Additive manufacturing by electron beam melting (EBM) is a complex process, which still lacks reliable tools for process monitoring. Demanding processing conditions such as high temperature, high vacuum, and X-ray radiation impede the continuous operation of standard process monitoring devices such as light-optical camera systems. To overcome this deficit, the detection of backscattered electrons (BSEs) is a highly promising approach. A detection system for BSEs is used for recording the in operando signal during melting inside an EBM system. The acquired data are postprocessed by mapping the data points to spatial coordinates. A comparison between the obtained intensity map and the as-built surface shows a remarkable correlation, which might be suitable for process monitoring and quality control purposes.

**Introduction:**

Electron beam melting (EBM) is an additive manufacturing process, which is based on the selective consolidation of metal powder layers. Like other additive processes, it enables the cost-effective fabrication of complex components in small batches. In addition, the operation conditions during EBM facilitate the processing of sophisticated materials such as nonweldable superalloys[1] or intermetallics.[2] These characteristics make EBM ideally suited for challenging applications such as the production of aerospace components. Nevertheless, to compete with conventional manufacturing methods, high-quality standards have to be fulfilled, which is currently seen as a barrier for the breakthrough of additive manufacturing technologies.[3] Better insight by process monitoring is necessary but so far, there is still a lack of reliable tools for metal additive manufacturing.

EBM is an additive powder-bed fusion process, which builds up bulk metallic components by a defined sequence of process steps. First, a thin layer of powder is applied by a recoater system within a vacuum chamber. This layer is heated up by a fast and defocused electron beam, thereby inducing slight sintering of the particles. The weak connectivity between the particles is necessary to provide a minimum of mechanical strength and electrical conductivity. These properties are necessary for the following step when a focused electron beam with high power density is used for selective melting of the current layer cross-section. After lowering the build platform and applying the next powder layer, the cycle may be repeated until the desired geometry is completed.

The EBM process requires high vacuum and is performed at a base temperature slightly below the melting point of the processed material. As a consequence, the evaporation of volatile alloy elements during melting causes severe metallization on all surfaces, which are not shielded from melt pool exposure. In addition, the interaction between electron beam and material produces damaging X-ray radiation. In summary, the environment is extremely challenging for most process monitoring devices.

Most of the work done on process monitoring during EBM focuses on the use of infrared (IR) thermography, where protection from heat and radiation damage is achieved by positioning the IR camera outside the vacuum chamber behind a lead glass window. The application of IR thermography may be separated in two types of application. First, it may be used to record heating, melting, and cooling with a high frame rate to gather the thermal history of a layer. The acquired information may be used to identify thermal inhomogeneities leading to defects[4–6] and even to predict the microstructure of the final component.[7] Metallization of the view port is usually counteracted by a sacrificial spooling Kapton film.[5–7] Drawbacks of this approach are the high amount of data to be processed[8] and the susceptibility to errors, for example, due to inaccurate temperature calibration or failing of the Kapton film.[7] To overcome these limitations regarding monitoring of an entire build process, a second type of IR imaging is applied. By only recording single-layer images of the molten surfaces, protection from metallization may be achieved with a more robust mechanical shutter system. Due to different emissivity, the acquired IR images still contain information about the defects within the layer,[9,10] which may be mapped to 3D space for further characterization of the samples.[9,11,12] However, interpretation of the temperature information is impeded by different intensity decays due to the melt order of the samples.[8]

In addition to its commercial near-IR (NIR) monitoring tool called Arcam LayerQam, EBM system manufacturer Arcam AB (Mölndal, Sweden) also promotes a X-ray detection system...
called Arcam xQam whose application is currently limited to autocalibration of the electron beam.

As an alternative process monitoring approach, the detection of backscattered electrons (BSEs) has been suggested for EBM. It was shown that electron optical (ELO) images may be obtained using the electron beam in a way comparable with scanning electron microscopy. By recording the topography of the molten surfaces, it was demonstrated that image features and defects inside the final sample may be correlated and that this finding may be used to deduce processing windows in a fast and reliable manner. The installed BSE detector was robust against elevated temperatures, metallization, and X-ray radiation and delivered high-contrast images. Despite all benefits of this in situ ELO approach, it requires an additional process step for image acquisition and is only capable of imaging the final molten surface. Therefore, it increases the build time and is not suitable for a real-time correction of the process parameters by closed-loop control.

