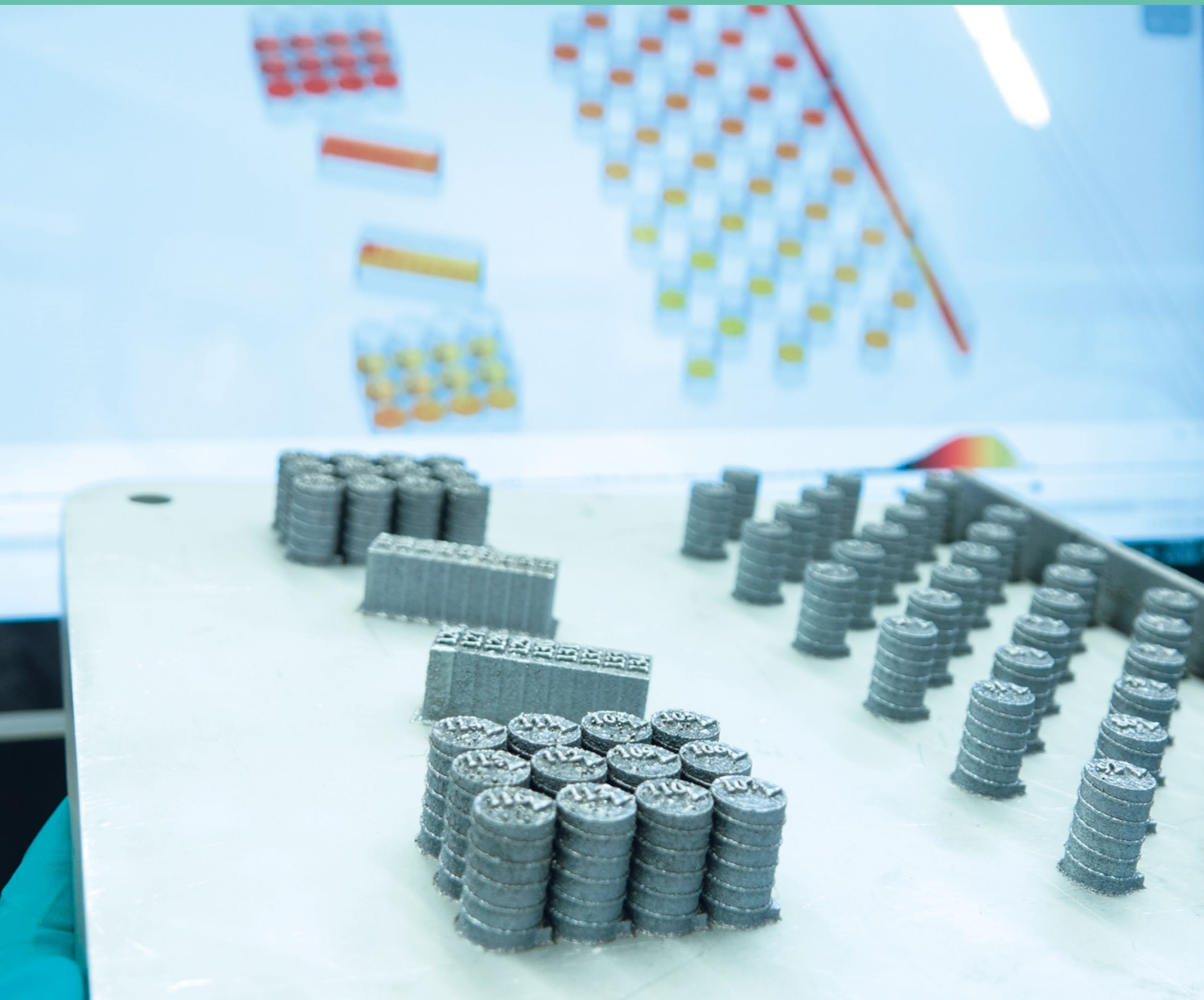
Fraunhofer IAPT

FRAUNHOFER RESEARCH INSTITUTION FOR ADDITIVE MANUFACTURING TECHNOLOGIES IAPT

OVERVIEW OF LPBF IN-PROCESS MONITORING SYSTEMS

AN ADDITIVE ALLIANCE STUDY | 2020



CONTENT

1_MOTIVATION

INSIGHTS TO BE GAINED

- **WHAT ARE IN-PROCESS MONITORING SYSTEMS (IPMS) AND WHY ARE THEY INDUSTRIALLY RELEVANT?**
- **WHICH INDUSTRIALLY RELEVANT IPMS ARE AVAILABLE IN THE MARKET?**
- **HOW DO IPMS TECHNOLOGIES COMPARE TO EACH OTHER?**
- **WHICH CRITERIA CAN BE USED TO SELECT AN IPMS?**

Additive Manufacturing (AM) of metals is paving its way to becoming a fully established industrial manufacturing technology. Recent technological advances have made this manufacturing method more affordable and reliable. At present, Additive Manufacturing is used across all industries, from automotive to aerospace and from medical to mechanical engineering.

A challenge that industry is currently facing with regard to additively manufactured parts is to meet the high-quality standards of safety-critical applications, as in the medical or the aerospace industries, for example. Resistance to fatigue failure and repeatable mechanical properties are two key aspects when manufacturing parts for safety-critical applications. Laser Powder Bed Fusion (LPBF) produces high-quality parts. However, the complexity of the layer-by-layer production process means that every part is unique, and individual testing is needed in applications with the highest quality standards. In view of the high process complexity involved, Additive Manufacturing faces challenges to ensure defect-free manufacturing of parts. Expensive and time-consuming methods such as μCT inspection and Hot Isostatic Pressing (HIP) have been used to ensure the quality of parts produced with LPBF, resulting in additional production time and manufacturing costs. In-Process Monitoring Systems (IPMS) have the potential of reliably detecting process deviations that could cause part defects. This eliminates or minimizes the need for Non-Destructive Testing and HIP, effectively reducing the costs of manufacturing parts.

The aim of this study is to give an overview and to benchmark commercially relevant IPMS for LPBF machines. The systems will be compared on the basis of several technical criteria to give readers a guideline as to which IPMS is most relevant for their application.

2_ABOUT FRAUNHOFER IAPT

ABOUT FRAUNHOFER IAPT

Fraunhofer IAPT is one of the leading research institutes in the field of AM. We specialize in the areas of design, processes and systems.

Our objective is to scale up additive processes and technologies and facilitate their transfer to industry, thereby enabling the manufacture of completely new und resource-efficient products.

We can provide you with customized solutions and help launch you as a competitive player in the field of Additive Manufacturing.

More information can be found here: www.iapt.fraunhofer.de

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3_ABOUT THE ADDITIVE ALLIANCE

The Additive Alliance is the independent industrial research network for Additive Manufacturing of the Fraunhofer-Gesellschaft. The network was created in 2014 to promote knowledge sharing and has since become established as a relevant institution in AM. Regular network meetings of the more than 30 members encourage the exchange of ideas between all AM stakeholders, allowing them to make a significant contribution to the industrial future through long-term cooperation.

It all began with a small group at the Laser Zentrum Nord, focusing on laser applications. In those days the network was referred to as Light Alliance. Since then, the network and its events have developed steadily. The most significant development was probably the shift away from pure laser material processing to 3D printing and changing the name of Light Alliance to Additive Alliance in 2018, when the LZN became part of the Fraunhofer Gesellschaft. Fraunhofer IAPT has been in existence for more than two years now and is destined for further ongoing development to maintain the high expectations associated with the Fraunhofer brand.

The Additive Alliance has identified two key values of Fraunhofer that we want to represent. We want to provide our members with exclusive knowledge, and explore topics that they consider most relevant. In this regard, we aim to meet the highest standards of objectivity.

As from 2020, we would like to work together with all members to regularly identify topics for detailed research, which will be investigated in studies by the experts at Fraunhofer IAPT. The aforementioned values constitute the basis for preparing the studies. This first edition of our studies presents you with the results of our work. We hope you enjoy reading the first issue and look forward to working with you to determine the topics for the next edition.

Our gratitude goes to our members as follows. It would not have been possible to prepare this study without them.

3D SYSTEMS	aalberts	Additive Industries
AIRBUS	ALTAIR	BeAM an AddUp company
BIONIC PRODUCTION	cenit	DB
DMG MORI	eos	FANUC
FFT	GE Additive	H&H Innovation H&H Smart Products
HHLA		Premium AEROTEC
RENISHAW apply innovation™	SIEMENS Ingenuity for life	SIGMA LABS
HEXAGON simufact	SLM SOLUTIONS	stratasys
toolcraft	TRUMPF	YXLON Technology with Passion
formnext		

4_ABOUT THE AUTHORS

PLEASE DO NOT HESITATE TO CONTACT OUR EXPERTS WITH ANY QUESTIONS

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5_APPROACH OF THE STUDY

5.1_OVERVIEW OF IN-PROCESS MONITORING SYSTEMS

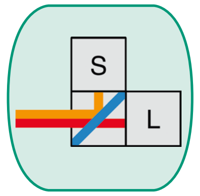
Quality assurance of safety-critical components made with LPBF involves non-destructive part inspection such as μ-CT scans and in many cases Hot Isostatic Pressing (HIP), which add considerable time and costs to the production process. IPMS offer a potential solution to minimize the need for Non-Destructive Testing (NDT) or HIP that could double the costs of producing safety-critical parts with LPBF. IPMS integrate sensors in the LPBF machines to monitor process characteristics such as melt pool emissions or powder bed morphology, providing an insight into process stability as the part is built.

This study provides an overview of several commercially available IPMS, listing their main characteristics to provide a benchmark between them.

