

In-process monitoring systems

for metal additive manufacturing

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Executive summary

As additive manufacturing (AM) enters serial production, new approaches for quality assurance are needed. For this, a range of new process monitoring systems are available. Some solutions are provided by AM system manufacturers for their own systems, whereas others are offered by third parties. This paper provides an overview of the technological principles behind these systems and explains their primary benefits in development and serial production.

This white paper is for you, if you

- Want to understand the technological principles behind in-process monitoring
- Want to learn about the possibilities for quality assurance in additive manufacturing
- Are planning to select a monitoring system for your metal 3D printing system



This whitepaper gives an overview of current monitoring systems and examples of how they are used in the direct metal laser sintering (DMLS) processes. The importance of monitoring systems can be seen in the most recent systems placed on the market over the past 2 years – nearly every machine manufacturer in the field of additive manufacturing provides a monitoring solution for their machines. Third-party non-machine manufacturers and universities are also developing and implementing monitoring systems. Some users are even investigating the possibility of creating their own monitoring system to establish a fully featured QM-system. This trend highlights the relevance of monitoring systems for laser sintering.

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Introduction – Motivation for Monitoring

As additive manufacturing technology progresses, its use range is shifting more and more towards serial production, which creates a higher demand for process stability due to the reproducibility requirements placed on component quality.

Monitoring systems make it possible to analyze the DMLS process in real time, providing information about the intrinsic characteristics of the process, and offering conclusions about the quality of parts. This opens up new potential for the fields of quality assurance and process and application development.

Quality Assurance

In the field of quality assurance, monitoring systems enable the real-time detection of process abnormalities/indications that can be correlated with defects in the built part. A quality score is assigned to every built part based on the number of abnormalities/indications detected. An acceptable quality score threshold can be defined by the user based on their specific requirements. Thus, monitoring systems heavily reduce the need for expensive post-build quality assurance tests. Multiple monitoring systems can be combined into an overall quality score in order to detect a wider range of anomalies and/or achieve a higher detection rate. The weighting of each monitoring system can be defined independently by the user. Furthermore, the real-time recorded data can be used to implement closed-loop controls. This feature could allow a healing process for part defects, for example by re-exposing affected areas with different parameter settings to reduce the scrap rate. Another important aspect for quality assurance is that monitoring systems can support the documentation and traceability of the manufacturing process by storing the recorded data. As the use range of the technology shifts towards serial production, and in industries with high quality requirements like the aerospace sector, documenting the process results is becoming more and more important.

Process and Application Development

Compared to other well-known manufacturing processes like casting or milling, DMLS technology has a highly innovative character, which leads to a range of new intrinsic process phenomena. By closely monitoring the DMLS building process, the effects of changing different parameter settings can be observed. Process developers will be able to analyze the process behavior with high frequency and spatial resolution, gaining insights that would have never been recognized from visual inspection alone. The indications identified in the monitoring data can then be associated with abnormalities or non-nominal process phenomena in the laser-sintering process. The knowledge gained from this analysis leads to improved process understanding and therefore accelerates process development and qualification.

The DMLS process is characterized by a high number of input parameters with strong mutual interdependencies. The process stability of new parameter combinations for new materials or refined process characteristics can be analyzed in real time using the data acquired from monitoring. Thus, the monitoring data recorded from a process with nominal exposure parameter settings can be used as a reference and compared against processes with different parameter settings. For example, new scanning strategies can be evaluated in terms of energy input to the powder. By correlating the monitoring signals with this factor of influence, the system can be used to compare the energy input of new scanning strategies against nominal ones based on the

data measured in real time – this can save time and reduce the costs of post-build part analysis. In addition, by comparing recorded monitoring data from system to system, processes can be transferred much more quickly to new laser-sintering machines by taking advantage of the extra information.

In the field of application development, monitoring systems provide valuable information for identifying the most critical areas of a part and optimizing them in terms of part geometry and part position on the building platform. For instance, any overheating in downskin areas can be accurately located by the monitoring signals, since it correlates with the light emitted by the process. This information can help to adapt scanning strategies and achieve homogenous process behavior in areas with special geometries. Support structures play a key role in thermal diffusion, since they connect the parts to the building platform. With the new z- and volume-segmentation feature of EOSPRINT 2.0, extra information is invaluable, allowing the effects of different parametrization of each segment of the part to be visualized in real time while it is being built.

Two different in-process monitoring technologies by EOS for metal systems

The first monitoring technology is EOSTATE MeltPool Monitoring, which uses a photodiode in the laser beam path to measure the light emitted from the melt pool. The advantages of this solution are its high resolution, the in-depth insights into the melt pool that it provides and its ability to precisely determine the location of any process deviations that occur.

The second technology is EOSTATE Exposure OT. This monitoring system is based on a camera that collects light emissions in the near-infrared spectrum, similar to a thermal imaging camera. This yields one image per layer, which can be automatically analyzed for indications of quality issues. This approach expands the range of detectable process phenomena, while combining low data rates with high performance in real-time analysis. MTU Aero Engines have already begun using this monitoring solution in their serial production lines for AM aero engine parts.

Both systems have their own strengths when it comes to monitoring different aspects of the AM process. Since it is closely integrated into the laser beam path, MeltPool Monitoring is more sensitive to deviations in the AM process resulting from laser power fluctuations, whereas Exposure OT is very sensitive to effects resulting from scanning speed deviations and variable hatch distances. Both systems are fully capable of reliably detecting deviations in the process before they lead to defects that might impact the part properties.