The aim of this work is to overcome these limitations by recording the BSEs directly during melting of the layers, denoted as in operando approach. The measurement of secondary emission was already successfully used in electron beam welding (EBW), to study keyhole oscillations. The new in operando ELO approach would not increase the build time and is supposed to deliver information about the process quality in real time. A similar monitoring principle was already investigated for selective laser melting (SLM) and is implemented in many industrial SLM systems. Using a semipermeable mirror, a photodiode and a complementary metal-oxide-semiconductor sensor are installed in coaxial position to the laser beam to measure the intensity of the light emitted from the melt pool. The recorded signal was used to control the melt pool properties or mapped to spatial coordinates and correlated with defects inside the final sample.

**Experimental Section:**

The experiments were conducted using the ATHENE system and its integrated BSE detection hardware. A more detailed description of this in-house developed EBM system can be found in Arnold et al. In a first experiment, single-square-shaped areas with a size of 15 mm × 15 mm were molten on a base-plate made of X15CrNiSi20-12 stainless steel at room temperature. The experiment was supposed to deliver basic information about electron backscattering during melting without considering the complex conditions of an EBM process, for example, the interaction between beam and powder bed. The beam power was constant at 600 W, whereas the deflection speed and the hatch line spacing between adjacent melt tracks were altered between (1.00, 0.50, 0.25) m s⁻¹ and (50, 100, 200) µm, respectively, to keep a constant area energy density of 12 J mm⁻².

In a second experiment, three cuboid samples with dimensions of 15 mm × 15 mm × 10 mm and a constant layer thickness of 50 µm were produced by EBM. The samples and their columnar supports were built on a steel base-plate, whereas the feedstock consisted of plasma-atomized Ti–6Al–4V Grade 23 powder supplied by Tekna Plasma Europe (Mâcon, France) with a particle size distribution between 45 and 105 µm. The process target temperature was adjusted by preheating at 1023 K (750 °C), and a controlled vacuum of 3 × 10⁻³ mbar He atmosphere was applied. While the hatch line spacing was constant at 100 µm, beam power and deflection speed were varied between the samples. The parameters were chosen to produce a porous (150 W; 1.00 m s⁻¹), a dense (1000 W; 5.00 m s⁻¹), and a bulging surface (1000 W; 3.33 m s⁻¹).

All areas were molten using a standard hatch pattern whereby the scan direction of adjacent hatch lines was alternated by 180°, often referred to as a snake-like or back-and-forth manner. In case of the EBM samples, the hatch direction was rotated by 90° after each layer. All in operando ELO signals were recorded in a way that the scan pattern of the squares started in the upper left corner and had primary deflection in x-direction.

A RIGOL MSO1104Z oscilloscope was used for recording BSE- and deflection signal during melting and saving the data via an USBTMC interface to hard drive for further processing. In case of the EBM samples, this was only done at the final layer of the specimens due to the not yet automated measurement procedure. The goal of the data postprocessing was the conversion of the continuous, 1D BSE signal into a 2D intensity map of the melt cross-section, which facilitated the interpretation of the data. The spatial mapping of the BSE data was achieved by analyzing the synchronously recorded deflection coil signal. The start and end times of the single melt tracks were extracted and used for segmentation of the BSE signal. The resulting signal segments were assigned to the lines of the desired intensity map using the known spatial position of the melt tracks. The resulting image resolution in y-direction was equivalent to the hatch line spacing, that is, (50, 100, 200) µm px⁻¹ for the first experiment and 100 µm px⁻¹ for the second experiment. The resolution in x-direction was limited by beam scanning speed and sampling rate of the oscilloscope, and was usually significantly higher than in y-direction. To achieve an image with square-shaped pixels, the data was accordingly downsampled in x-direction. A test had shown that the related loss of information was negligible for qualitative evaluation of the images. Because the described postprocessing did not contain any further analysis but essentially was a simple restructuring of the recorded data, the computational effort was low. Finally, the images were normalized via dividing the measured signal by beam power to account for the dependency of BSE emission on incident beam current.