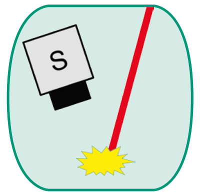
The following section describes the general sensor arrangements, the sensor technologies used in the system and the process characteristics monitored during the process, together with a general description of the user interface for displaying process information.

5.1.1_SENSOR ARRANGEMENT

There are two types of sensor arrangement:



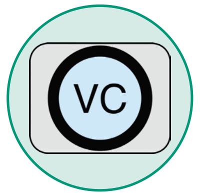
On-axis: The sensor's field of view is aligned with the laser spot; the sensor is mounted in the machine's optical bench and is aligned with the optical axis of the laser beam. The installation is usually achieved by implementing a beam splitter (blue) that transmits the wavelength of the laser and reflects the wavelength detected by the sensor, or vice versa. The figure shows a simplified diagram of the on-axis arrangement, with the radiation measured (orange) by the sensor (S) and the radiation emitted (red) by the laser (L).



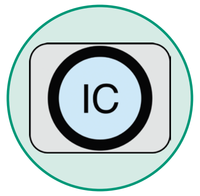
Off-axis: The sensor is mounted either inside the building chamber or outside, in which case the process is monitored through an observation window. This sensor arrangement monitors the building platform from a fixed position. The figure shows an off-axis sensor (S) capturing the process emissions.

5.1.2_SENSOR TYPES

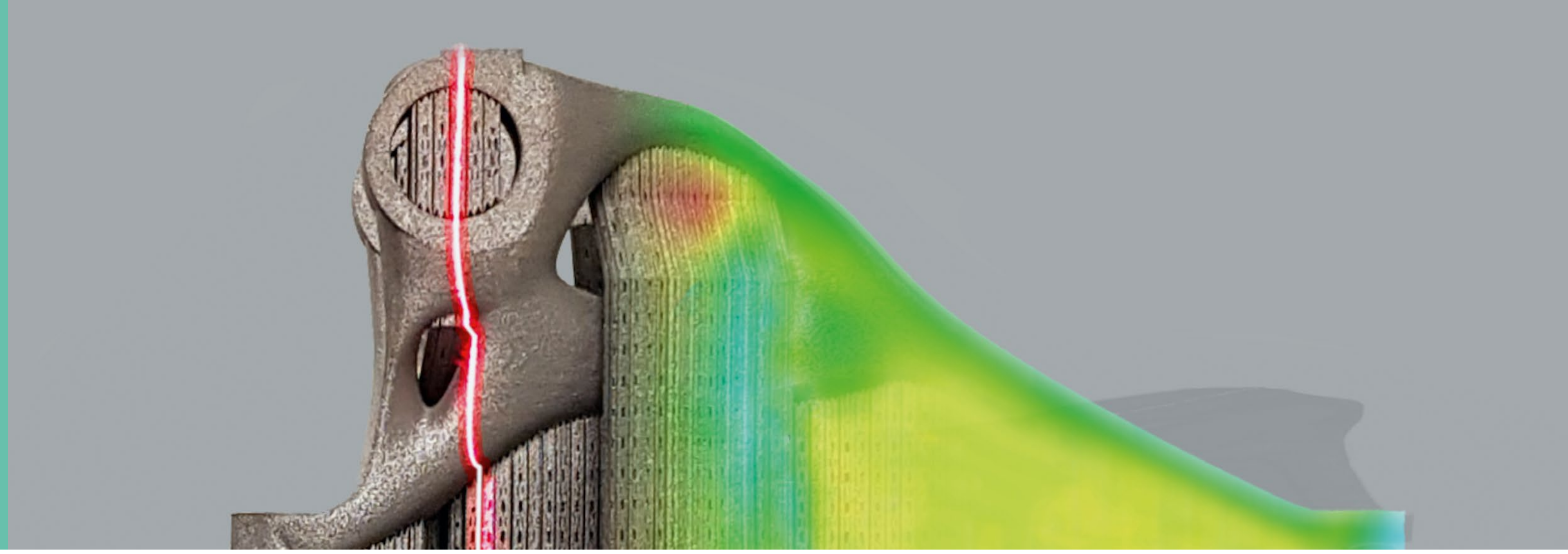
Photodiode: Sensor that converts light photons emitted by the process into an electrical signal. Output signal voltage is proportional to light intensity. Photodiodes operate in wavelengths from 400 to 1700 nm and have high sampling rates.



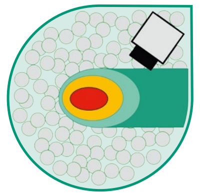
Visual camera: Digital camera that captures the light emitted by the process in the visual spectrum (380–740 nm) using a sensor and converts it into images. Visual cameras used for process monitoring are generally industrial-grade with an output of grayscale images.



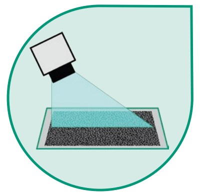
Infrared camera: Digital camera that captures the light emitted by the process in the infrared spectrum (1000–14000 nm) using a sensor array and converts it into images. The output of infrared cameras consists of grayscale images where the pixel values are proportional to the process temperature.



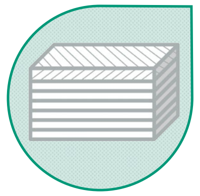
5.1.3_PROCESS CHARACTERISTICS



Melt pool emissions: The melt pool is the area of liquefied metal formed when laser radiation melts the powder material. The melting process emits radiation in the visual and infrared wavelengths of the spectrum that can be used to characterize the process.



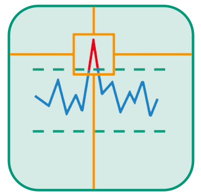
Powder bed morphology: A homogeneous powder bed is important for a stable melting process. Powder bed morphology can be characterized by analyzing 2D pictures using computer vision techniques or structured light 3D scanning. Problems can arise with this process characteristic, such as inhomogeneous recoating or protruding parts that could interrupt the LPBF process.



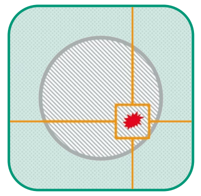
Morphology of the solidified layers: The morphology of the solidified layers reveals information about process stability and the geometry of the final part.

5.1.4_USER INTERFACE

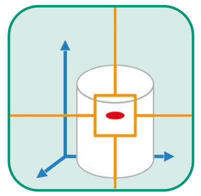
Process chart: Process information is shown as a plot of a process characteristic vs. the layer number, part number, or batch number. Process deviations are generally shown as fluctuations from established thresholds.



2D layer visualization: Process characteristics are shown as a 2D image of every layer. Process deviations are highlighted within the layer.



3D model visualization: Process data is plotted as a 3D model of the manufactured part. Process deviations are plotted in a 3D render.



5.2_APPROACH OF THE TECHNICAL REVIEW OF IN-PROCESS MONITORING SYSTEMS

Each of the IPMS included in this study will be presented and analyzed using the following criteria*:

(1) Company:
Brief description of the system manufacturer.

(2) Name and software version:
Commercial name of the IPMS and software version analyzed in this study.

(3) Key facts:
Statement whether the IPMS is manufacturer-agnostic** or not, current machine installations of the IPMS as retrofit or factory option, and list of materials that have been used to test IPMS functionality.

(4) Unique features:
Features that make the system unique and cannot be assigned to a standard category.

(5) Installation procedure:
Description of the installation procedure for retrofitting the IPMS in an LPBF machine.

(6) Setup procedure:
Description of the steps required to set up the IPMS for each application.

(7) System architecture:
Explanation of the sensors used by the system and their position in the machine, information about multi-laser support and external equipment included in the system.

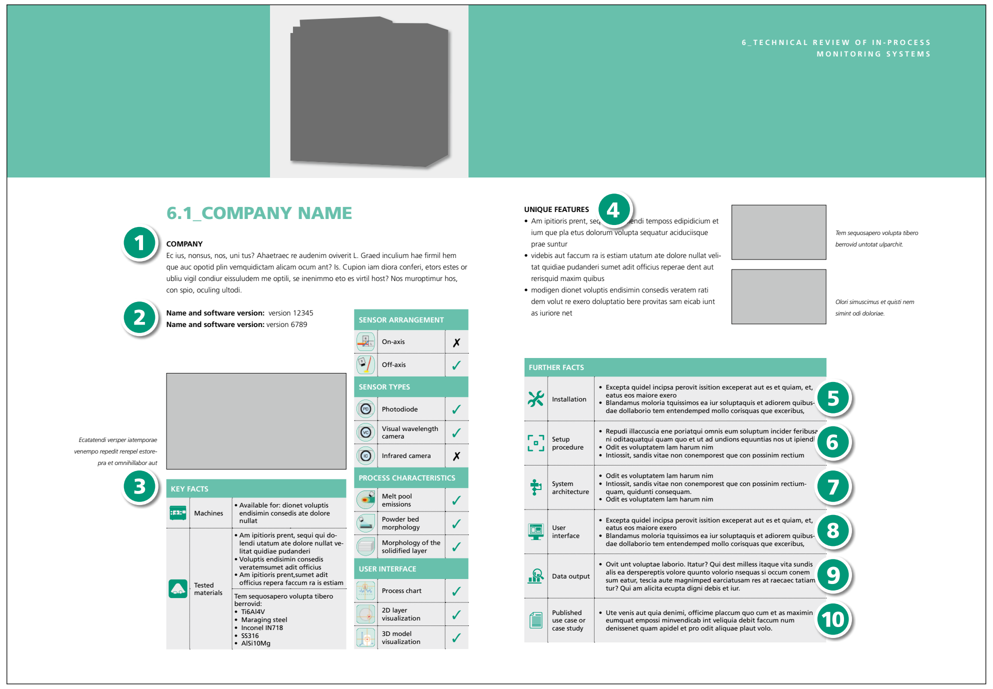
(8) User interface:
Description of how the LPBF process information is visualized and communicated to the user.

