Whitepaper

This Whitepaper Gives Information About:

- → Producing or planning on producing porous structures by means of additive manufacturing
- → Assessing mechanical properties of lattice structures during the build
- → State-of-the-art alternatives to cost-intensive quality assurance methods

Correlation of In-Process Monitoring Data and Mechanical Properties of Lattice Structures

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In-Situ Process Monitoring of Lattice Structures Manufactured by DMLS®

The monitoring system EOSTATE ExposureOT can be used to assess the relative density and compression strength of lattice structures. Any decrease in energy density that results in a lower EOSTATE ExposureOT value leads to a decrease in strut thickness and therefore a lower relative density. This method therefore allows fundamental lattice parameters to be evaluated in situ during the build process. Transferring this knowledge to the related application can significantly reduce the effort associated with non-destructive or destructive testing. Generating these monitoring data does not affect the process and does not incur any additional costs after installation. EOSTATE ExposureOT can be retrofitted to any EOS M 290.

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Introduction to EOSTATE Process Monitoring

Quality control is a major challenge for additively manufactured parts in quality-sensitive industries (healthcare, aviation, etc.). In the healthcare industry, a number of technical requirements must be fulfilled before placing a product on the market.

Metallic implants, for instance, must be strictly tested to ensure that they meet the relevant standards. On the other hand, implants are well suited for additive manufacturing due to special requirements such as:

→ Highly complex geometries,

→ Patient-specific design,

→ Fast process chain, from medical imaging to surgery -ready implants [Sing et al. 2015].

These stringent demands make the quality assurance of additive manufactured implants particularly challenging. Conventional non-destructive testing methods such as radiographic testing (RT) or computed tomography (CT) are often cost- and time-intensive or ineffective.

Most manufacturers of powder bed fusion systems provide some kind of online process monitoring system to detect defects on a layer-by-layer basis [Grasso et al. 2017]. These monitoring systems can be distinguished by their sensor type and how their sensors are integrated into the machine. Commonly used sensors include photodiodes and industrial cameras, which capture the light emitted by the AM process. Filters are used to analyze specific wavelength regimes. The sensors can be integrated either along the beam path of the laser (on-axis) or adjacent to the optical path of the laser (off-axis).

EOS provides both on- and off-axis diodes and camera sensors to provide comprehensive monitoring and maximum flexibility in terms of customer requirements. For more information, refer to the whitepaper "In-Process Monitoring Systems for Metal Additive Manufacturing" available at www.eos.info.

With the camera-based system EOSTATE ExposureOT, EOS is the first company to offer an in-process monitoring tool that replaces X-ray and CT inspection [EOS, MTU 2019]. A camera is mounted behind a protective glass window on top of the build chamber so that its field of view covers the entire build plate. For simplicity, the data provided can be considered as a long-exposure image of the process light for each layer.

The main principle of defect detection of EOSTATE ExposureOT is to register areas where the laser is obstructed by process waste (smoke, spatter, etc.). After integrating over time, the process light of areas experiencing any such effects deviates noticeably from the process light of an unobstructed process. The process light emissions have a high inherent noise level. EOSTATE ExposureOT smooths out the noise over time to achieve a high signal-to-noise ratio (SNR). For lattice structures, this approach is not applicable. The exposed area is too small to generate blobs in the image data. An adapted evaluation method for lattices is therefore described in the section "Adapting EOSTATE ExposureOT Evaluation" on page 5.

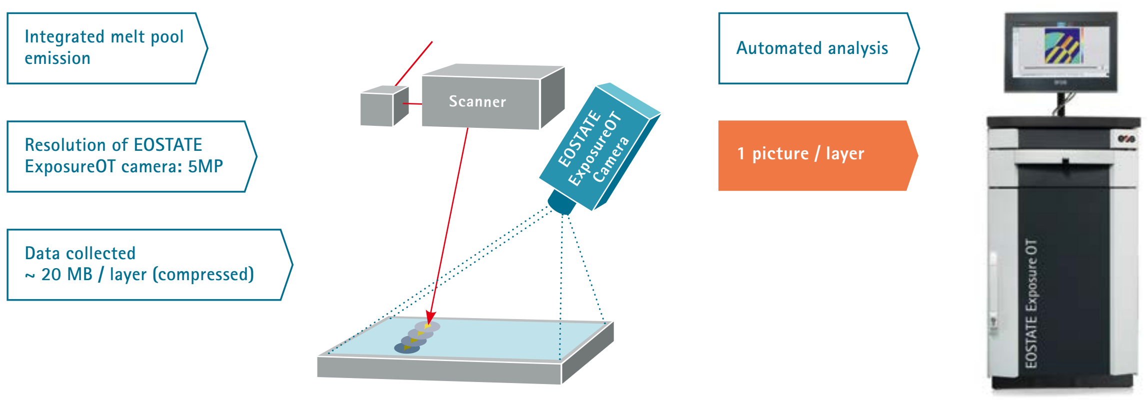

Figure 1: The operating principle of EOSTATE ExposureOT with its key characteristics allowing users to efficiently monitor build jobs.