The quality assurance potential for additive manufacturing offered by these technologies is unrivalled. In addition to the standard tracking of data by various types of sensors in the machine, process monitoring offers insights into every spot on every layer in every part of every job.

The EOSTATE Monitoring Suite will combine all relevant monitoring systems into one software environment to provide a maximally holistic and informative quality assurance solution for additive technology.

Current Situation

The process monitoring systems currently available on the market can be classified in terms of their sensor type, as well as the way that these sensors are integrated in the machine. Most systems use photodiodes or industrial cameras to monitor the building process. The technique of integrating sensors into the beam path of the laser using a semi-transparent mirror (beam splitter) is described as on-axis integration. By comparison, integrating sensors onto the roof of the building chamber—or directly inside it—is described as off-axis integration. If the sensors are integrated inside the build chamber, it is important to ensure that the basic machine properties, such as the flow conditions, are not affected, since this might directly influence the part quality.

In most cases, in-process monitoring methods are based on observing the light emitted by the process (in both the visible and infrared spectra) at high spectral and/or temporal resolutions. Placing different filters in front of the sensors allows them to focus on specific wavelengths, as well as blocking any unwanted effects from laser light back-reflection or building chamber lightning on the sensors.

Systems based on either diodes (on- and off-axis) or cameras (on-axis) require scanner position data to map the sensor data to the position of the process. By recording the X/Y-scanner coordinates in parallel to the signal from the sensors, the data can be visualized as a mapping according to the actual job layout. The spatial resolution of the melt pool system depends on the scanning speed, as the temporal distance between two data points is fixed.

In the best-case scenario, off-axis camera-based systems can observe the entire build platform at sufficient resolutions. The optical resolution of off-axis camera-based systems directly influences the effective spatial resolution.

Combining on-axis based systems with synchronized scanner position data can potentially allow higher resolutions of the melt pool behavior to be captured, relative to off-axis camera-based systems. In multifield machines, each laser has its own on-axis sensor, so it is possible to accurately identify the laser that generated each signal. The high-frequency read-outs of on-axis sensors also hold significant potential for closed-loop control system. However, the holistic view provided by an off-axis camera can detect other local phenomena than just those that occur where and when the laser is currently sintering, such as splashes and pre-/post-process phenomena. These systems also offer more analysis possibilities for the overlap areas of multifield machines, since the spatial resolution is separated from the nominal scanner position data.

The sensors and integration methods used by each supplier can vary. SLM Solutions offers an on-axis monitoring system based on two diodes (Alberts, Schwarze and Witt 2016), whereas the strategy adopted by Concept Laser is to use one diode and one camera, both integrated on-axis (Toeppel, et al. 2016). The system offered by Sigma Labs is based on an on- & off-axis photodiode combined with an off-axis pyrometer integrated directly into the building chamber (Sigma Labs Inc. 2017). Stratonics uses a 2 gamma-pyrometer camera on a CMOS basis, which can be integrated either on- or off-axis but only covers part of the building platform (Stratonics Inc. 2017). Renishaw has now introduced its InfiniAM Spectral, which is an on-axis sensor system consisting of an "Infrared thermal sensor (1090nm to 1700nm) and a "near infrared

plasma sensor" (700nm to 1040nm) (Renishaw plc 2017).

In general, it is important to be aware that any changes in the hardware performed by third parties can lead to malfunctions of DMLS systems and have implications regarding safety and warranty. As mentioned before, installing hardware directly into the build chamber may interfere with the gas flow, and any additional electrical or optical elements may decrease the original machine performance in terms of part quality. In addition, interpreting the monitored signals is non-trivial, since a large number of optical effects have to be taken into account before the monitoring signal can be used to evaluate the quality of a process.

To achieve high resolution and detect off-melt pool effects, we recommend an on- & off-axis integrated system. This is for example implemented by our EOSTATE Monitoring Suite, which features EOSTATE MeltPool as an on- & off-axis photodiode-based system in parallel to EOSTATE Exposure OT, which is an off-axis camera-based system.

EOS Monitoring Solutions

EOS is currently the only laser sintering machine provider that offers two different in-process monitoring solutions.

With EOSTATE MeltPool and EOSTATE Exposure OT, users can achieve new levels of additive manufacturing excellence in quality assurance as well as process and application development. At the moment, both systems run in separate software environments. However, they will soon be integrated into a common monitoring suite concept with the release of MeltPool and OT-Monitoring for the EOS M 400-4.

1. EOSTATE MeltPool Monitoring

The photodiode-based MeltPool Monitoring was the first tool for in-process monitoring to be released in the EOS portfolio, available since April 2016. The key hardware components are given by two off-the-shelf photodiodes mounted in the build chamber: an off-axis diode that observes the melt pool radiation emitted from the entire platform in the near-infrared (NIR) spectrum, and an on-axis diode, which is coupled into the beam-path via a customized semi-transparent mirror (beam splitter). The beam splitter is a very sensitive part; it is the only optical element added to the beam path of the unequipped system and can potentially alter the performance of the system. Any changes in the focus position and the beam quality induced by the beam splitter should be carefully examined to avoid unwanted changes in process quality.

The on-axis setup allows the emitted melt pool radiation intensity to be observed in a small region around the melt pool. The observed spectrum is in the visible and NIR range. Both the on- and off-axis spectra are selected by placing an appropriate band-pass filter in front of the diodes. The two photodiodes collect data at a sampling frequency of 60 kHz. The signals are amplified, digitized and stored by a high-performance industrial PC in the form of 16-bit values. The PC also collects synchronous information about the x-y position of the scanner, the exposure type, laser modulation (on-off information) and the laser power recorded directly from the hardware controller, which is linked to the

corresponding intensity measurements recorded by the diodes. This setup can visualize and evaluate the melt pool intensity profile at every spot of every layer to high levels of accuracy.