The as-built samples were further investigated by laser scanning microscopy using an Olympus LEXT OLS4000. Standard LSM was used to acquire optical images of the molten surfaces, whereas CLSM enabled 3D measurements of the surface topography. The image stitching feature was applied to acquire images of the total sample surfaces with a spatial resolution of approximately 3 µm px⁻¹ for both LSM and CLSM.

**Results:**

**Base-Plate Experiment:** Figure 1 shows the molten surfaces of the base-plate experiment. The scaling of the linear color map is adjusted for each image to obtain a maximum contrast (Table 1). The upper part of the figure shows the optical images obtained by laser scanning mode (LSM) to give a qualitative impression of the surfaces. Measurement by confocal laser
scanning mode (CLSM; middle part) is used for the comparison with the in operando ELO images (lower part).

Despite keeping the area energy density constant, the analysis by LSM/CLSM shows a different surface topography for each hatch line spacing. The 50 μm sample has a range (i.e., distance between lowest and highest points) of around 450 μm. There are two big, distinct elevations with a rather smooth profile, which are extended in y-direction. The middle part of the surface is flat but shows a slight, periodic texture. The 100 μm sample shows a very high range of around 1000 μm. Again, there are two big elevations extending in y-direction whose profiles are rough and jagged. The 200 μm sample is rather flat with a range of around 300 μm. On the left and the right sides, there is a slight elevation of the surface. The visibility of the single melt tracks increases with bigger hatch line spacing.

The lower part of Figure 1 shows the images obtained by processing of the in operando ELO signal. For all three samples, the normalized signal lies in a similar range of 1.7–2.8 V kW⁻¹ (Table 1) and the line-by-line reconstruction of the image is clearly visible. On the left and the right sides, the 50 μm sample shows two big, distinct regions of low signal intensity. In the middle part, the intensity is higher but shows a weak periodic pattern. The 100 μm sample shows a complex distribution of the signal intensity. The upper part of the image has a low but, toward the center, gradually increasing intensity. The main part with a medium intensity can be distinguished from the left and right sides by a clear boundary. These outer regions show several local intensity maxima, which seem to have a line-like shape. In addition, the left one of those regions encloses a medium-sized area with low signal intensity. The 200 μm sample is poor in details. The upper part of the image shows a lower intensity than the other parts that are dominated by a line-wise alternating intensity pattern.

**Powder-Bed Experiment:** Figure 2 shows the molten surfaces of the powder-bed samples produced in the EBM process. Again, the scaling of the linear color-map is adjusted for each image to maximize the contrast (Table 1). The upper part of the figure shows the optical images obtained by LSM to give a qualitative impression of the surfaces. Measurement by CLSM (middle part) is used for the comparison with the in operando ELO images (lower part).

**Table 1.** Color-map scales and process parameters of images in Figure 1 and 2. The measured BSE signal is normalized to the beam power to achieve comparable values between different samples.

