location; adjacent layer temperature and residual stress formations	Installed
Pore and defects formation	Acoustic emission sensors - Avisoft Bioacoustics	To scan the whole surface between each deposited layer and be able to detect any dimensional deviation and to check the layer height.	Installed

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8. Real-time process monitoring for automatic control

This section describes the intended plan for how real-time process monitoring will be extended to automatic control of the prints.

8.1. Overview of the plan for automatic control

The aforementioned sensors will be integrated on the 6 pilot lines to monitor the printing process in real time. The data from the previous layer would be used to automatically correct the part quality, point to point, for the next layer. As part of DILAFACT, the predictive algorithm correlates the process parameters with the resulting part quality, applied in triplicate:

1. A prediction of the process parameter progression, point by point, before the print. This works well for laser texturing, a very predictable process, but is expected to be less effective for LPBF and DED.
2. A live prediction of part quality during the experiment. For example, a live readout of the relative density point to point based on the current process parameters and live sensor feedback.
3. Real-time and quasi-real time feedback control—using the predictive algorithm to change the process parameters to optimize quality factors, such as density, based on the previous layer measurements.

A block diagram showing the process flow is shown in Figure 20.

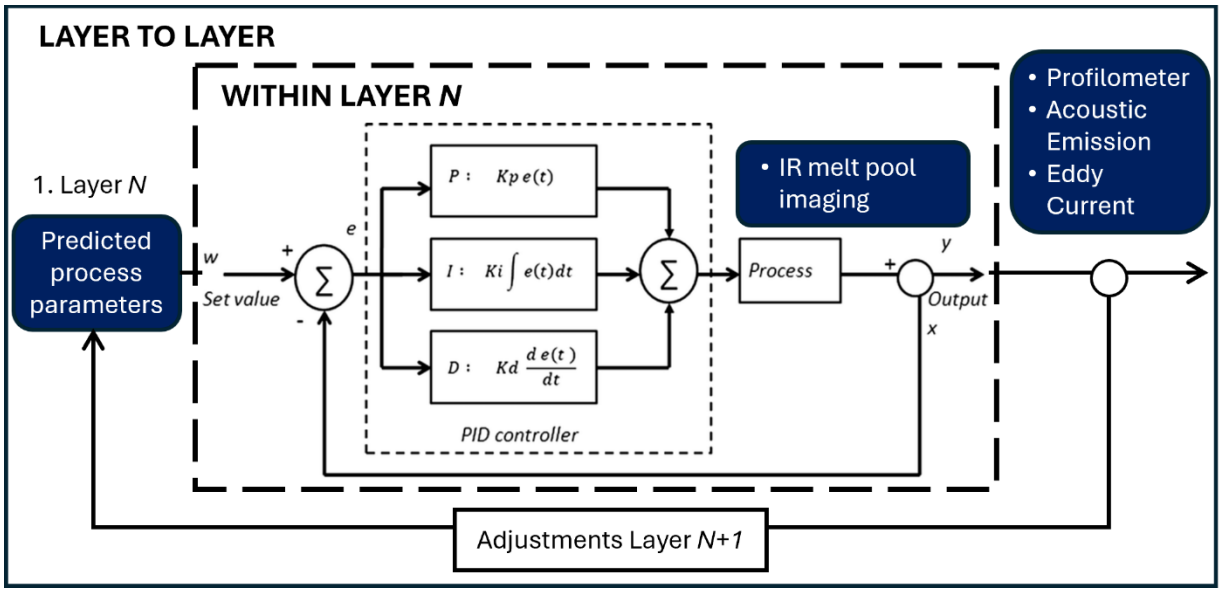


Figure 20. Block diagram of proposed process flow incorporating real-time and quasi-real time feedback control.

The predictive algorithms will be developed by machine learning (ML) trained and validated against real measurements. The algorithm selection is outlined in Deliverable D3.3, and the

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first results of the trained model are shown in Deliverables D3.4 (LPBF), D3.5 (DED), and D3.7 (laser surface texturing). The core function of the regression-based ML models is to determine the relative relationships between input features and a target variable, making them fundamentally useful for linking process parameters to metrics of part quality. The following subsections detail the proposed automatic control on each of the pilot lines.