Using the recorded scanner position data, MPM can accurately identify the points of origin of photodiode signals. By integrating the on-axis photodiode directly into the beam path even in multi-laser machines like the EOS M 400-4, MPM allows each laser to be visualized and analyzed separately. In overlapping areas, this feature can prove invaluable, allowing the influence of different lasers on the same spot (overlap area) to be differentiated.

The spatial resolution of the melt pool system depends on the scanning speed, since the temporal distance between two data points is fixed. The scanning speed as a function of the material, the parameters and the exposure type. The measurement data from the photodiode can be spatially visualized by mapping it to the scanner position data. With a maximal spatial resolution of up to 50 $\mu\text{m}/\text{pixel}$ in the Analysis Toolbox, **MPM allows hatch-based process visualization.** Since the distance between two hatches is larger than 50 μm in most cases, they can be differentiated visually.

The intensity of the dataset needs to be corrected for both the on-axis and off-axis diode. The on-axis correction is necessary due to the dispersion and angle-dependent transmission of the optical system. The scanner mirrors and the f-theta lens are optimized to have a homogenous reflection/transmission at the wavelength of the laser (1064 nm). But since the wavelengths of light recorded by the on-axis diode are shorter than 1064 nm, this light will be affected by the optical system as it travels upwards towards the photodiode. In practice, this results in an inhomogeneous intensity distribution across the platform that does not properly reflect the true process emissions.

The off-axis data is also inhomogeneous in raw form, because the corresponding diode also needs to be corrected to account for the angular and distance-dependent transmission. Here, an intensity correction is needed to account for the fact that the build process appears brighter in areas that are built in close proximity to the diode relative to areas that are built further away.

Based on the measurement data recorded by a specially designed setup, a correction mask is calculated under the assumption that the process light is isotropic across the entire build area. After applying this correction to the dataset, the resulting process intensity measurements are isotropic and hence unaffected by the position.

The data is stored and visualized by the so-called Online Software, which can apply three different algorithms to the corrected signal in live acquisition mode: Absolute Limits, Signal Dynamics and Short Time Fluctuations.

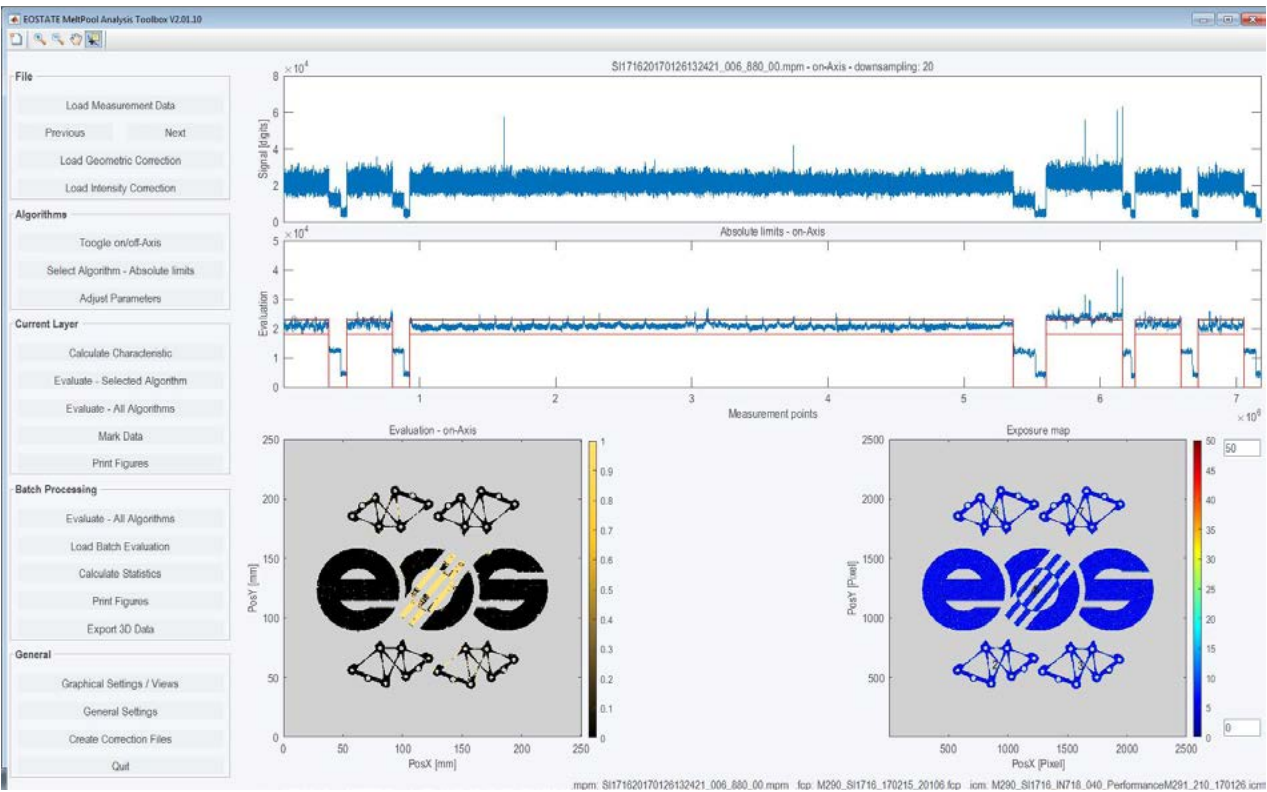
The algorithms are designed to highlight process phenomena that might influence

the part quality.