| Sample            | Height [μm] | BSE signal [V kW⁻¹] | Power [W] | Velocity [m s⁻¹] |
|-------------------|-------------|---------------------|-----------|------------------|
|                   | Min         | Max                 | Min       | Max              |
| Base-plate, 50 μm | 68          | 493                 | 2.05      | 2.76             | 600  | 1.00 |
| Base-plate, 100 μm| 104         | 1122                | 1.98      | 2.66             | 600  | 0.50 |
| Base-plate, 200 μm| 268         | 565                 | 1.76      | 2.48             | 600  | 0.25 |
| Powder-bed, porous| 230         | 577                 | 1.52      | 1.93             | 150  | 1.00 |
| Powder-bed, dense | 161         | 450                 | 1.36      | 1.75             | 1000 | 5.00 |
| Powder-bed, bulging| 490         | 1425                | 1.26      | 1.67             | 1000 | 3.33 |
The LSM/CLSM analysis of surface topography shows that the porous sample has a rather flat surface with several scattered voids. The range of this sample is about 350 μm. The dense specimen is almost perfectly flat with only small elevations toward the boundaries of the sample. This is also reflected by the small range of around 300 μm. In contrast, the bulging sample has a very uneven surface with a smooth cross-shaped elevation in x/y-orientation, a distinct local maximum in the center of the sample and strongly elevated edges. The range is at a high value of around 950 μm. On the surfaces of all three EBM samples, the single melt tracks are slightly visible. The lower part of Figure 2 shows the images obtained by processing of the in operando ELO signal. After normalizing the images to the respective beam power, the signal lies in a similar range of 1.2–2.0 V kW⁻¹ (Table 1). Compared with the base-plate experiment, the line-by-line reconstruction of the images is hardly visible. The porous sample shows a smoothly varying intensity distribution with single spots of very low signal. In contrast, the dense sample has a very homogeneous but noisy intensity distribution. The bulging sample has a similar signal structure but, in addition, distinct regions with lower intensity are visible.

**Discussion:**

The comparison of the surfaces acquired by CLSM and the images obtained by processing of the in operando ELO signal indicates some remarkable correlations in both experiments. In case of the 50 μm base-plate sample, the in operando ELO image shows a low intensity of the BSE signal where the surface of the sample is bulging. The shape of these low-intensity regions fits very well to the shape of the corresponding elevations. Even details such as the protrusion in the right region or the slight texture in the brighter middle part are depicted correctly. In the 100 μm base-plate sample, the elevated structures are also clearly visible in the in operando ELO image, and details such as shape and size of the topographical features are depicted remarkably accurate. The 200 μm base-plate sample hardly shows any distinctive features. Nevertheless, the small elevations at its left and right edges also correlate weakly to a small decrease in intensity of the corresponding in operando ELO image.

Transferring the concept to the powder-bed delivers a similar result. The porous powder-bed sample shows an excellent correlation between actual pores on the surface, and the intensity decreases in the in operando ELO signal. This is valid for both the position as well as the size of the pores. As to be expected, the dense powder-bed sample with its flat surface shows no remarkable details in the in operando ELO image. In contrast, the correlation between the two imaging methods is more complex for the bulging powder-bed sample. Using the in operando ELO approach, the elevated structures are not clearly visible as those in the base-plate experiment. Instead, some regions of lower signal intensity can be found that seem to be connected to the
cross-like-shaped elevations of the surface but no systematic rule is evident.

Considering these observations, the question arises what actually affects the BSE signal during melting and consequently leads to the described correlations of different qualities. Commonly, backscattering of electrons is quantified by the electron backscattering coefficient \( \eta \), which is the ratio between BSE current and incident beam current. The influence of various variables on \( \eta \) can be found in literature\(^{[21,22]} \) where the main factors were identified. Although being derived for application in scanning electron microscopy (SEM), the basic findings should be just as valid for the current study.

First of all, the atomic number of the sample atoms has a significant influence on the backscattering of electrons\(^{[23]} \) and delivers the common material contrast in SEM imaging. In case of the presented experiments, only single material systems (X15CrNiSi20-12 and Ti-6Al-4V) were used. In addition, the formulae for multicomponent systems predict that possible changes in alloy compositions during melting are too small to have a measurable influence on the backscattering behavior.\(^{[24]} \)

The change of \( \eta \) due to transitions between the solid and liquid (i.e., quasiamorphous) state of the alloys is also negligible because the electron channeling contrast is too weak\(^{[21,22]} \) to be detected by the current measurement set-up.