8.2. Real-time feedback control using IR imaging

Coaxial IR sensors will be installed on several pilot lines:

- Pilot line 1 (Hymax DED, CRM Group): one 1D IR pyrometer, one 2D IR camera
- Pilot line 3 (SLM 280, DTI): one IR sensor (pyrometer or camera to be determined)
- Pilot line 6 (Laser texturing, DCU): one 1D IR pyrometer

These sensors allow for in-situ, *indirect prediction* of defect generation through the algorithm's correlation between sensor measurements and part quality.

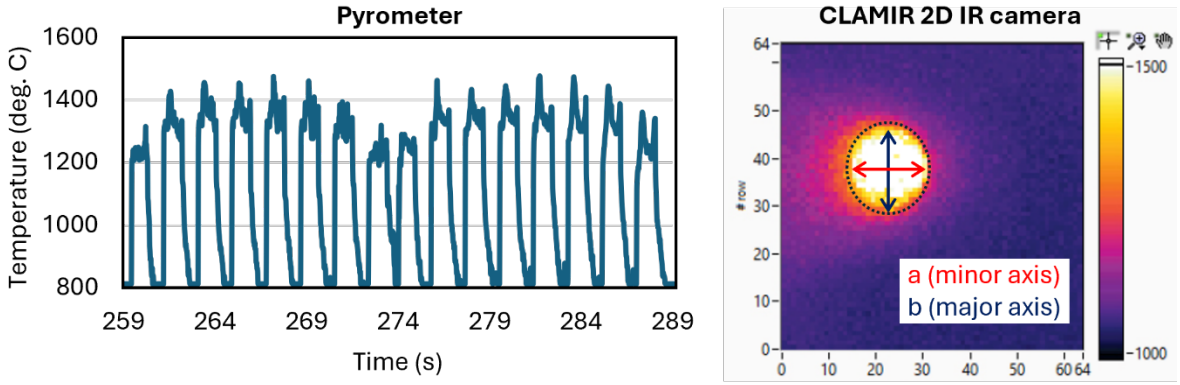


Figure 21. Example of processed data extracted from 1D and 2D IR sensors.

The two IR sensors will provide a live temperature profile at the surface of the melt pool. The pyrometer measures the temperature at the center of the melt pool at a frequency of up to 10 kHz. The CLAMIR camera measures a series of temperature profiles over a two-dimensional area at a frequency of up to 4 kHz. The following features can be extracted or calculated from the two IR sensors for each moment in time:

Directly extracted	Calculated
Temperature at the center of the melt pool (measured redundantly)	Relative melt pool width, calculated w.r.t. a user-defined reference width
Melt pool area	Melt pool shape, calculated as the axis ratio of a fitted ellipse
Melt pool width	

During the training phase, the sensors will be used to collect feedback from parametrization studies covering the design space. The algorithm will be trained to choose the process parameters correlated with good quality prints. The predictive algorithm will automatically calculate the process parameters for each point on the following surface, adjusted to optimize multiple measures of part quality.

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During the *in-situ* feedback control phase, the process parameters will be automatically adjusted according to the live temperature profile. Based on its training, the algorithm will determine the best process parameters to adjust the melt pool and implement it through PID control. Melt pool geometry and thermal profile are common features used for feedback control in laser-based metal printing [8], [9].

8.3. Quasi-real time feedback control using profilometry or acoustic emission

Sensors will be installed on three pilot lines for dimensional control:

- Pilot line 1 (Hymax DED, CRM Group): one profilometer
- Pilot line 5 (AconitMINI LPBF, DCU): one acoustic emission sensor
- Pilot line 6 (Layer texturing, DCU): one acoustic emission sensor

These sensors allow for in-situ direct measurement of dimensional defects including warping, layer height variation, and waviness.