Those process phenomena may be either systematic (machine failure) or statistical in nature. Examples include overheating, splash processes (gas flow issues) or large ejections from the melt pool. The processed signal is evaluated by applying a threshold approach: whenever the (processed) signal exits the threshold band, the position is marked as an

indication. This approach allows the process to be evaluated in terms of "inside process window" and "outside process window." To develop parameters or analyze the recorded data in more depth, EOS offers the Offline Software Analysis Toolbox shown in Figure III 1. The Analysis Toolbox can also export each layer as a tiff-image for external analysis.

Figure III 1: EOSTATE MeltPool Monitoring – Analysis Toolbox



The top of Figure III 1 shows the time series analysis of one layer. In this case, a simple threshold approach is applied to the highlighted areas of the layer, where the process conditions were intentionally set to abnormal levels. The lower part of the figure shows the corresponding evaluation mapping of the signal. The yellow points represent areas where the process lies outside the defined limits.

2. EOSTATE Exposure OT

The second system in the EOS Monitoring portfolio is the camera-based Exposure OT, available since July 2017.

This system has already proven its capability as a quality assurance tool, developed in close strategic cooperation with MTU Aero Engines in accordance with their high quality expectations for the serial production of aerospace parts (EOS GmbH Electro Optical Systems 2017).

The system consists of an sCMOS-based camera with specially designed optics to gather high-resolution and high-focal depth images in the NIR wavelength range from the entire build platform during laser processing. The light emitted from the hot laser interaction zone and its surroundings is focused onto the camera chip after passing through a neutral density filter and being spectrally filtered to a narrow infrared wavelength band. Whereas MPM associates photodiode signals with their points of origin (X- and Y-coordinates of the scanner position), OT assigns the data recorded at each pixel to the appropriate point of the building platform.

The camera hardware and the specially designed optics are mounted on the top of the building chamber using a specially designed camera-holder. This camera-holder features a mirror that reflects the process emission light into the camera. This allows the camera to be mounted at the top of the process chamber without changing the machine hardware or influencing the process. With a camera resolution of 2560 x 2160 pixels, the system achieves a spatial resolution of 125µm / pixel across the entire build area (EOS M 290).

The camera captures 10 frames per second, which are permanently superimposed to give a holistic image of the layer. Thus, after each layer, all images captured by the camera are combined into a single image, forming a process map that can also be correlated with the light emitted by the process.

Due to distortion effects caused by the optical components and the non-centralized positioning of the camera, the images need to be geometrically corrected by the software.

An additional radiometric correction step for these systems is also planned in the near future. This correction will essentially be performed by measuring a light source that emits a known spectral radiance/ luminance from inside the process chamber and adjusting the system sensitivity to a nominal level. This correction procedure will provide a basis for comparison between different machine and should allow users to transfer analysis profiles from one machine to another. An annual recalibration service will also be offered to ensure the long-term stability of the camera systems.

The look and feel of the software GUI follows the new user-friendly EOSPRINT 2.0 concept. The software architecture of EOSTATE Exposure OT Monitoring is designed according to a Client-Server model. The EOSTATE Exposure OT System Service is a background service that takes care of all data acquisition operations, camera controlling, machine communication and process state synchronization, including gathering integral and maximum images for every layer and collecting meta data about the job. All data is saved to an OT-specific database. The service performs analysis in real time. Standard analysis profiles featuring multiple analysis algorithms can be selected and predefined. The part-specific analysis results are stored for each layer.

The EOSTATE Exposure OT Client is used to connect to a constantly running OT System Service and the OT Database (local or remote) for visualization, analysis, setup und parametrization. It can be installed on either the OT Industry-PC (default) or on a third-party PC (online or offline). The client is divided into three user roles, with different functions for each role:

- **Operator:** View monitoring images from the current or last completed job, including any detected indications; comment function; export monitoring data for offline usage
- **QA-Engineer:** Load and view monitoring results; conduct additional analysis; browse and categorize any detected indications; change analysis parameters/ profiles; generate report
- **Support:** Manual recording; geometry correction calculation; absolute intensity calibration; process intensity correction calculation; generation of geometric and intensity corrections; radiometric calibration

The analysis workflow of the QA Engineer role is structured into 4 steps. The first step is to load a recorded job from the database or any other storage medium. The analysis profile management features allow new analysis profiles to be defined or existing analysis profiles to be adjusted based on a range of different algorithms. **Currently, OT monitoring features three sophisticated analysis algorithms based on Threshold-Indication Detection. For each algorithm, multiple parameter sets can be defined to adapt the algorithms to user-specific application and quality requirements.**

After selecting a profile, analysis can be performed. In the next step, the results can be viewed, and any detected indications can be investigated, either as exported tabular data or in an image-based form (See Figure III 2). In step four, the detected indications can be classified and evaluated. On the basis of an automatically generated quality report, the user can decide whether the part was built to nominal or non-nominal specifications – which can potentially lead to significant cost reductions for post quality analysis such as CT scans.