In-Situ Quality Control of Lattice Structures

Lattice structures are an important element of implants produced using metal additive manufacturing. They provide unique customer benefits such as tailor-made mechanical properties and osseous integration, among various others. [Küster et al. 2019]

The small exposed areas of lattice structures per layer make in-process monitoring particularly difficult. The process light which is captured and analyzed is only generated for short time spans and in very limited areas, leading to a reduced SNR. Therefore, high data acquisition rates and resolutions seem necessary to monitor the building process of lattice structures. However, this results in large amounts of data, increasing the costs associated with data handling, evaluation and storage.

Lattice Properties and Process Energy

To understand how monitoring the build process of lattice structures can be both effective and viable, we shall briefly summarize the work performed by Küster and Orye [Küster et al. 2019] on the mechanical properties of lattices. The cited authors analyzed a test series of cylindrical lattice specimens with the same lattice type built on an EOS M 290 with hard recoating and different process parameters in accordance with ISO 13314. Their main claim is that a strong correlation exists between strut thickness and compression strength (see Figure 2). The results suggest that the strut thickness is primarily determined by the energy input. The higher the process energy, the larger the melt pool, resulting in a larger strut diameter. However, the effect of changes in energy input on the internal strut density is small and can therefore be neglected.

The experience in monitoring applications acquired by EOS over many years supports these findings. In a properly developed process, local defects should appear randomly [Ladewig et al. 2016]. A large exposed area in an unfavorable environment is needed to generate enough statistical probability for local defects to affect the part quality.

In lattice structures, excess energy will not lead to porosity since there is a lot of loose powder around the melt pool. The powder absorbs the excess energy by melting, resulting in thicker struts. On the other hand, a lack of energy is not always critical. A good process is always slightly overpowered, hence the strut thickness may decrease without negatively affecting the fusion. If this occurs locally on a single strut, it only results in a reduced strut thickness for this particular strut. This local effect is then compensated by the surrounding struts.

The mechanical properties of any given lattice structure therefore largely depend on the amount of energy available to the process. This differs greatly from any bulk parts where local process deviations are highly significant and the influence of the laser power is more complex.

The aim of this paper is to establish the correlation between EOSTATE ExposureOT values and the energy input of a lattice process. By incorporating the findings of Küster and Orye into this correlation, the mechanical properties of a lattice structure can be linked to the process monitoring values (see Figure 2). In a bulk material, this direct link is more challenging due to the complex interaction of the laser with the powder and bulk material. Statistical process fluctuations of different intensities and sizes might also be present. These phenomena would need to be characterized for a complete correlation.

The simplified correlation between mechanical properties and process energy for lattice structures allows this relationship to be extended to monitoring signals without large amounts of statistical data.

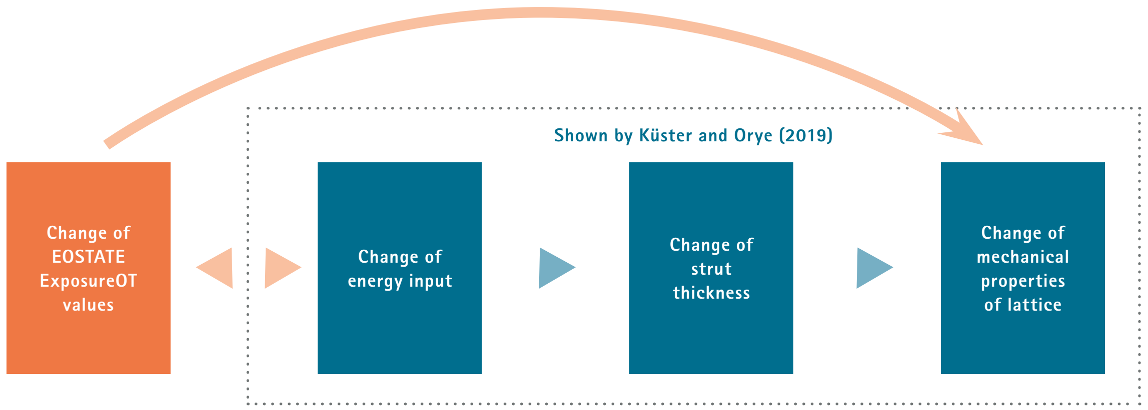

Figure 2: Küster and Orye (2019) linked the mechanical properties of porous structures to the available process energy. By correlating EOSTATE ExposureOT values with the process energy, a link is established between process monitoring and the mechanical properties of the final lattice structure.