(9) Data output:
Specifications of the resolution and format of the raw data, processed information and information about automatic anomaly detection.

(10) Published use case or case study
Publication containing information about the IPMS and its capabilities. Section 8 (Further Reading) contains additional titles with more information about the IPMS.

* *It is not possible to guarantee that the information listed under the above categories is complete, due to non-disclosure agreements between the IPMS manufacturers and their customers.*

** *Manufacturer-agnostic refers to the capacity of an IPMS to be installed in machines from different manufacturers.*

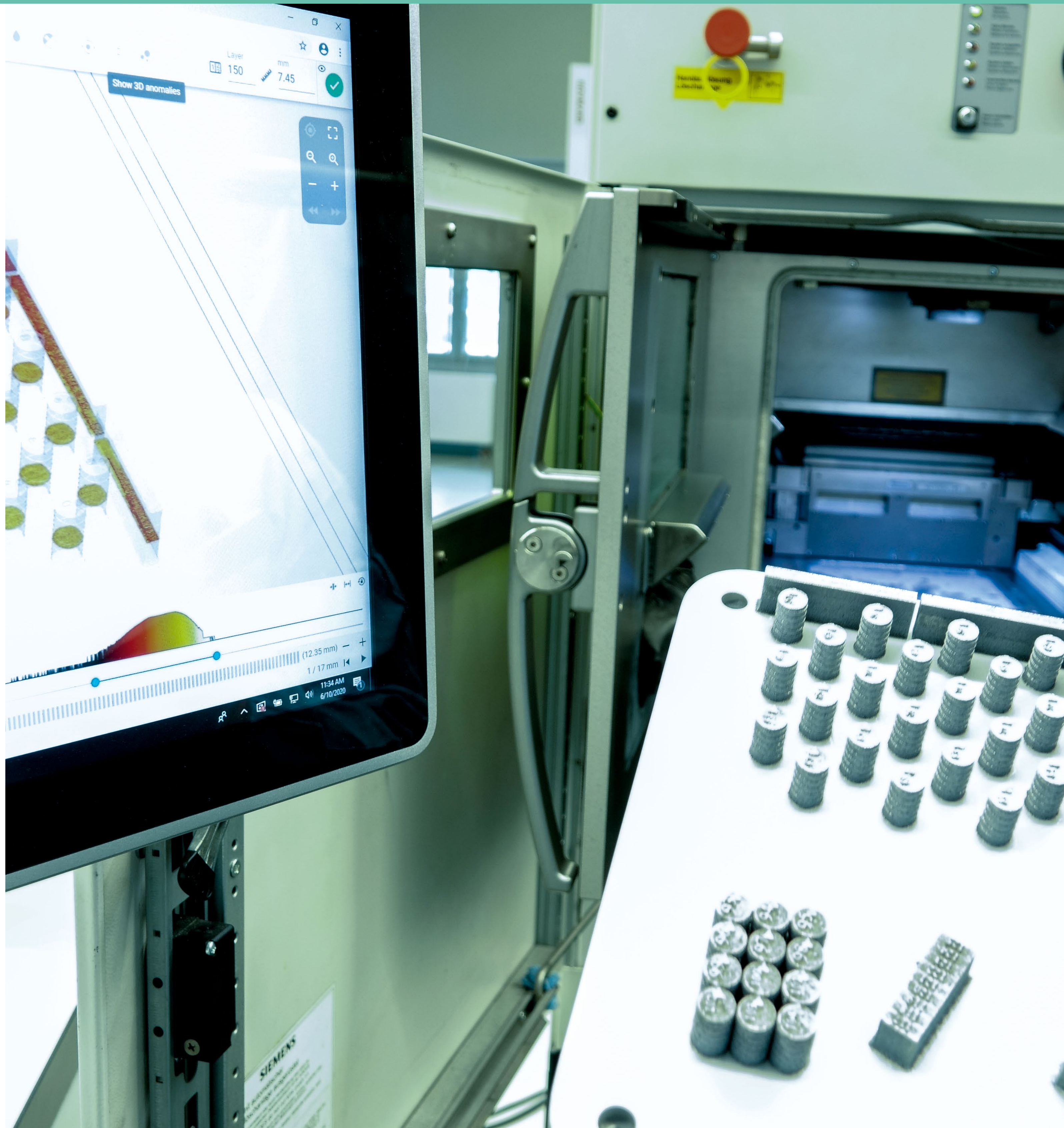


6_TECHNICAL REVIEW OF IN-PROCESS MONITORING SYSTEMS

This section describes each of the IPMS included in the study. The information about each system has been compiled in a standardized format to make the technical descriptions comparable. Careful consideration has been given to the Unique Features section as it highlights the unique attributes of each IPMS.

In the scope of this work, the IPMS of the following manufacturers were reviewed:

6.1	**3D Systems**
6.2	**Additive Assurance**
6.3	**EOS**
6.4	**GE Additive**
6.5	**Open Additive**
6.6	**Renishaw**
6.7	**Sigma Labs**
6.8	**SLM Solutions**
6.9	**TRUMPF**
6.10	**Velo3D**



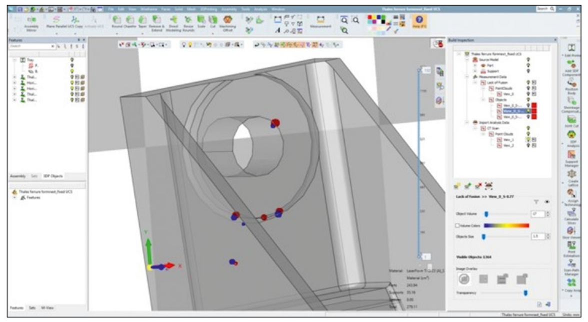
3D SYSTEMS

6.1_3D SYSTEMS

COMPANY

3D Systems is a manufacturer of SLA and LPBF machines. The company was founded in 1986; it is based in South Carolina, USA.

DMP Monitoring: version 1.2.6.1785
3DXpert (inspection module): version15 SP2P3



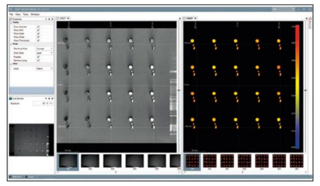
3D visualization highlighting process defects in a part

KEY FACTS	
Machines	• Available for: 3D Systems DMP Flex 350, Factory 350, ProX 320
Tested materials	• DMP Monitoring (DMP Vision + DMP Meltpool) is material-independent and does not require material validation. • DMP Inspection requires material validation for melt pool data, but not for vision analysis. Validated materials for DMP Inspection: • Ti6Al4V • Maraging steel • Inconel IN718 (in development) • SS316 (in development) • AlSi10Mg (in development)

SENSOR ARRANGEMENT	
On-axis	✗
Off-axis	✓
SENSOR TYPES	
Photodiode	✓
Visual wavelength camera	✓
Infrared camera	✗
PROCESS CHARACTERISTICS	
Melt pool emissions	✓
Powder bed morphology	✓
Morphology of the solidified layer	✓
USER INTERFACE	
Process chart	✓
2D layer visualization	✓
3D model visualization	✓

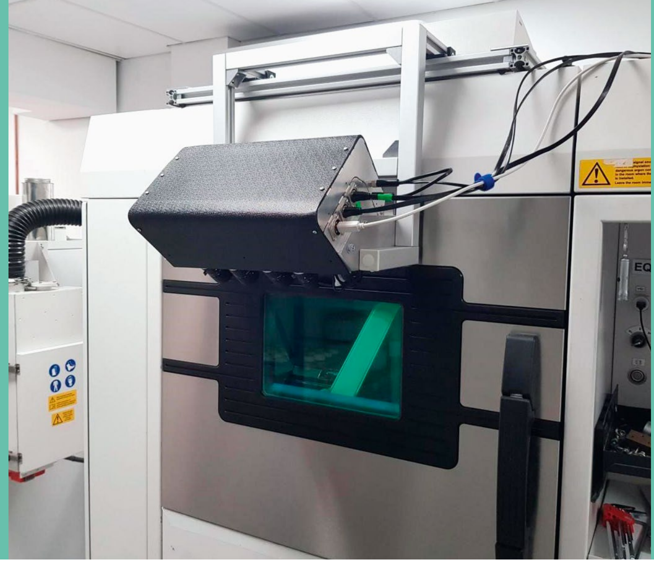
UNIQUE FEATURES

- DMP Inspection within the 3DXpert software visualizes data from DMP Vison and DMP Meltpool. The underlying algorithms of DMP Inspection detect quality issues in the build.
- DMP Meltpool measures process emissions as a function of time.
- Direct, real-time comparison between the photographs of the build plate taken by DMP Vision and the melt pool emissions data from DMP Meltpool.



2D layer visualization of the exposed surface and the meltpool monitoring data

FURTHER FACTS	
Installation	• DMP Meltpool requires installation of two photodiodes outside the process chamber. • DMP Vision requires installation of a visual wavelength camera outside the process chamber. • Typical installation time: 2 days
Setup procedure	• DMP Meltpool: run a print job for adjusting the photodiode gains. • DMP Vision: run the camera calibration procedure. • Run a test job to test DMP Meltpool and DMP Vison settings.
System architecture	• DMP Meltpool: two off-axis photodiodes • DMP Vison: one visual wavelength camera • Data acquisition and processing units integrated in the machine • Additional PC or laptop required for the 3DXpert software
User interface	• 3DXpert: 3D visualization of process data, where anomalies are displayed as 3D objects. Process anomalies detected with DMP Meltpool are automatically highlighted and classified. Data analysis from DMP Vision is semi-automatic; anomalies are highlighted, but not classified. • DMP Meltpool and DMP Vison: 2D layer display of process energy and 2D layer display of powder bed and scanned layer
Data output	• Data-reduced model containing only relevant process information • Histogram of number of anomalies for every layer • Defect analysis in .txt document: location of process anomalies in XYZ coordinates and classification • DMP Vision: 2D images of the powder bed before and after laser exposure; pixel resolution 100–150 µm • DMP Meltpool: 2D bitmaps of the scanned layer showing the observed energy intensity; 1 data point every 20µs, spatial resolution changes with scan speed
Published use case or case study	• Coeck et al. (2019). Prediction of Lack of Fusion Porosity in Selective Laser Melting Based on Melt Pool Monitoring Data. *Additive Manufacturing*, 25, pp. 347-356.