Figure III 2: EOSTATE Exposure OT – QA Engineer role

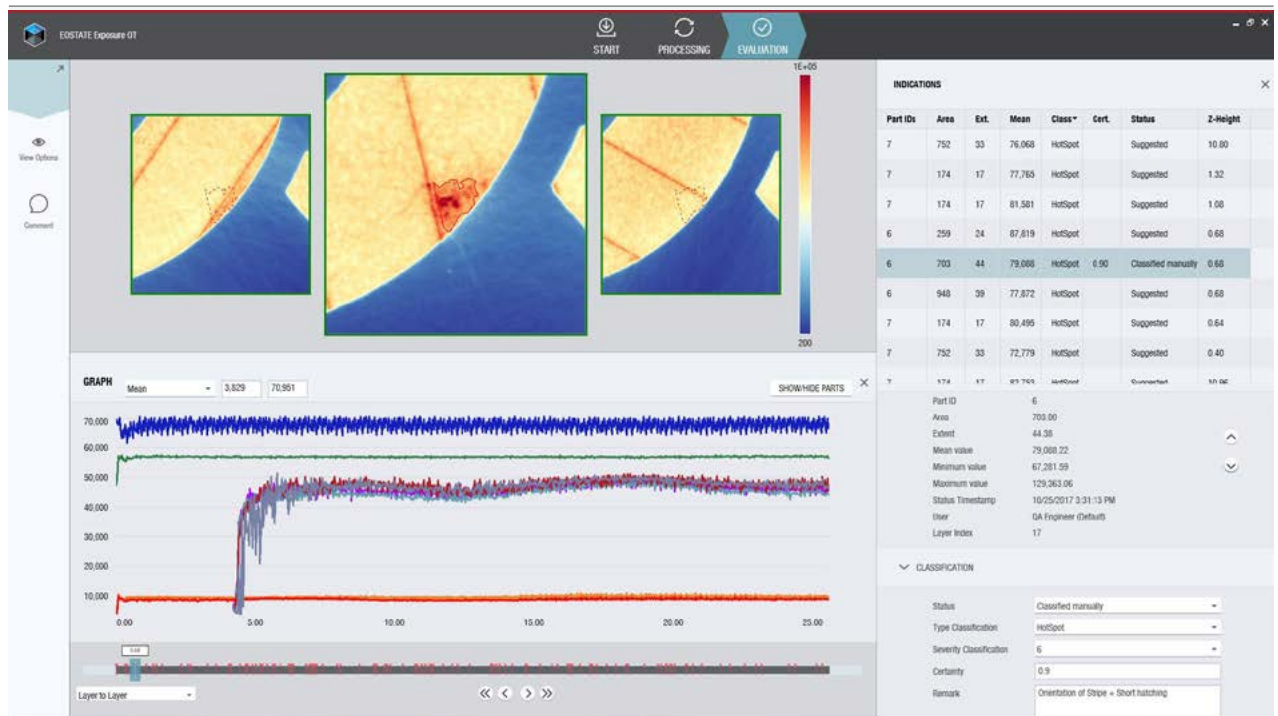


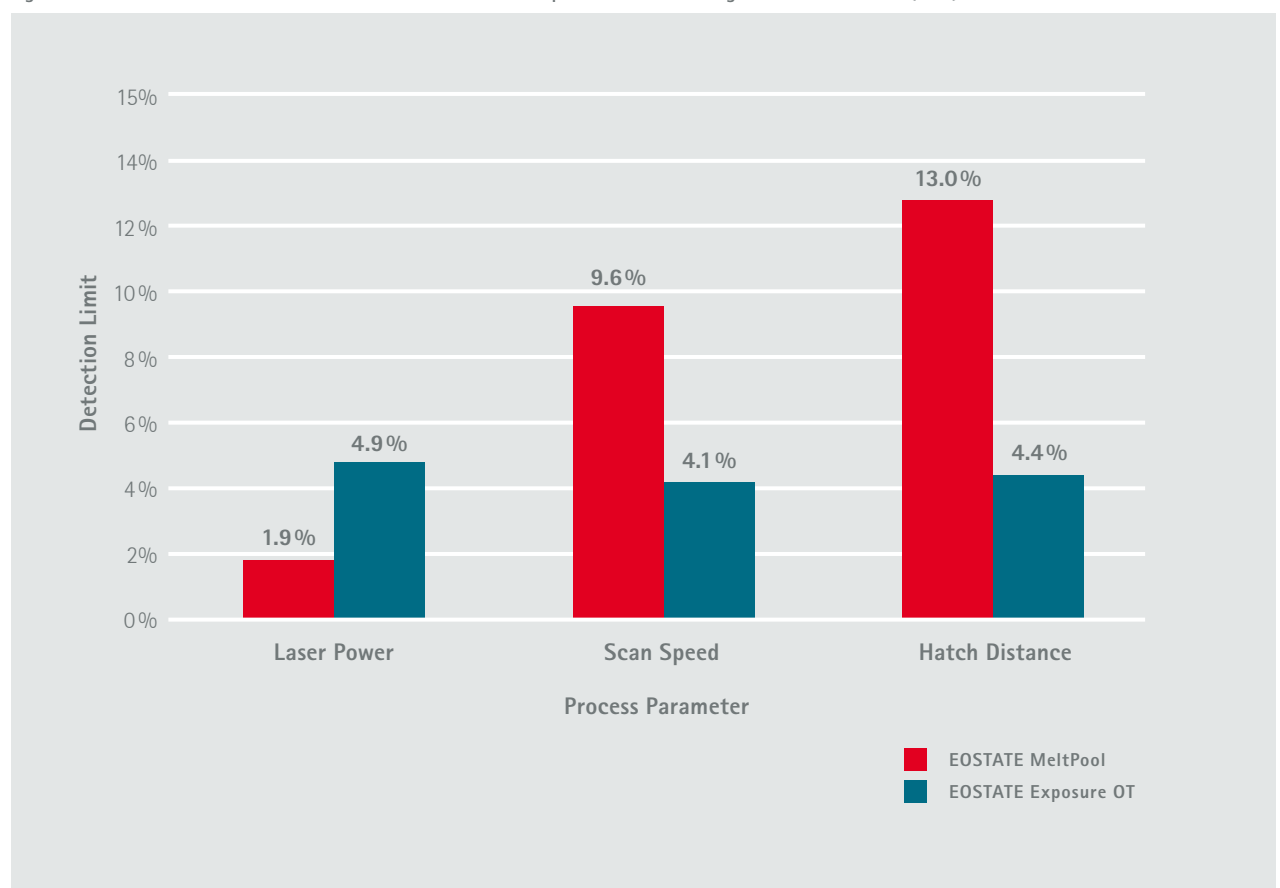
Figure III 2 shows the QA Engineer role of the EOSTATE Exposure OT software. The middle image shows a zoomed-in part of a build where a process anomaly was identified by the algorithms. The shape of this indication is highlighted by a red border, which is also shown in the visualization of the previous and subsequent layers. The graphs show the mean grey value of each part for each layer. On the right, the user can scroll through all detected indications in the job and classify them manually. Finally, reports can be created and exported.