Adapting EOSTATE ExposureOT Evaluation

To assess the EOSTATE ExposureOT of lattice structures, the evaluation has to be adapted to consider the overall energy input instead of local phenomena.

Fuchs and Eischer [Fuchs et al. 2018] showed that the EOSTATE Monitoring systems are sensitive to changes in the process energy of just a few percent. To reach this sensitivity level, the light emitted by the lattice process needs to be averaged over a certain area and/or time span. The EOSTATE ExposureOT monitoring software receives part position information from the build job and can therefore average the EOSTATE ExposureOT values inside each part and layer (see Figure 3). As well as being visualized inside the software, these data can be automatically exported as a "csv" file and further processed using any statistical tool such as Minitab.

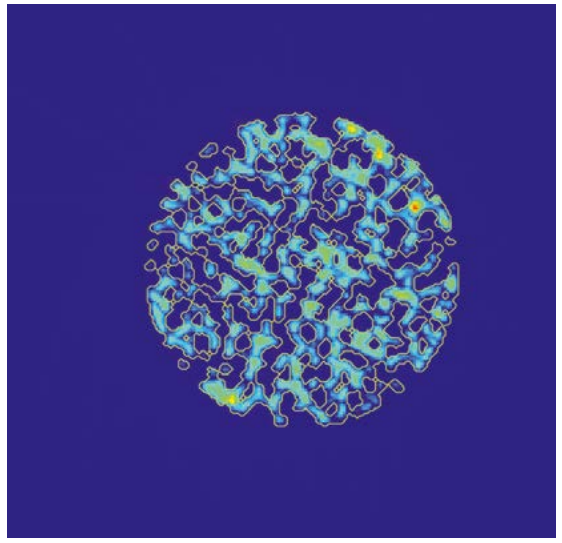

Figure 3: This pseudo-colored image of a single part and a single layer shows the different process light emissions. The part boundary is highlighted in yellow. Only the area inside the borderline is evaluated.

For the purpose of this study, the EOSTATE ExposureOT values of 100 layers of each specimen were averaged. The evaluation started from layer 101 to eliminate any influence of the build plate.

Parameter	Energy increase [%]			Tolerances [%]		Energy reduction[%]		
Laser power	+30	+20	+10	+3	-3	-10	-20	-30
Scan speed	-30	-20	-10	-0.015	+0.015	+10	+20	+30
Hatch distance	-30	-20	-10	-2.4	+2.4	+10	+20	+30

Table 1: Parameter change values considered by this study

EOSTATE ExposureOT Sensitivity Assessment

To evaluate the sensitivity of EOSTATE ExposureOT to the energy in a lattice process, two test series of lattice specimens were evaluated. The first series contained only specimens with nominal parameters, in order to generate reference values. The second series featured certain parameter variations. The sensitivity of ExposureOT was analyzed from the changes between the two build series.

Experimental Setup

The jobs consist of cylindrical specimens built according to ISO 13314 (see Figure 5 and Figure 7). A total of 112 specimens were built with EOS Titanium Ti64ELI on the EOS M 290. The lattice structures were built with an infill parameter and no contours. The custom parameter was optimized for this specific lattice geometry. A HSS blade was used for recoating.

The parameter changes of the second build series were split in two groups. The group titled "Tolerances" is based on the theoretically possible variations if the EOS quality processes are in place (see Table 1). To expand the evaluation range, more significant changes such as ± 10 %, ± 20 % and ± 30 % were applied ("Energy increase/reduction" in Table 1). Three major process parameters were modified from the nominal values: laser power (LP), scan speed (SS) and hatch distance (HD). This allowed the impact of each parameter to be evaluated individually. The parameter changes are evaluated by their influence on the energy density, calculated according to the following formula:

$$\text{Energy Density}\left[\frac{J}{mm^3}\right] = \frac{LP}{SS \times HD \times \text{layer thickness}}$$

Beside the EOSTATE ExposureOT values, the two main properties of lattice structures were determined - the relative density and the compression strength. As an important design parameter, the relative density was tested by underwater weighing based on the Archimedes principle. The compression strength was tested according to ISO 13314.