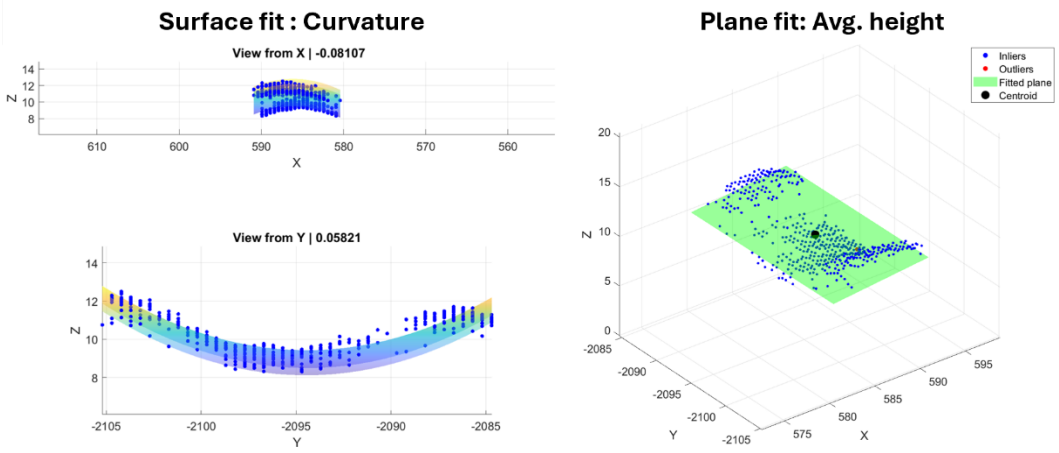


Figure 22. Example of features extracted from 2D profilometry of sample final layers.

On the DED machine at CRM Group, a laser profilometer will scan each layer to measure dimensional homogeneity. If the print design is such that the laser head will always follow a fixed axis, the profilometer will scan immediately behind the laser head during the print. If the print design requires that the laser head be tilted, the system will take a full profile measurement along a pre-defined, fixed axis after each layer is fully printed. An in-house Python script translates the measurements into a point cloud of heights as measured from the baseplate, which can be segmented into a "mesh" of rectangular elements describing the surface. A plane and a two-dimensional surface can be fit over each mesh element. From the best-fit plane, the average height and a quantitative "planarity" can be calculated. The Hessian matrix of the two-dimensional surface quantifies the local curvature of the mesh element.

An acoustic emission sensor, installed on the AconityMINI machine at DCU only, will be used to measure the dimensional accuracy and layer height during printing. The sensor is

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mounted near the powder bed and can measure the dimensional accuracy and warping of the solidified metal, i.e. just after the scan. In addition, this sensor can directly record the presence of internal defects as they are generated, which will be stored for the DILACERT validation.

The sensor feedback can be used for quasi-real time correction, as these sensors inherently measure with a time delay behind the laser. Two approaches will be attempted. First, the parameters will be adjusted in-layer to correct global trends such as a gradually decreasing layer height. The local height and planarity will be controlled primarily by the powder deposition rate, scan speed, laser power, and laser spot size. Dimensional accuracy will be prioritized over internal defect generation. The algorithm will first adjust process parameters to correct the dimensional problems, and then from the restricted parameters space will adjust to correct for predicted internal defect generation as outlined in Section 8.2.

If in-layer correction is not possible, for example due to calculation time, the dimensional conformity will be adjusted layer by layer. Using the measurements from the previous layer, the algorithm will recalculate the process parameter progression for the following layer, as shown in Figure 20.

8.4. Quasi-real time feedback control using eddy current monitoring

An eddy current sensor will be installed on several pilot lines for dimensional control:

- Pilot line 2 (Ianus cell, Prima Additive)
- Pilot line 3 (SLM 280, DTI)
- Pilot line 4 (NOMAD®03, Fieldmade)
- Pilot line 5 (AconitMINI LPBF, DCU)

The eddy current sensor allows for in-situ direct measurement of internal defects such as pores and cracks as they are generated.

An eddy current monitor will be mounted next to the laser head to record the presence of internal defects as they are generated, which will be stored for the DILACERT validation.

The sensor feedback can be used for quasi-real time correction, as these sensors inherently measure with a time delay behind the laser. Two approaches will be attempted. First, the parameters will be adjusted in-layer to attempt to reduce the number of defects per layer. The eddy current resistance will be included in the ML algorithm training as an additional variable to be considered when adjusting process parameters by PID control.

If in-layer correction is not possible, the eddy current signal will be used to recalculate the process parameter progression for the following layer.

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9. Conclusion

The most common defects encountered in DED, LPBF and laser texturing processes have been described. A large range of sensors exist or are in development in order to monitor closely the laser process production and gain confidence in terms of part quality. These sensors were also described in detail.

For each pilot line, the focus of sensor deployment and relevant solutions have been identified.

At the request of the reviewer, section 8 has been added to describe the automatic control aspect for possible real-time process monitoring.

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