EOS Performance – Correlation Ti64

The performance of a monitoring system can be evaluated in terms of its ability to detect process changes provoked by non-nominal process parameters. EOS investigated the sensitivity of EOSTATE MeltPool Monitoring and EOSTATE Exposure OT to changes induced by varying the process parameters of laser power, scan speed and hatch distance with the EOS Titanium Ti64 (material and process parameter). The porosity of the build cubes was analyzed by metallographic micro section. The job layout was designed in accordance with the principles

of good practice for Design of Experiments (DoE). This statistical experimental design allows the number of experiments to be reduced by varying several factors simultaneously in a single experiment and evaluating them to specific extents (Kleppmann, Taschenbuch Versuchsplanung 2008, p. 198 ff.). For the analysis, the mean intensity value of every part and layer is calculated from the MPM and OT data. In this study, the sensitivity of the systems is determined by calculating the smallest change in a process parameter that is detectable by the monitoring system (Detection Limits). The Detection Limit is given as a percentage of the nominal value of the process parameter. Mathematically, these values are calculated from the point-slope equation, using the quotient of the standard deviation (to 2 sigma) of the nominal built parts over the gradient, which is calculated by performing a linear regression of all parts (the nominal and non-nominal part mean intensity values of MPM/OT). The results are

Figure IV 1: Detection Limits of EOSTATE MeltPool and EOSTATE Exposure to detect changes in the Laser Power (Ti64)