Results and Evaluation

Figure 4 shows the relative EOSTATE ExposureOT values as a function of the relative energy density for each process parameter. This reveals a correlation between the energy density and the EOSTATE ExposureOT values. The correlation changes depend on the modified input parameter (LP, SS and HD). The dependence of the EOSTATE ExposureOT values is practically proportional (linear) to the LP input change. HD and SS show nonlinear behavior as the energy input increases.

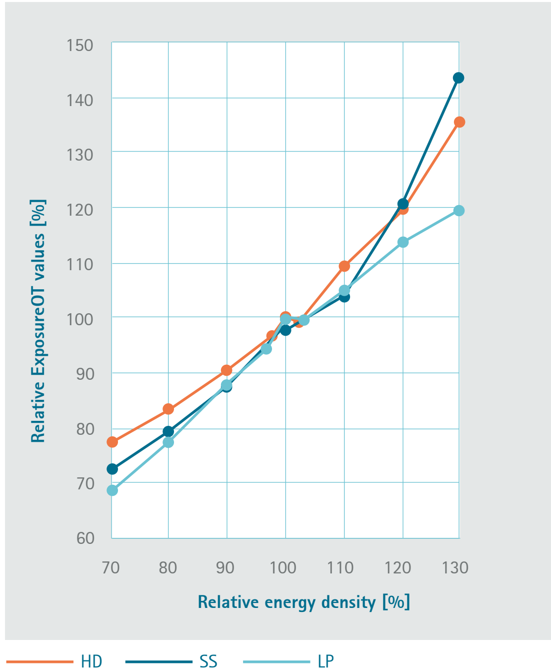

Figure 4: Parameter changes have a significant influence on the EOSTATE ExposureOT signal.

The applied energy density calculation stated above oversimplifies the real process behavior to some extent. The energy of a process is not proportional to the hatch distance since entire hatch vectors can appear or disappear at the border of a part. The scan speed is not fully proportional to the energy input of a certain area. The turnaround times in between the hatching lines are not affected by changing the scan speed. These turnaround times still make up for a significant amount of the overall exposure time. It is however evident that EOSTATE ExposureOT is sensitive to changes in all three parameters. The graph shows that laser power is the most linear of all parameters, which is also corroborated by Küster and Orye [Küster et al. 2019], who showed that the LP has the strongest influence on the material properties of lattice structures.

Additionally, the EOSTATE ExposureOT data were evaluated in relation to the tested properties of the lattice structures. The tests in the study of Küster and Orye were performed using the Archimedes testing principle. The tests were only conducted for parameter changes from ±10 % to ±30 %.

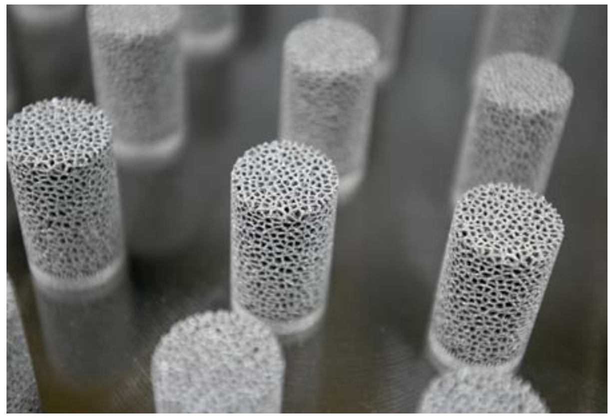

Figure 5: The cylindrical test specimens allow convenient testing and evaluation.

Figure 6 shows the relative EOSTATE ExposureOT values as a function of the measured relative density. Since Küster and Orye showed that the strut density is not affected by variations in the parameters, the increased relative density signifies an increase of strut thickness. The previously mentioned high influence of laser power on the lattice structure is also clear in this representation.

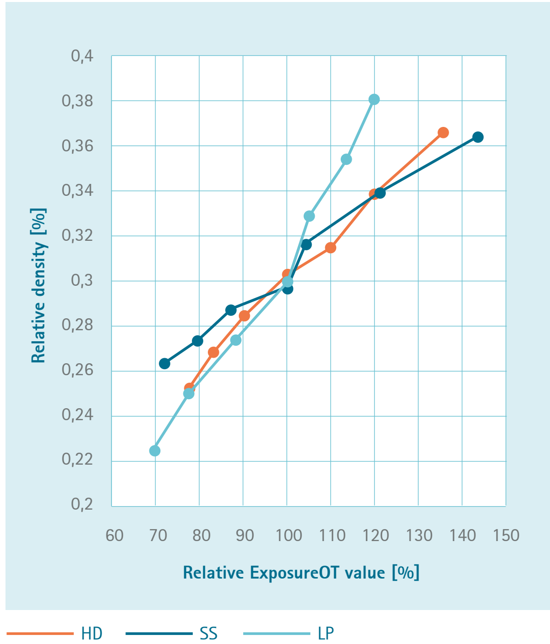

Figure 6: Changes in the LP influence the EOSTATE ExposureOT values and the relative density the most.