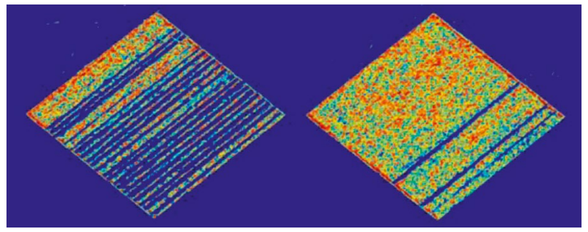
ADDITIVE ASSURANCE

6.2_ADDITIVE ASSURANCE

COMPANY

Additive Assurance is an independent manufacturer of IPMS for LPBF machines. The company is a spinoff of the Monash University in Melbourne, Australia; it has been operating independently since 2019. The process monitoring system is installed on several machine types.

AMiRIS: version 0.6.1



False color melt pool data showing an intermittent laser fault

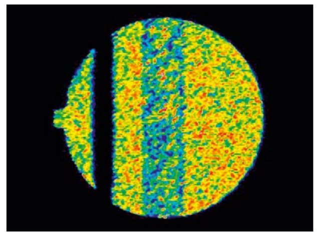
SENSOR ARRANGEMENT	
On-axis	✗
Off-axis	✓
SENSOR TYPES	
Photodiode	✗
Visual wavelength camera	✓
Infrared camera	✓
PROCESS CHARACTERISTICS	
Melt pool emissions	✓
Powder bed morphology	✓
Morphology of the solidified layer	✓
USER INTERFACE	
Process chart	✓
2D layer visualization	✓
3D model visualization	✓

KEY FACTS	
Machines	• Manufacturer-agnostic • Retrofit installations completed to date: EOS M280, M290; Renishaw AM250, AM400; Sisma MySint3000; TRUMPF TruPrint3000; Concept Laser MLab, xLine 1000r, xLine 2000r; SLM Solutions 250, 280; 3D Systems ProX DMP320 • Other systems on demand
Tested materials	Database available for: • Ti6Al4V • SS316L • Hasteloy X

UNIQUE FEATURES

- Non-invasive installation, no modification necessary to the optical bench or build chamber of the machine, hardware kit is installed outside the door of the process chamber.
- Uses machine learning algorithms to analyze melt pool emissions and morphology.
- Minimum setup and installation time. The material database is constantly updated and other common materials such as aluminum alloys will be added in early 2021.

2D layer visualization showing individual laser tracks and fusion defects in high resolution



2D layer visualization showing melt pool intensity

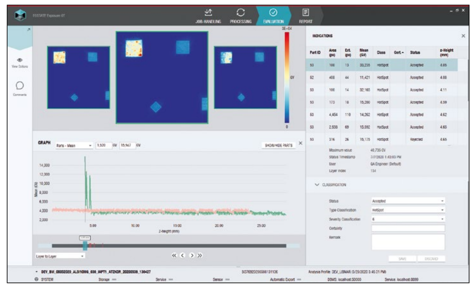
FURTHER FACTS	
Installation	• Cloud installation: the hardware is shipped to the customers who perform the installation by themselves. Support guidance is available with video tutorials and remote video conferencing. Typical installation time is 30 minutes. • On-premises installation: the hardware is installed by Additive Assurance employees on the customer's premises; this is offline installation. The installation time varies depending on the specific application.
Setup procedure	• If the material already has an existing database, no calibration of the system is required. • If no material database exists, basic functions are available for detecting defects. Advanced defect detection features can be unlocked by registering the print jobs and training the system algorithms.
System architecture	• Off-axis CMOS-based sensors working in the near-infrared spectrum • Private cloud-based analysis and visualization system, accessible by web portal • On-premises air-gapped version available where required
User interface	• High-resolution raw images of scanned layer emissions • 2D layer data displaying process data • 3D representation of the build job
Data output	• Raw images in custom file format • Process stability module: monitors energy input and ensures that conditions are within a consistent range • Defect detection module: automatic detection of process anomalies using machine learning • Configuration-dependent resolution, from 10 to 40 µm features
Published use case or case study	• Jurg (2020). Quality Assurance for Additive Manufacturing. White paper, available on request.

6.3_EOS

COMPANY

EOS is a manufacturer of LPBF and SLS machines. The company was founded in 1989 and is based in Krailling, Germany. EOSTATE monitoring suite includes the condition monitoring module EOSTATE Base and three independent modules for process monitoring: EOSTATE Exposure OT, EOSTATE Meltpool and EOSTATE PowderBed.

EOSTATE Exposure OT: version 1.5
EOSTATE Meltpool: version 2.2
EOSTATE PowderBed: version 1.5



EOSTATE Exposure OT 2D layer visualization

KEY FACTS	
Machines	• EOSTATE PowderBed available for: EOS M 290, EOS M 400-4, EOS M 400, EOS M 300-4 • EOSTATE Exposure OT available for: EOS M 290, EOS M 400-4, EOS M 300-4 • EOSTATE Meltpool Monitoring available for: EOS M 290, EOS M 400-4, EOS M 300-4 (in development)*
Tested materials	• Ti6Al4V • AlSi10Mg • AlF357 • 1.2709 • CHSteel 20MncrZr • SS17-4PH • SS316L • SS316LVPro • SSPH1 • SSGP1 • SSMP1 • SSCX • Cu • CoCr • MS1 • NickelAlloyHX • Inconel IN625 • Inconel IN718 • Inconel IN939

**These are commercially available products; customized solutions might be available for other EOS machines.*

SENSOR ARRANGEMENT	
On-axis	✓
Off-axis	✓
SENSOR TYPES	
Photodiode	✓
Visual wavelength camera	✓
Infrared camera	✓
PROCESS CHARACTERISTICS	
Melt pool emissions	✓
Powder bed morphology	✓
Morphology of the solidified layer	✓
USER INTERFACE	
Process chart	✓
2D layer visualization	✓
3D model visualization	✗

UNIQUE FEATURES

- EOSTATE Exposure OT is a combined hardware and software solution that monitors process conditions in the entire build plate without information loss.
- EOSTATE Exposure OT characterizes the process by measuring the heat emissions and integrating them in the time domain.
- EOSTATE Exposure OT can be calibrated using a special EOS tool.

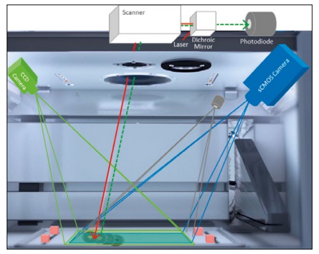


Diagram showing the sensor arrangement of EOSTATE's process monitoring systems

FURTHER FACTS	
Installation	• EOSTATE Exposure OT is a combined hardware and software solution. The camera is implemented in the machine in an off-axis position. Modification of the machine optics is not required. • EOSTATE Meltpool is a combined hardware and software module. The sensor is implemented in the beam path in an on-axis position. Modification of the machine optics is only required for installation in EOS M 290 machines. • EOSTATE PowderBed uses a camera already installed in the machine. The software features can be activated via a license. No modification of the machine is required. • Typical installation time: approx. 2 days
Setup procedure	• Print jobs for intensity correction and geo correction • Optional: standardization of Exposure OT values between different EOS machines using a special tool from EOS
System architecture	• EOSTATE PowderBed: includes one off-axis visual wavelength camera • EOSTATE Exposure OT: optional module consisting of off-axis infrared camera and electronics integrated in the housing of the EOS M 400-4 and EOS M 300-4. An external electrical cabinet is only required for installations in EOS M 290 machines. • EOSTATE Meltpool: optional module consisting of on-axis photodiode and electronics integrated in the housing of the EOS M 400-4 and EOS M 300-4. An external electrical cabinet is only required for installations in EOS M 290 machines.
User interface	• GUI has role-based functionality and is organized along the workflow. • Visualization of results: measurement results are visualized as a 2D intensity map per layer, part statistics are visualized as a 2D graph with selectable statistical value, analysis results are summarized in a list with identified indications, with automatic categorization.
Data output	• Measured values: image files as .raw, .tiff, .jpeg • Part statistics: average values and standard deviations per layer as .csv file • Analysis results: indications including automatic categorization as .csv file
Published use case or case study	• Ladewig et al. (2017). Materialcharakterisierung bei der Additiven Fertigung mittels Optischer Tomografie. Presentation at the Symposium Zerstörungsfreie Materialcharakterisierung, Berlin, November 28, 2017.

GE Additive

6.4_GE ADDITIVE

COMPANY

GE Additive – part of GE – is a world leader in Additive Design and Manufacturing and includes additive machine providers Concept Laser and Arcam EBM, along with additive material provider AP&C. GE Additive added LPBF to their portfolio in 2016 on acquiring Concept Laser, which is based in Lichtenfels, Germany.

The company's development of quality assurance systems started in 2010 with the launch of QM Meltpool, followedby QM Coating in 2011 and QM Meltpool 3D in 2015. Their latest system MSPC (Meltpool Statistical Process Control) will be released in 2020.