Although the influence of the atomic number is considered to be of minor importance, a second parameter is expected to dominate the recorded BSE signal. The surface topography of the sample strongly influences the local incident angle and, therefore, the interaction between beam and material. When varying the beam incident angle, not only the absolute value of \( \eta \) changes but also the angle of maximum emission.\(^{[25]} \) Meanwhile, the BSE detector remains in fixed central position, that is, coaxial around the primary beam above the build area. Due to the large working distance of around 400 mm, the detector covers a limited solid angle. Thus, it only records the fraction of BSEs with appropriate exit angle, which explains its sensitivity to variations in surface topography.

The topography contrast can be seen at the edges of the bulging areas in Figure 1 and 2 where a change of the local incident angle results in a variation of the measured BSE signal. The effect is even more pronounced at the steep edges of pores. Inside these cavities, multiple scattering of the electrons decreases the signal intensity even more and thereby further facilitates the detection of pores. In contrast, an even surface reflects the major part of the BSEs in direction of the incident beam, which coincides with the position of the BSE detector in the current experiment. Therefore, while comparing CLSM and in operando ELO imaging, it must be noted that the imaging principles are strongly different. While the first is designed to return absolute elevation data, the second delivers information about the interaction between electron beam and material, which is virtually independent of the absolute height. This leads to the images of the porous surface which are quite similar for both methods, whereas the images of the bulging samples are more difficult to compare. Future investigations will show if it is possible to derive metrics that allow for a quantitative correlation between the two imaging techniques.

It should be noted that the capability of displaying elevated surface features by in operando ELO imaging strongly differs between base-plate and powder-bed experiments. Although the structures are clearly visible using the base-plate, the influence of elevations is more complex in the powder-bed. A possible reason lies in the different boundary conditions for melt pool formation between rigid solid and loose powder. In addition, an influence from using different alloy systems should be considered as well and will be investigated in future experiments.

While evaluating the quality of the images obtained by the in operando ELO approach, several factors have to be considered. First of all, it should be considered that the electron beam does not only interact with a solid surface but also with a dynamic pool of molten metal that possesses an undefined and changing surface topography. This is probably the explanation for the high noise occurring in many images, especially in those recorded during melting of very uneven samples. Those samples are produced by a high energy input that results in a large melt pool volume. A future investigation will evaluate the possible correlation between energy input and in operando signal noise.

In addition, several other process parameters influence the imaging results. As shown in Figure 1, the hatch line spacing is the lower resolution limit of the images. Because the hatch line spacing is a fundamental parameter to control the energy input, improving the resolution is not possible without further implications. In theory, both beam current and deflection speed affect the signal-to-noise ratio. Varying incident angle and beam quality across the build area create a dependency of the signal on the beam position. Subsequent experiments will be conducted to evaluate the significance of these factors and the possible implications on the process monitoring capability of the in operando ELO approach. Furthermore, a multidetector system, which is currently under development, will deliver additional information about the spatial distribution of electron backscattering to facilitate the interpretation of the measured BSE signals.

An enhanced understanding of the correlation between in operando BSE signal and beam–material interaction is necessary to apply the approach to a real-time feedback control system. It should be emphasized that the presented concept of mapping the recorded in operando signal to a 2D intensity map is considered a tool to identify quantitative process quality metrics in future experiments. To eventually apply these findings to a system that is capable of automatically optimizing process parameters in real time, a direct analysis of these metrics in the continuous in operando signal is to be preferred to achieve the best performance.

**Conclusion:**

For the first time, the acquisition of ELO images during the melting step of the EBM process was performed. The obtained signal intensity maps show a remarkable correlation to the final topography of the molten samples. The approach is capable of detecting pores and bulging areas, whereas the image quality differs between base-plate and powder-bed experiments. It is assumed that the image contrast is dominated by the effect of surface topography on the emission of BSEs, but further understanding of the signal formation has to be acquired in subsequent experiments. As soon as the reliable interpretation of the in operando ELO signal is accomplished, it might be the essential part of a powerful feedback control system. By gathering information about
the molten surface quality in real time, the system could be capable of optimizing process parameters during melting. An advanced control system like that would make a big contribution to the reliability of the additive manufacturing process and the quality of the produced components.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

additive manufacturing, backscattered electrons, electron beam melting, in-process monitoring, in situ measurements, quality control

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