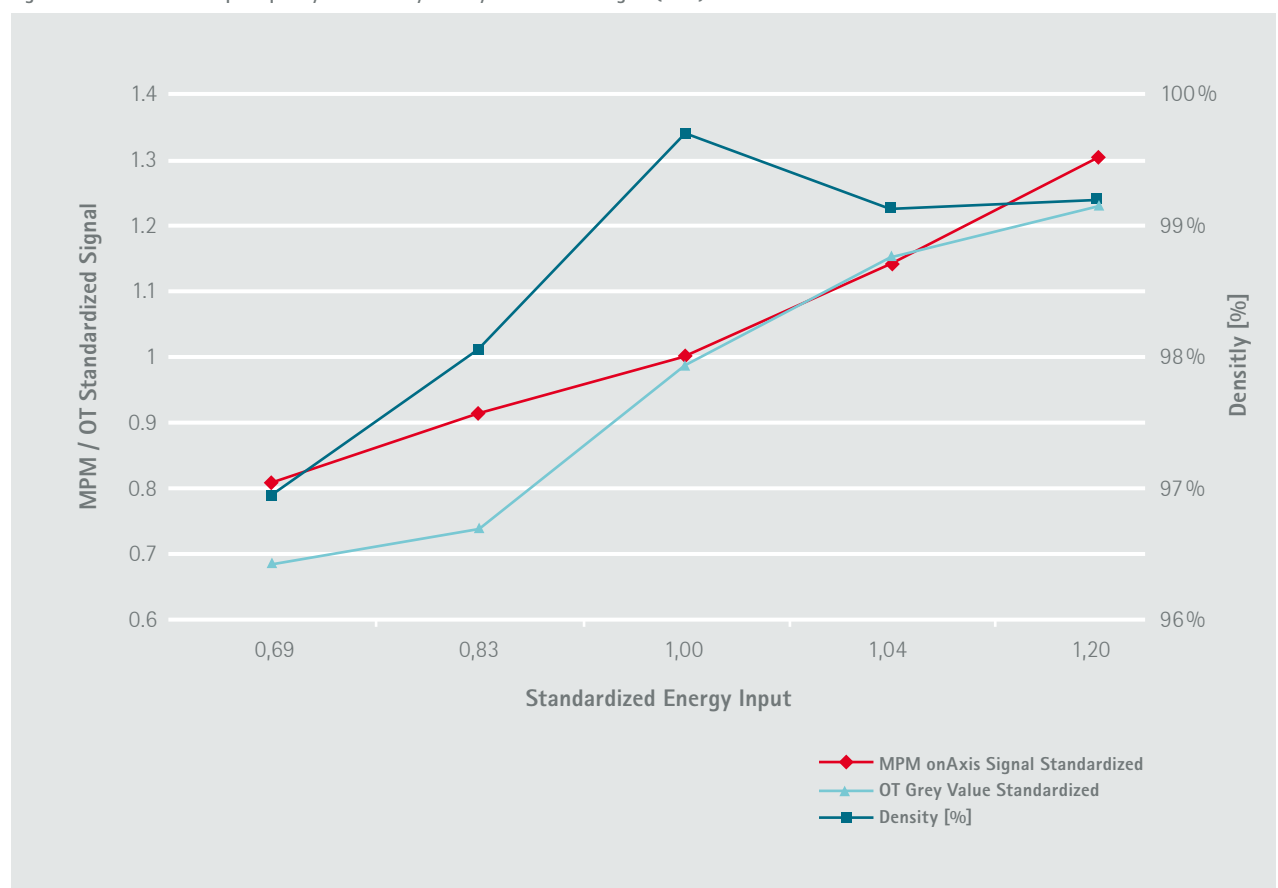


shown in the following graph: Figure IV 1 shows the sensitivity of the two monitoring systems as a percentage. EOSTATE MeltPool can detect changes of <2% in the Laser Power relative to the nominal values for this process parameter and material, <10% in the Scan speed and 13% in the Hatch Distance. EOSTATE Exposure OT is able to identify process changes of <5% in the Laser Power, <5% in the Scan Speed and <5% in the Hatch Distance, relative to the nominal values in each case.

In summary, this means that MPM is slightly more sensitive to changes in the Laser Power, whereas OT is more sensitive to changes in the Scan Speed and the Hatch Distance. Since both the Laser Power and the Scan Speed are fundamental parameters of the DMLS process, the best results are achieved by monitoring with both MPM and OT. These monitoring systems allow process variations to be detected before they create part defects such as increased porosity.

These findings were verified by correlating the recorded signals with the porosity levels, which were measured by metallographic micro section analysis. It was found that, whenever the monitoring signals recorded by EOSTATE MeltPool and EOSTATE Exposure OT fall below a certain level, the porosity level rises significantly (see Figure IV 2). This shows that these monitoring systems are capable of detecting changes in the process parameters that influence part quality, justifying the benefit of EOS Monitoring systems as a quality assurance tool. The analysis also demonstrated the stability of the standard EOS Ti64 Performance process, since slight changes in the process parameters relative to nominal values do not considerably change the porosity level.

Figure IV 2: Correlation of part quality measured by density level to MPM signal (Ti64)



Process Flow – Monitoring Investigation

The flow of the inert gas as it spreads throughout the platform plays a key role in the process stability and influences the part quality. The flow speed and profile are crucial in the machine and process development and EOS has invested a great deal of effort into optimizing it. The goal is to efficiently remove the process by-products (splatters, smoke, condensate) in order to prevent them from interacting with the laser beam. Therefore, the flow should be as laminar as possible, and the volume rate should be as high as possible. On the other hand, significant powder removal from the platform by the flow must be avoided, since any powder carried away by the flow ends up in the filter system of the machine. In summary, the choice of flow speed, volume rate and design always involves a trade-off between maximizing the process by-product removal and minimizing the powder removal.

Figure V 1: Comparism of MPM-, OT- and microscope-image (MP1)

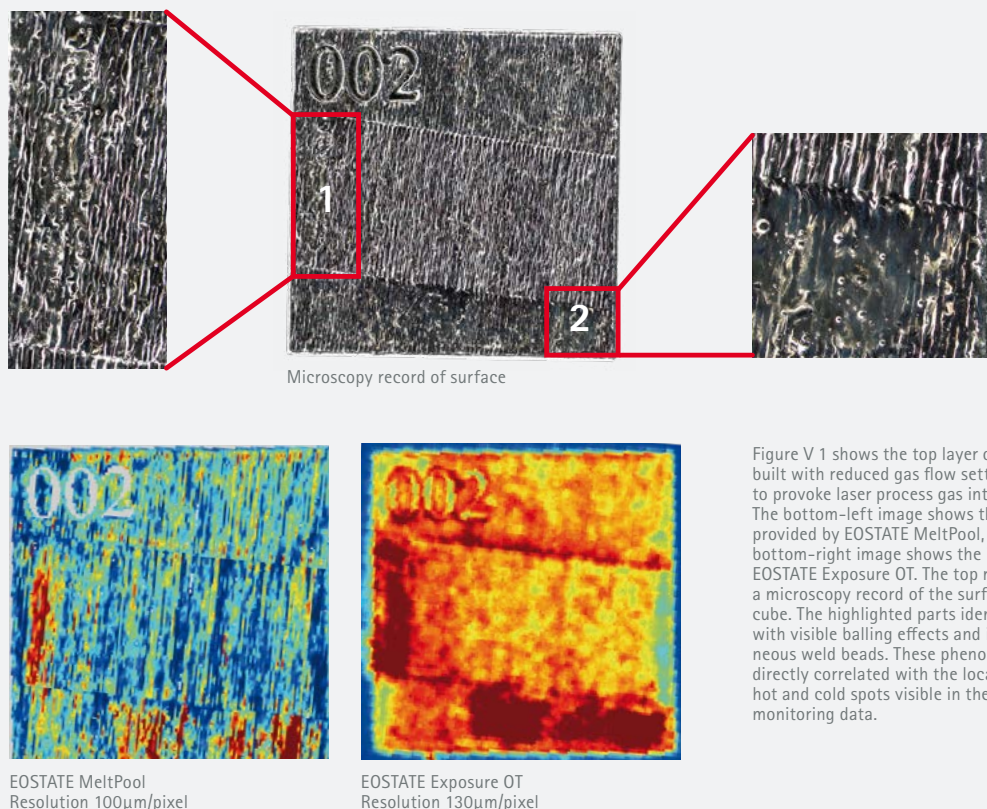


Figure V 1 shows the top layer of a cube built with reduced gas flow settings in order to provoke laser process gas interactions. The bottom-left image shows the visualized provided by EOSTATE MeltPool, and the bottom-right image shows the image from EOSTATE Exposure OT. The top row shows a microscopy record of the surface of the cube. The highlighted parts identify areas with visible balling effects and inhomogeneous weld beads. These phenomena are directly correlated with the locations of hot and cold spots visible in the process monitoring data.