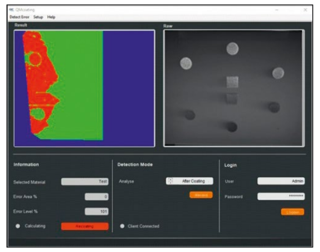
GE Additive MSPC: version 1.0

KEY FACTS		
Machines	• QM Coating included as factory standard for all GE Additive DLMS machines • QM Meltpool3D currently available as factory option for: ConceptLaser M2, ConceptLaser MLine, ConceptLaser XLine	
Tested materials	• MSPC for automatic defect detection: CoCr, more coming in 2020/21	
	QM Meltpool3D and QM Coating: • 316L (stainless steel) • M300 • 17-4PH • Remanium star@CL (CoCr alloy) • rematitan@CL (Ti alloy) • Ti6Al4V	• Cp-Ti • Ti6Al2Sn4Zr-2Mo • Ti5Al5V-5Mo3Cr • Ti48Al2Cr2Nb • IN625 • IN718 • AlSi7Mg • AlSi10Mg

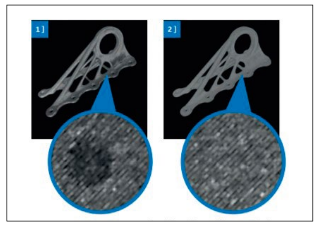
SENSOR ARRANGEMENT	
On-axis	✓
Off-axis	✓
SENSOR TYPES	
Photodiode	✓
Visual wavelength camera	✓
Infrared camera	✗
PROCESS CHARACTERISTICS	
Melt pool emissions	✓
Powder bed morphology	✓
Morphology of the solidified layer	✓
USER INTERFACE	
Process chart	✓
2D layer visualization	✓
3D model visualization	✓

UNIQUE FEATURES

- MSPC builds on QM Meltpool3D, adding automated anomaly detection capabilities to melt pool monitoring.
- QM Coating uses computer vision to detect recoater errors and can be configured to trigger recoating events or pause the print job.



QM Coating recoating error



QM Meltpool 3D part visualization

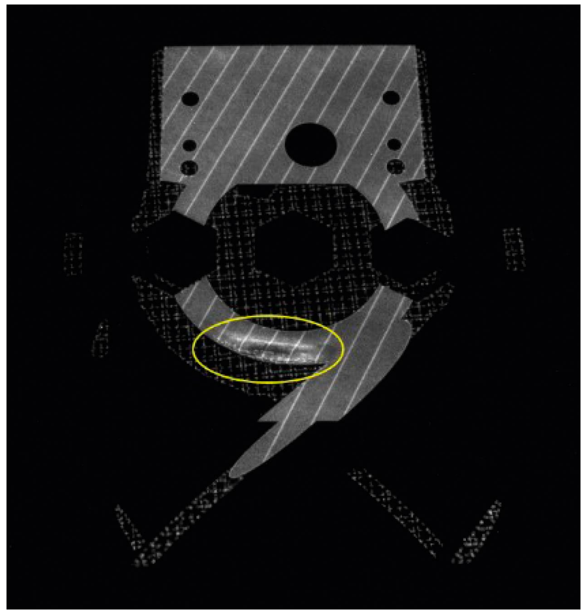
FURTHER FACTS	
Installation	• QM Meltpool 3D: integrated directly in optical system • QM Coating: camera mounted outside process chamber • MSPC: adds only computing hardware in electrical cabinet
Setup procedure	• QM Meltpool 3D: calibrated during commissioning • QM Coating: calibration on powder change • MSPC: requires calibration build job to acquire machine "fingerprint"
System architecture	• QM Meltpool 3D: one on-axis photodiode and one on-axis high speed camera per laser, supports up to four lasers • QM Coating: one off-axis medium resolution visual camera • Data acquisition and processing systems are integrated in the LPBF machine.
User interface	• MSPC: visualization of anomalies on a per-layer and per-part base. 2D layer view for highlighting localized error clusters • QM Meltpool 3D: most recent layer displayed as 2D visualization • QM Coating: most recent layer displayed as 2D visualization including detected defects
Data output	• Raw data: TDMS files with positioning data of laser, metadata for classification, and sensor values • 2D images of layers with resolution of down to 35 µm/pixel • The system features automatic anomaly detection (currently tested for CoCr). • QM Coating features automatic defect detection using thresholds. MSPC works with statistical process control based on a physical model for automated anomaly detection. Feature resolution: 300 µm
Published use case or case study	• Kolb et al. (2018). Melt Pool Monitoring for Laser Beam Melting of Metals: Assistance for Material Qualification for the Stainless Steel 1.4057. *Procedia CIRP*, 74, pp. 116–121.

6.5_OPEN ADDITIVE

COMPANY

Open Additive is an independent manufacturer of open platform LPBF machines and IPMS. The company was established in 2019 and is a spinoff of a defense-oriented company with over sixty years of experience in research and engineering. Open Additive is based in Ohio, USA.

AMSENSE: version 1.0.4.4



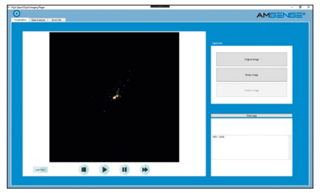
AMSENSE TOMOTHERM highlighting a delamination defect (2D visualization)

KEY FACTS	
Machines	• Manufacturer-agnostic • Open Additive PANDA-6" and PANDA-11" • Retrofit installations completed to date: EOS M280; Concept Laser M1, M2; 3D Systems ProX320
Tested materials	• Ti6Al4V • AlSi10Mg • F357 • SS316L • GRCop42 • CoCr • IN718

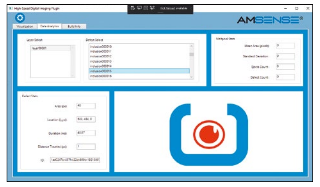
SENSOR ARRANGEMENT	
On-axis	✗
Off-axis	✓
SENSOR TYPES	
Photodiode	✗
Visual wavelength camera	✓
Infrared camera	✓
PROCESS CHARACTERISTICS	
Melt pool emissions	✓
Powder bed morphology	✓
Morphology of the solidified layer	✗
USER INTERFACE	
Process chart	✗
2D layer visualization	✓
3D model visualization	✗

UNIQUE FEATURES

- AMSENSE has specially designed hardware and software to monitor spattering.
- AMSENSE is designed as an open platform allowing the user to add custom plugins to expand system functionality.
- The system allows the customer to install additional sensors.



AMSENSE user interface showing SPAT-TRAK module



AMSENSE user interface showing statistical module

FURTHER FACTS	
Installation	• Installation is performed by Open Additive personnel on the customer's premises. • A custom-made solution is designed for each machine depending on the space and specifications required. • The sensors are installed inside the process chamber.
Setup procedure	• The camera gain settings are adjusted by running a configuration build for each material.
System architecture	• One off-axis visual camera takes pictures of the powder bed before and after exposure. • Two off-axis infrared cameras operating in the near-infrared spectrum, one for the spatter tracking module (SPAT-TRAK) and another for the tomography module (TOMOTHERM). • High-end data processing computer and analog input board supporting customer-added analog sensors and/or cameras
User interface	• TOMOTHERM: 2D visualization of the tomography data related to the peak temperature of the melt pool • SPAT-TRAK: 2D display of spatter movement during the process • Statistical module showing melt pool status and anomaly statistics
Data output	• Raw data: the images of all cameras are exported in an open data format. • TOMOTHERM: 2D images of the tomography data; resolution: 100 µm/pixel • SPAT-TRAK: 2D images of spatter tracking; resolution: 200–250 µm/pixel • Statistical module output: number of melt pool anomalies, size, and location
Published use case or case study	• Evans et al. (2020). Modeling and Monitoring of the Effect of Scan Strategy on Microstructure in Additive Manufacturing. *Metall Mater Trans A*, 51, pp. 4123–4129.

RENISHAW apply innovation™

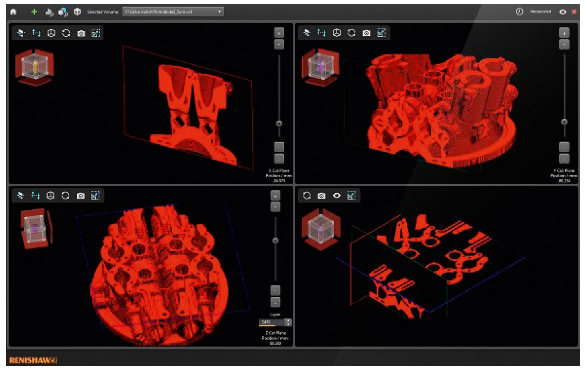
6.6_RENISHAW

COMPANY

Renishaw is a multinational engineering firm manufacturing high-precision metrology devices, healthcare technology and LPBF machines. Renishaw was established in 1973 and is based in Wotton-under-Edge, United Kingdom.

InfiniAM Spectral
InfiniAM MeltVIEW
InfiniAM Visual

Note:
No information about the latest version of the systems was provided by the manufacturer.



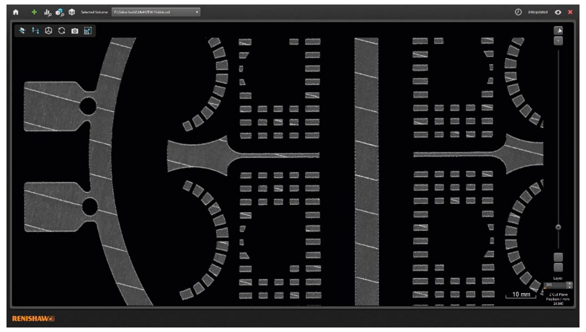
3D model visualization of InfiniAM MeltVIEW

KEY FACTS	
Machines	• Build chamber camera: available for all RenAM machines • MeltVIEW: available for RenAM 500 Q, T, D, and S machines
Tested materials	No information was provided by Renishaw.