The values of the compression test are displayed in Figure 8 as a function of the relative EOSTATE ExposureOT values. The results are remarkably similar to the relationship with density measurements, showing that EOSTATE ExposureOT is capable of sensing these changes with a roughly linear correlation (also stated by Küster and Orye).

Any decrease in energy density that results in a lower EOSTATE ExposureOT value leads to a decrease in strut thickness and therefore a lower relative density. This results in lower compression strength. Concretely, a 10.0 % decrease in the LP reduced the ExposureOT values by 11.7 %. This produced a relative density 8.7 % lower and a compression strength reduced by 34.8 %. This confirms Küster and Orye's conclusion that the LP has the biggest impact on the mechanical properties of the lattice structure. The sensitivity of EOSTATE ExposureOT with respect to the LP makes it a powerful tool to monitor the mechanical properties of a lattice structure during the build job.

Figure 7: The build job contains cylindrical lattice specimen on the entire build plate.

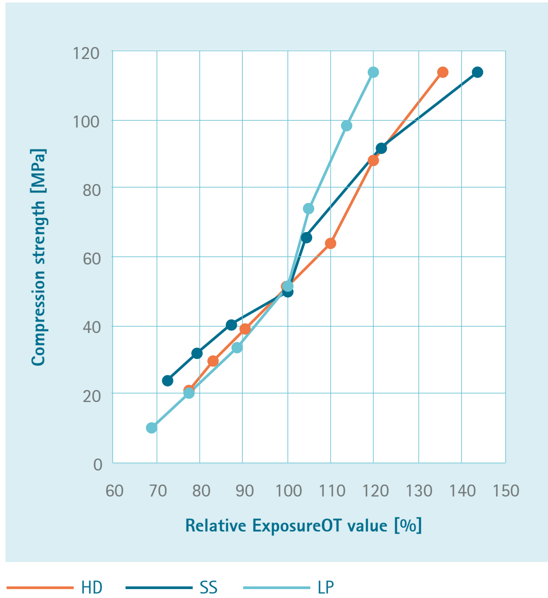

Figure 8: The compression strength shows similar behavior to the relative density in terms of the EOSTATE ExposureOT values.

Conclusion and Outlook

This paper shows that EOSTATE ExposureOT is capable of assessing the fundamental lattice parameters in situ during the building process. Transferring this knowledge to the relevant application can significantly reduce the effort associated with non-destructive or destructive testing. This monitoring data is generated without affecting the process by any means and once installed, it is not causing any additional costs. EOSTATE ExposureOT can be retrofitted to any EOS M 290.

An extended analysis could incorporate other aspects such as the effect of heat sinks. If lattice structures are built directly onto the build plate, a thinning of the struts occurs in the first layers. This effect is thermally driven and is expected to be clearly visible in EOSTATE ExposureOT data.

This investigation represents the first step toward demonstrating the capability of EOSTATE ExposureOT and process monitoring in general to assess the part quality of porous structures. Further statistical data are needed to strengthen this correlation and extend it to other mechanical parameters. EOS is constantly working together with customers improve their monitoring capabilities and bring technology to the next level.

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Marek studied Mechanical Engineering at TU München. His enthusiasm for Non Destructive Testing is shown in his research theses on computed tomography at Airbus Helicopters and ultrasonic testing at Siemens. In 2017, the challenge of examining additive manufactured parts brought him in to the world's leading technology supplier in the field of industrial 3D printing. In the Additive Minds team at EOS, he specialized in the in-process monitoring of metal additive manufacturing. He is responsible for workshops, consultancies and customer projects involving our monitoring solutions.

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Davy's passion for additive manufacturing started in 2012 during his master thesis in Mechanical Engineering at KU Leuven. After his studies, he started working as a project engineer focusing on the development and serial manufacturing of medical applications. This experience was his first contact with lattice structures and the medical industry. For the last 3 years he has been responsible as an Additive Manufacturing Consultant within EOS for all process-related consulting topics. Together with multiple industry leaders he developed high-end processes for lattice structures, thereby pushing the boundaries of additive manufacturing.

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