Even with an optimally adjusted flow speed and profile, undesirable interactions can occur between the process by-products and laser beam. This can for example be caused by fluctuations in the powder particle size distribution or chemical composition (pollution), increased ejection of process waste due to short hatch vectors or an alignment of the flow direction and the stripe hatching direction or single hatch vectors. In order to reduce the latter phenomenon, EOS has invented and patented the F01 exposure strategy, which avoids exposure in undesirable hatching and stripe directions.

Strong interactions between the laser beam and process by-products are visible to the naked eye to various degrees of severity during the melting process and also on the surface of recently built materials. These process interactions are known and described as splashy processes, spatters, hot spots and cold spots. In Figure V 1, the MPM and OT monitoring data of a coupon built in non-nominal process conditions is shown next to a microscopy image of the surface. In this example, the flow rate was deliberately reduced to enhance the interaction of process by-products and the laser source. Among other things, hot spots are visible in the results, marked by the red box as well as cold spots, marked by the red box 2 in the middle microscopy image of Figure V 1, on the surface.

These indications are detected by both MPM and OT, but with some differences, as described earlier: MPM associates the photodiode signals with their points of origin (X- and Y-coordinates of the scanner position). Therefore, the points of origin of the hot and cold spots can be precisely localized. OT assigns the recorded data to the points of detection based on the spatial resolution of the camera chip. Thus, the hot and cold spots are visualized over the whole area that may be affected by these phenomena.

Cold spots can arise from shading of the laser due to the smoke, which leads to a lower energy deposition and a dimmer monitoring signal.

Ladewig et al. propose that the hot spots can be explained by Raman Scattering of the particles in the cloud of smoke. The particles are stimulated by the laser beam and release their gained energy by radiation. Since the area of emittance is larger than the normal process, the recorded process light appears brighter, but in fact the energy reaching the powder is lower (Ladewig, et al. 2016). In addition, it was shown that the defocusing of the laser that occurs within the cloud of smoke can also induce the balling effect that is clearly visible in Figure V 1. The hot spots and cold spots detected by both monitoring systems can be clearly associated with an area of increased balling on the surface of the real part. When these large ballings are remelted in the next layer, there is a risk of lack of fusion, since the laser energy may not suffice to fully remelt the large particle. Therefore, accurately detecting and classifying these kinds of indications of process phenomena can be invaluable, as made possible by the EOSTATE in-process monitoring solutions.

Summary and Outlook

The demand for monitoring systems is clear from the constantly increasing number of monitoring systems offered on the market. Machine providers, research institutes and even users themselves have invested significant research time in investigating possible solutions for monitoring systems. The fields of application of these systems range from quality assurance to supporting R&D projects such as process development. Different providers use a variety of different types of sensors and integrate them into their monitoring systems in different ways. Most systems consist of a photodiode or a camera that can be integrated either on- or off-axis into the machine. EOS offers solutions for both technologies: EOSTATE MeltPool Monitoring is an on- and off-axis photodiode-based system, and EOSTATE Exposure OT offers an off-axis camera-based alternative. In the near future, EOS plans to release a new EOSTATE Monitoring Suite featuring process-, system- and powder-bed-monitoring systems with an integrated overall analysis of all signals. **A study found that the sensitivity of the EOS monitoring systems to changes in the process parameters (e.g. laser power) is higher than the deviation in the parameters required before part defects occur (e.g. higher porosity level), which demonstrates the viability of these systems as a quality assurance tool.** Multiple studies also justified the significant role that can be played by these systems in the field of R&D, for example by allowing the

impact on process quality of variations in the gas flow to be analyzed from the recorded data in order to find the most suitable settings.

The possibilities offered by monitoring systems for quality assurance in additive manufacturing exceed those of any other technology. Beyond simply tracking data from sensors in the machine, process monitoring provides insight into every spot of every single layer in every part of every job.

With the EOSTATE Monitoring Suite, EOS plans to combine all relevant monitoring systems into a single software environment to provide as holistic and informative a quality assurance solution as possible for additive technologies.

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Lukas Fuchs
Application Development Consultant

Lukas first encountered additive manufacturing in 2012 while studying laser physics. After receiving his master's degree, he specialized on the in-process monitoring of 3D metal printing as an Application Development Consultant for 3 years. During this time, he collaborated with leading users of this technology worldwide and participated in the development of monitoring systems at EOS. As of 1st of June 2018, he is working as a Business Development Manager for turbomachinery at EOS.

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For his thesis for his bachelor's degree in industrial engineering, Christopher worked on feasibility studies of additively manufactured parts at EOS. Continuing with a master's degree, he completed his studies with a thesis focusing on the sensitivity and correlation analysis of in-process monitoring systems at EOS. After starting in 2016 as a technical project manager, Christopher is now responsible for the development of EOSTATE MeltPool monitoring.

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If you have any remarks
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