SENSOR ARRANGEMENT	
On-axis	✓
Off-axis	✓
SENSOR TYPES	
Photodiode	✓
Visual wavelength camera	✓
Infrared camera	✗
PROCESS CHARACTERISTICS	
Melt pool emissions	✓
Powder bed morphology	✓
Morphology of the solidified layer	✓
USER INTERFACE	
Process chart	✓
2D layer visualization	✓
3D model visualization	✓

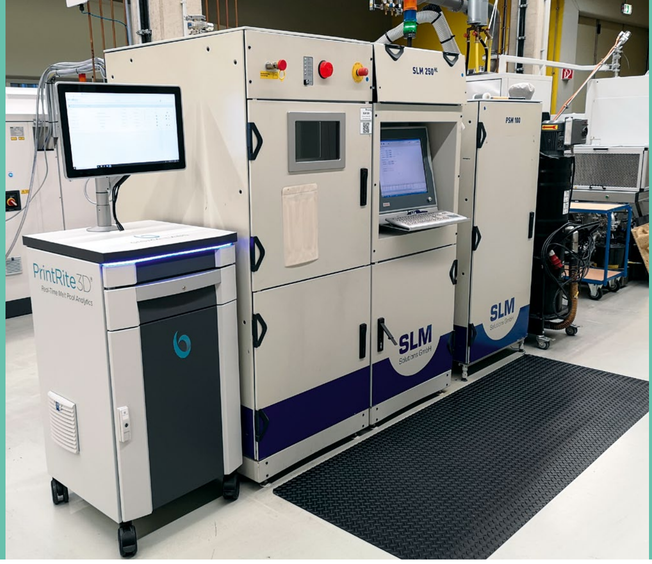
UNIQUE FEATURES

- The InfiniAM Central remote process monitoring software enables simultaneous live monitoring of several LPBF machines.
- The InfiniAM Spectral software can be used to view the data from the build chamber camera and the MeltVIEW hardware as 2D images or 3D renders.



2D layer view of InfiniAM MeltVIEW

FURTHER FACTS	
Installation	• The build chamber camera is available as standard equipment. • MeltVIEW is available as an upgrade option. • No information about typical installation time was provided by the manufacturer.
Setup procedure	• InfiniAM MeltVIEW: a test print job after installation is recommended to set up the thresholds for thermal emissions.
System architecture	• Build chamber camera: visual wavelength camera mounted outside the build chamber • InfiniAM MeltVIEW: two on-axis photodiodes mounted in an opto-mechanical module for each laser
User interface	• InfiniAM Spectral with InfiniAM MeltVIEW hardware: process graphs, 2D layer visualization and 3D render of the build job based on melt pool emissions
Data output	• Raw data: InfiniAM MeltVIEW records a layer-specific data file with timestamp, sensor voltage output and x, y positions in the build chamber. InfiniAM Visual produces jpegs of the powder bed before and after laser exposure. • Processed data: InfiniAM Spectral with InfiniAM MeltVIEW and InfiniAM Visual can export the individual or combined process data as 2D images of the layers. Resolution of the 2D images: 40–200 µm
Published use case or case study	• No information was provided by the manufacturer.



SIGMA LABS
The QA Standard for Additive Manufacturing

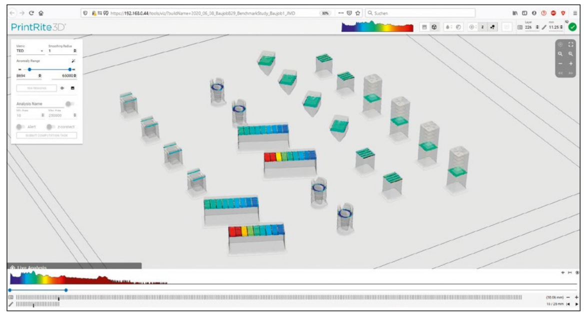
6.7_SIGMA LABS

COMPANY

Sigma Labs, Inc. is a leading provider of third-party quality assurance software to the Additive Manufacturing industry. It specializes in the development and commercialization of real-time monitoring solutions known as PrintRite3D for 3D metal printers.

The company was founded in 2010; it is based in New Mexico, USA. Sigma Labs has performed installations in North America, Europe, and Asia and is working with multiple OEMs to certify their machines as “PrintRite3D ready”.

PrintRite3D: version 6.0



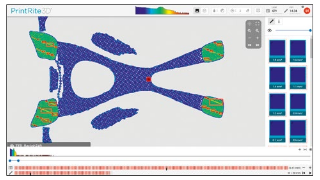
PrintRite3D print job visualization

KEY FACTS		
Machines	• Manufacturer-agnostic • Available as a factory option for Additive Industries MetalFab1 • Retrofit installations completed to date: EOS M 270, M 280, M 290; Concept Laser M2; SLM 125, 250, 280; Renishaw AM400; 3D Systems ProX300; Additive Industries MetalFab1, Sodick, DMG Realizer LT12 & LT30, TRUMPF3000	
Tested materials	• Ti6Al4V • AlSi10Mg • 718plus • SS316L	• MS1 • Inconel 625 • CoCr

SENSOR ARRANGEMENT	
On-axis	✓
Off-axis	✗
SENSOR TYPES	
Photodiode	✓
Visual wavelength camera	✗
Infrared camera	✗
PROCESS CHARACTERISTICS	
Melt pool emissions	✓
Powder bed morphology	✗
Morphology of the solidified layer	✗
USER INTERFACE	
Process chart	✓
2D layer visualization	✓
3D model visualization	✓

UNIQUE FEATURES

- The PrintRite3D system is offered as factory option in the Additive Industries MetalFab1 machine.
- The PrintRite3D system has been integrated with the Materialise Control Platform (MCP).
- Data is reduced by condensing the raw data into four quality metrics, including black body temperature measurement. The metrics are used in combination for detecting process anomalies, enabling correlation to µCT analysis based on machine learning.



PrintRite3D 2D layer view

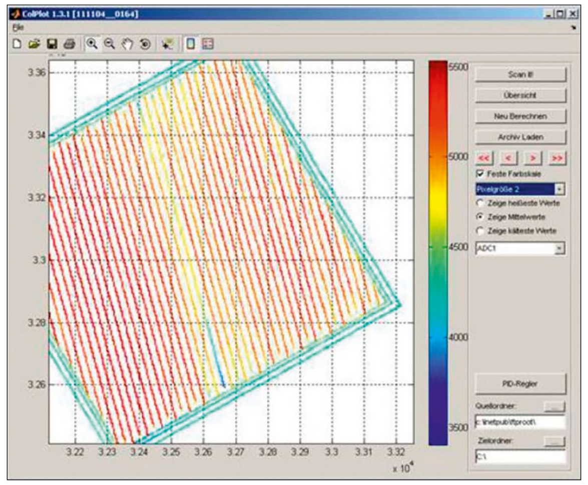
FURTHER FACTS	
Installation	• Installation entails fitting components in the LPBF machine’s optical bench as well as scan field and laser power correction. • The system can be installed in multiple machines and run by a central hub server. • Typical total installation time: 1 day
Setup procedure	• Run print jobs to optimize sensor amplitude and perform distortion correction. • Run print jobs to determine the process window of each material and correlate it to the system signals to establish thresholds by printing samples. • Typical system qualification time: 3.5 days
System architecture	• Three on-axis photodiodes per laser • Multi-laser support (currently tested for up to four lasers) • One external rack with data acquisition units, data processing server and user interface
User interface	• The system can be accessed through a web interface. • Process monitoring graphs featuring component quality metrics for every layer • 2D layer data display of the quality metrics • 3D visualization of the build job, highlighting process anomalies
Data output	• Raw data: positioning data of the laser spot and photodiode voltages • Processed sensor data: four quality metrics derived from the raw data • The system features automatic anomaly detection. • Resolution of 2D layer visualization: 100 µm per pixel • Real-time serial production build status dashboard
Published use case or case study	• Lane et al. (2020). Thermal Calibration Melt Pool Monitoring Sensors on a Laser Powder Bed Fusion System. *NIST Advanced Manufacturing Series 100-35.*

6.8_SLM SOLUTIONS

COMPANY

SLM Solutions is a manufacturer of LPBF machines. The company is based in Lübeck, Germany. Although it started pursuing research into LPBF technology in 1990, it was formally founded in 2011. There are two in-process monitoring modules in the ADDITIVE.QUALITY Solution by SLM Solutions: Melt Pool Monitoring and Layer Control System.

Melt Pool Monitoring (MPM): version 4.47
Layer Control System (LCS): version 3.0.23



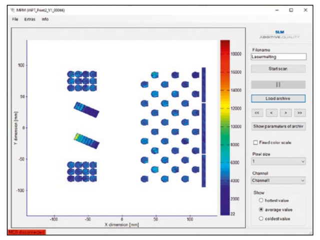
MPM 2D layer visualization showing the thermal emissions of individual scan vectors

KEY FACTS		
Machines	• Available for: SLM125, SLM280, SLM500, SLM800	
Tested materials	• HX • IN625 • IN718 • IN 939 • Ti6Al4V • AlSi10Mg • 361L	• 15-5PH • 17-4PH • 1.2709 • H13 • Invar 36 • CoCr • CuSn10CuNi2SiCr

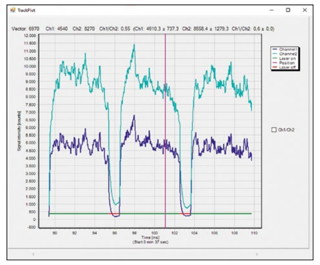
SENSOR ARRANGEMENT	
On-axis	✓
Off-axis	✓
SENSOR TYPES	
Photodiode	✓
Visual wavelength camera	✓
Infrared camera	✗
PROCESS CHARACTERISTICS	
Melt pool emissions	✓
Powder bed morphology	✓
Morphology of the solidified layer	✓
USER INTERFACE	
Process chart	✓
2D layer visualization	✓
3D model visualization	✗

UNIQUE FEATURES

- Uses the machine's build job data to plot thermal emissions for each individual scan vector.
- Real-time 2D layer visualization and process chart displays showing the intensity of thermal emissions in the process.
- Configurable data acquisition rate
- Material-independent



MPM 2D layer visualization of thermal emissions



MPM process chart

FURTHER FACTS	
Installation	• LCS is installed as factory standard on all SLM Solutions machines. • MPM requires modification of the optical bench. • Typical installation time for retrofit installation: 8 days for single laser machines, 12 days for dual laser machines, 15 days for quad laser machines
Setup procedure	• The position and focus of the MPM system is adjusted using a calibration plate. • MPM requires test print jobs to adjust the photodiode gains for aligning multiple MPM devices on one machine setup.
System architecture	• Melt Pool Monitoring: two on-axis photodiodes for each laser • Layer Control System: one off-axis visual camera for SLM125 and SLM280 and two off-axis visual cameras for SLM500 and SLM800 • Data acquisition is integrated in the machine. • Data processing can be done on an external computer.
User interface	• Thermal emissions can be plotted for print jobs, individual parts and individual scan vectors. • 2D layer data display with thermal emissions of the individual scan vector
Data output	• Raw data: MPM produces an encrypted binary format, LCS produces images in .jpg formats with a pixel resolution of ~250 µm. • Processed data: MPM produces images with 16-bit values indicating irradiated process emissions; their quotient is an indication of process temperature. In the scan direction, data resolution depends on scan velocity (for 1 m/s → 10 µm); perpendicular to the scan direction, pixel size is determined by the hatch distance.
Published use case or case study	• Alberts et al. (2017). In Situ Melt Pool Monitoring and the Correlation to Part Density of Inconel® 718 for Quality Assurance in Selective Laser Melting. In *International Solid Freeform Fabrication Symposium* (pp. 1481–1494), August 7–9, 2017, Austin, Texas, USA.

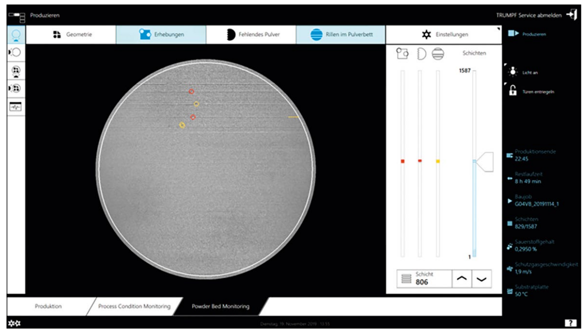
6.9_TRUMPF

COMPANY

TRUMPF is a company that produces lasers together with machinery and tooling solutions. It was founded in 1923 and is based in Ditzingen, Germany. TRUMPF launched its first laser metal fusion Additive Manufacturing machines in 2003.

With almost two decades of experience in additive technology, TRUMPF provides complete packages for powder bed processes that are fit for purpose in industrial applications, consisting of machines, services and digitization, all from a single source.

Monitoring version: version 06/2020



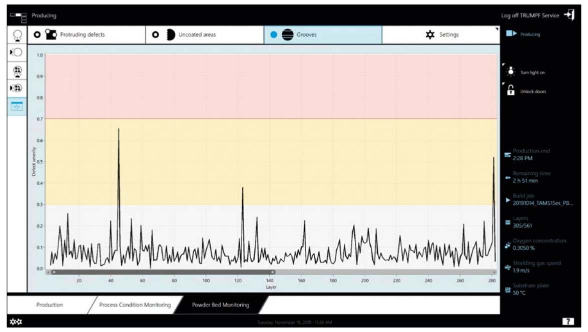
TruPrint 2D layer visualization highlighting process anomalies

KEY FACTS	
Machines	• Melt Pool Monitoring available for: TruPrint 2000, 5000 • Powder Bed Monitoring available for all TruPrint Machines: TruPrint 1000, 2000, 3000, 5000
Tested materials	• Compatible with all standard LPBF materials

SENSOR ARRANGEMENT	
On-axis	✓
Off-axis	✓
SENSOR TYPES	
Photodiode	✓
Visual wavelength camera	✓
Infrared camera	✗
PROCESS CHARACTERISTICS	
Melt pool emissions	✓
Powder bed morphology	✓
Morphology of the solidified layer	✓
USER INTERFACE	
Process chart	✓
2D layer visualization	✓
3D model visualization	✗

UNIQUE FEATURES

- The Melt Pool Monitoring module offers live process monitoring and process deviation alerts.
- The Powder Bed Monitoring tool is used for live image analysis and recoater feedback.



Process chart shown in the Monitoring TruPrint user interface

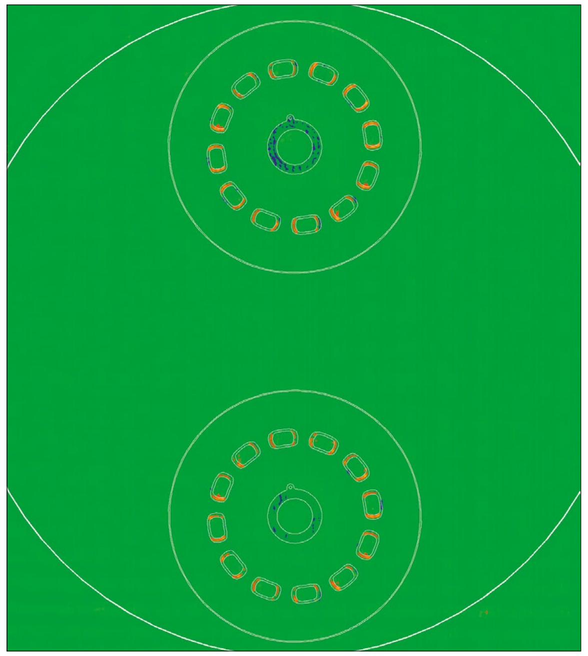
FURTHER FACTS	
Installation	• Melt Pool Monitoring and Powder Bed Monitoring available as factory option depending on the machine • Retrofit option available depending on the machine • Observation camera: off-axis visual camera is standard in all TruPrint machines.
Setup procedure	• Factory calibration • Customer site setup: Melt Pool Monitoring requires print jobs to adjust photodiode sensor gains and software detection thresholds. Powder Bed Monitoring requires camera imaging setup.
System architecture	• Melt Pool Monitoring: two on-axis photodiodes per laser • Powder Bed Monitoring: one off-axis visual camera • Data acquisition and processing units integrated in the machine
User interface	• Monitoring is fully integrated in the TruPrint human machine interface (HMI) for live detection of process results. • Monitoring Analyzer: desktop software application for monitoring data analysis with advanced evaluation features • 2D layer visualization: picture stack of Melt Pool Monitoring and Powder Bed Monitoring results for every layer
Data output	• Monitoring file interface: automatic file export of Melt Pool Monitoring, Powder Bed Monitoring and condition monitoring data based on user-readable open file structure • Condition and performance monitoring data transmitted by OPC UA
Published use case or case study	• Available on request

6.10_VELO3D

COMPANY

Velo3D is a company manufacturing LPBF machines. The machines use a combination of simulation, in-process monitoring and closed-loop process control to reduce the constraints of the LPBF process. The company was founded in 2014; it is based in California, USA.
Velo3D launched its first product in 2018.

Assure: version 1.2



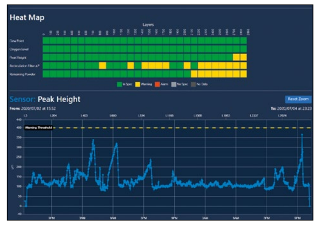
Height map of the powder bed before recoating

KEY FACTS		
	Machines	• Available for: Velo3D Sapphire
	Tested materials	• Ti6Al4V • IN718 • Al F357 • HASTELLOY X

SENSOR ARRANGEMENT		
	On-axis	✓
	Off-axis	✓
SENSOR TYPES		
	Photodiode	✓
	Visual wavelength camera	✓
	Infrared camera	✓
PROCESS CHARACTERISTICS		
	Melt pool emissions	✓
	Powder bed morphology	✓
	Morphology of the solidified layer	✓
USER INTERFACE		
	Process chart	✓
	2D layer visualization	✓
	3D model visualization	✓

UNIQUE FEATURES

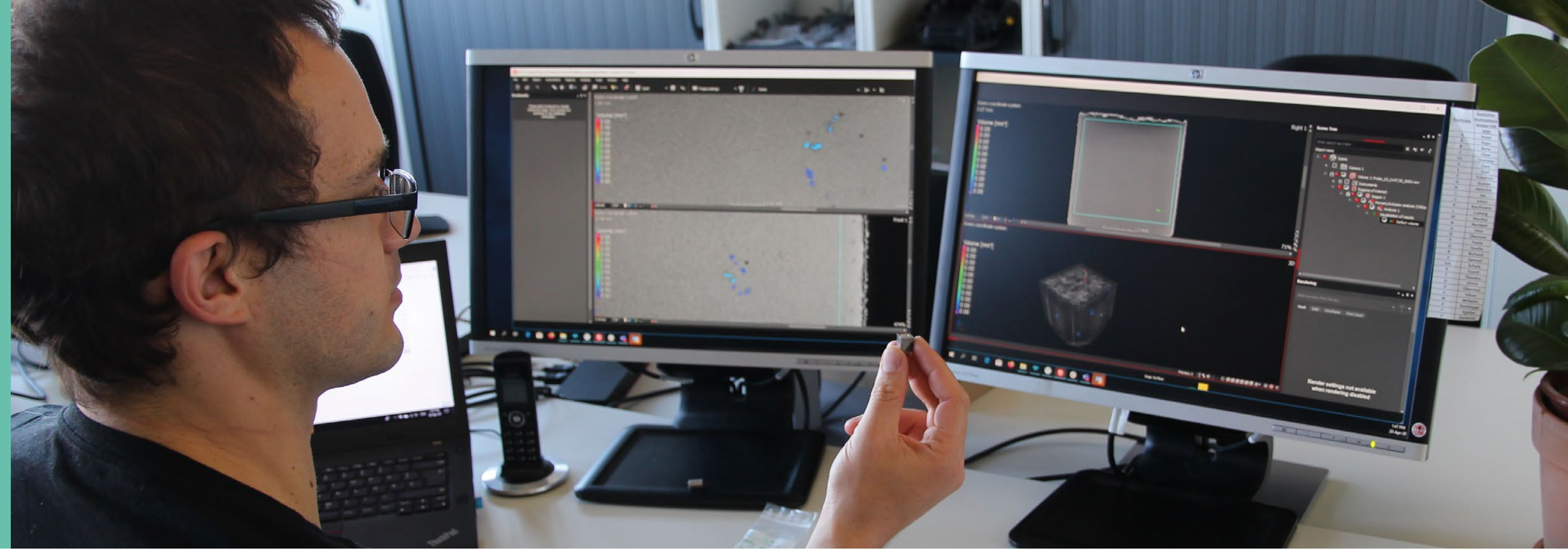
- Defect detection including probability of porosity and deterministic sensing of surface defects
- Assure features a structured light system that measures powder and solidified layer morphologies in three dimensions.
- One-click sensor calibration, no external instrumentation required
- The system sensors provide feedback for the machine's closed-loop melt pool process control system, a capability with optional activation by the user.



Velo3D build heat map (top) and peak height chart (bottom)

FURTHER FACTS		
	Installation	• The Assure process monitoring system is an integral part of the Velo3D Sapphire machines; it is not available as an add-on.
	Setup procedure	• Calibration of the whole optical system including process monitoring sensors is done with a single click. No external equipment is required for system setup.
	System architecture	• One on-axis photodiode per laser • One undisclosed sensor • Off-axis fringe projection system to measure the topography of the powder bed and the exposed layer • The system works with a 1kW dual-laser system.
	User interface	• The Assure user interface is an integral part of the machine software. • 2D layer visualization of the height map for the powder bed and the exposed layer; visualization of the defectivity metrics for every layer, consisting of the probability of porosity and surface defects (computed according to a combination of sensor inputs) • 3D render of the printed model representing the geometry of the measured part and highlighting process deviations
	Data output	• Raw data: the unprocessed data of all sensors is not encrypted and can be exported. • Processed data: 2D images of the built layers and their defectivity data, height map of the powder bed, resolution of the 2D layer images: 100 µm per pixel, resolution of the height map in z: 15 µm • 3D point cloud of the built model and its defectivity data
	Published use case or case study	• Carter (2019). Stratasys Direct Manufacturing Performs Field Validation of VELO3D Assure™. White paper.

6.11_TECHNICAL REVIEW AT A GLANCE



REVIEW CRITERIA*		3D Systems		Additive Assurance	EOS			GE Additive		Open Additive		Renishaw	Sigma Labs	SLM Solutions		TRUMPF	Velo3D
		DMP Vision	DMP Meltpool	AMiRIS	EOSTATE Exposure OT	EOSTATE Meltpool	EOSTATE PowderBed	QMM 3D	QM Coa-ting	AMSENSE TOMOTHERM	AMSENSE SPAT-TRAK	InfiniAM MeltVIEW	PrintRite3D	LCS	MPM	Monitoring TruPrint	Assure
First release in (year)		2018	2018	2019	2017	2016	2010	2010	2013	2019	2019	?	2010	2010	2017	?	2018
Tested materials	Titanium	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	?	✓	✓	✓	✓	✓
	Stainless steel	✓	(✓)	✓	✓	✓	✓	✓	✓	✓	✓	?	✓	✓	✓	✓	✗
	Tool steel	✓	(✓)	✓	✓	✓	✓	✓	✓	✗	✗	?	✓	✓	✓	✓	✗
	Aluminum	✓	(✓)	✗	✓	✓	✓	✓	✓	✓	✓	?	✓	✓	✓	✓	✗
	Inconel	✓	(✓)	✓	✓	✓	✓	✓	✓	✓	✓	?	✓	✓	✓	✓	✓
Machines	Manufacturer-agnostic	✗	✗	✓	✗	✗	✗	✗	✗	✓	✓	✗	✓	✗	✗	✗	✗
Installation types	Machine factory installation	✓	✓	–	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Retrofit installation	✓	✓	✓	✓	✓	✓	✗	✗	✓	✓	✓	✓	–	✓	✓	✗
Requisites for retrofit installations	Installation of sensors in optical axis	–	–	–	–	c.d.	–	–	–	–	–	✓	✓	–	✓	✓	–
	Installation of sensors inside process chamber	–	–	–	–	–	–	–	–	✓	✓	–	–	–	–	–	–
	Installation of sensors outside process chamber	✓	✓	✓	–	–	–	–	–	–	–	–	–	–	–	✓	–
	Typical installation time	2 days	2 days	30 min.	~2 days	~2 days	–	–	–	1 day	1 day	?	1 day	–	c.d.	?	–
Setup procedure	Test print job to correlate the IPMS signals to the process limits	–	✓	✓	✓	✓	–	✓	–	–	–	✓	✓	–	✓	✓	–
	Sensor sensitivity adjustment / intensity correction	–	✓	–	✓	✓	–	✓	✓	✓	✓	?	✓	✓	✓	✓	–
	Alignment of measuring field	✓	–	✓	✓	–	–	✓	–	✓	✓	?	–	✓	✓	✓	–
Data output	2D bitmap data resolution	100–150 µm	c.d.	10–40 µm	100–145 µm	60–100 µm	300–400 µm	35 µm	300 µm	100 µm	200–250 µm	40–200 µm	100 µm	250 µm	c.d.	?	100 µm
	Process chart	✓	✓	✓	✓	✓	(✓)	✓	✓	✗	✗	✓	✓	(✓)	✓	✓	✓
	Layer 2D view	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Model 3D view	✓	✓	✓	✗	✗	✗	✓*	✓*	✗	✗	✓	✓	(✓)	(✓)	✗	✓
	Automatic defect detection	✗	✓	✓	✓	✓	(✓)	✓*	✓*	(✓)	(✓)	✗	✓	✓	(✓)	✓	✓
	Production dashboard	✗	✗	✓	(✓)	(✓)	(✓)	✓*	✓*	(✓)	(✓)	✓	✓	✗	✗	✓	✓

Legend:
- ✓ *Applicable/available*
- ✓* *Available with additional analysis software*
- (✓) *In development*
- – *Not applicable/not required*
- ✗ *Not available*
- ? *Information not provided*
- c.d. *Case-dependent, see full description*

**Due to the inherent differences between the IPMS, it was not possible to rate the systems or their characteristics within the scope of this study. Although all IPMS are material-independent, the table only features information about tested and validated materials as disclosed by the manufacturers.*

7_CONCLUSIONS AND OUTLOOK

The development of In-Process Monitoring Systems started when Laser Powder Bed Fusion became established as a manufacturing technology for producing safety-critical parts. IPMS offer an opportunity to reduce the combined use of µCT scans and Hot Isostatic Pressing for quality assurance of safety-critical components. They even open up the possibility of controlling the LPBF process with closed-loop control systems. The demand for IPMS has increased with the number of applications for LPBF technology, and several firms including machine manufacturers and independent companies have taken on the task of developing a variety of in-process monitoring solutions in order to meet market demands.

One of the challenges for successful IPMS implementation is to develop an understanding for the relationship between system output and part defects. In order to meet these challenges, IPMS manufacturers have developed sophisticated solutions to detect deviations during the LPBF process that could lead to defects in the final component. Establishing the signal-to-defect correlation is key for correct application of an IPMS. Extensive validation and fine-tuning of the IPMS settings is often necessary in order to optimize system sensitivity for each application.

Usability has also been a prime focus in IPMS development. Early systems were complicated to use and demanded a considerable amount of post-processing effort for interpreting the data. Modern systems implement sophisticated data processing and visualization techniques so that users can take quick data-based decisions on whether a part should go through further checks or needs to be post-processed. Some of the latest systems implement machine learning algorithms for automatic detection of problematic process deviations; however, this often necessitates the use of extensive validation programs.

Quality standards together with machine and process qualification requirements are an additional challenge for widespread implementation of IPMS. At present, there are no quality standards stating which sensors or data processing techniques should be used to monitor the LPBF process. Furthermore, retrofitting IPMS to LPBF machines qualified for safety-critical applications would in many cases require resource-intensive and time-consuming effort, which is why some industries are still skeptical about exploring the benefits of IPMS.

Some LPBF machine manufacturers and independent companies are looking at the possibility of using IPMS output for closed-loop process control. This approach is largely in the research stage, but has been successfully implemented by some companies. However, process qualification still remains a hurdle for implementing this novel approach in the production of safety-critical components.

Although IPMS have developed considerably in the past ten years, further experimentation and validation activities will still be necessary before a solution satisfies the requirements of all industries involved in the production of safety-critical LPBF parts. At the moment, there is still no dominant design for an IPMS in the market; nonetheless, multiple solutions are available that are suitable for specific applications. The benefits of IPMS have already been proven in several individual cases and deserve thorough consideration when it comes to reducing the production costs of safety-critical LPBF parts.

8_FURTHER READING

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