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Abstract. The process observation in selective laser melting (SLM) focuses on observing the interaction point where the powder is processed. To provide process relevant information, signals have to be acquired that are resolved in both time and space. Especially in high-power SLM, where more than 1 kW of laser power is used, processing speeds of several meters per second are required for a high-quality processing results. Therefore, an implementation of a suitable process observation system has to acquire a large amount of spatially resolved data at low sampling speeds or it has to restrict the acquisition to a predefined area at a high sampling speed. In any case, it is vitally important to synchronously record the laser beam position and the acquired signal. This is a prerequisite that allows the recorded data become information. Today, most SLM systems employ f -theta lenses to focus the processing laser beam onto the powder bed. This report describes the drawbacks that result for process observation and suggests a variable retro-focus system which solves these issues. The beam quality of fiber lasers delivers the processing laser beam to the powder bed at relevant focus diameters, which is a key prerequisite for this solution to be viable. The optical train we present here couples the processing laser beam and the process observation coaxially, ensuring consistent alignment of interaction zone and observed area. With respect to signal processing, we have developed a solution that synchronously acquires signals from a pyrometer and the position of the laser beam by sampling the data with a field programmable gate array. The relevance of the acquired signals has been validated by the scanning of a sample filament. Experiments with grooved samples show a correlation between different powder thicknesses and the acquired signals at relevant processing parameters. This basic work takes a first step toward self-optimization of the manufacturing process in SLM. It enables the addition of cognitive functions to the manufacturing system to the extent that the system could track its own process. The results are based on analyzing and redesigning the optical train, in combination with a real-time signal acquisition system which provides a solution to certain technological barriers. © The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: [10.1117/1.OE.54.1.011008](https://doi.org/10.1117/1.OE.54.1.011008)]

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1 Introduction

Selective laser melting (SLM) is a manufacturing process which produces products from powder. On a layer by layer basis, powder is disposed at small thicknesses and melted by a laser beam. Each of these slices contributes to a sequentially built, three-dimensional part which is defined by geometric data. This building process, therefore, relies on the quality of the data, the homogeneity of the powder layer, and the precision of the illumination to deliver the expected product.

The temperature of the melting process has a major impact on product quality in SLM. It determines the structural properties of the solidified material and influences the residual stress as well as thermal deformation.^{1,2} From the perspective of manufacturing quality, information about the temperature of the melt pool could indicate how well the final product has been manufactured. Deviations could be analyzed and corrective action could be taken as soon as they are detected. One important aspect of this is to understand the cause–effect relationship.³

Since a product is built layer by layer in SLM, the manufacturing process can be documented from start to end. As the product is built from a powder-bed, one of the main factors for the build-up is the melting of the powder.

As such, the melting process influences properties of the product such as its shape and its density or its rigidity. Energy from the laser source is coupled into the powder, either with a solid product below it or in the case of overhang structures, with powder below. These two situations are expected to produce different melting conditions as thermal conduction and coupling of the laser energy are different. Thus, by spatially observing the course of the melting temperature, we can assess the current layer, adapting the processing strategy for subsequent layers. With this approach, the course of the temperature can be used to set up a self-optimizing strategy for SLM.^{4,5} Setting up an SLM manufacturing system involves adjusting the timing for the scanning device and the laser. Values for such parameters as laser-on delay and polygon delay have to be found for the current set up. This work involves putting samples into the processing chamber and analyzing them under a microscope. Industrial SLM machines mostly require only one set-up as long as the software is not changed and the powder properties remain constant. For systems with changing optics and changing laser sources, however, the time needed for set-up

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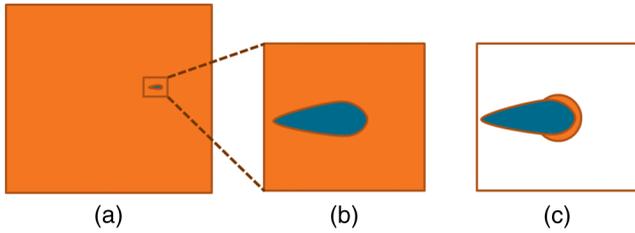


Fig. 1 Strategies for process observation: full-scan field (a), spatially resolved interaction zone (b), focused on melt pool (c).

can be considerably higher. In both cases, a standardized set-up/calibration routine could be beneficial to ensure that the entire manufacturing system operated properly, which will contribute to minimizing the cost for set up and reducing manufacturing defects to zero.

2 Sensor System Design

Currently, the majority of SLM manufacturing systems do not provide an option for process observation. While several research systems on the laboratory level have investigated this topic, some manufacturers of SLM systems are only now starting to integrate such devices.^{6,7} As all systems use scanning devices to position the processing laser beam on the powder bed, process observation has to be implemented coaxially if spatial resolution is required.

Figure 1 shows process observation strategies which aim at different information. The first drawing visualizes the approach to image the entire working area with the aim to detect the thermal properties of the build process in the entire

processing plane. With a plane of 150 × 150 mm, a thermal imaging camera with 1000 × 1000 pixel would provide a spatial resolution of 150 μm/pixel. The acquisition rate of such a camera could be expected to be in the range of some hundred images per second, which does not really capture the dynamic properties of the process.

If thermal properties in the interaction zone are of interest, an IR imaging system must be coupled coaxially to the processing laser. In this case, the imaged area would move over the powder bed along with the laser itself. Such a system could use 256 × 256 pixels which would allow an increased frame rate of perhaps 1 kHz. In this configuration, the melt pool and the surrounding area could be imaged. The implementation would require a magnifying optical system to relay the object to the camera through the *f*-theta lens.

The third strategy listed here is used in this report. It provides a focused detection of the thermal radiation from the melt pool as shown in Fig. 1 at a temporal resolution of 10 μs. Even at high-feed rates, this strategy is capable of continuously monitoring the temperature of the melt pool with data rates as shown in Table 1.

Coaxial coupling of the optical path for processing radiation and observation requires beam splitters which selectively combine and separate bands of wavelengths.⁸ Figure 2 shows the implementation and the general sketch of how to combine optical paths for different purposes. After passing through the two lenses, the focused beam is deflected by the two scanner mirrors. Before the emission from the melt pool arrives at the sensor system, it is reflected by the mirrors, propagated through the pre-focusing unit and transmitted

Table 1 Comparison of observation strategies with regards to temporal resolution, spatial resolution, and data rate.

Strategy	Acquisition rate (frames/s)	Data block	Data rate (MB/s)
Full-scan field imaging	300	1000 × 1000 pixels at 8 bit	300
Interaction zone imaging	1,000	256 × 256 pixels at 8 bit	66
Melt pool pyrometry	100,000	1 pixel at 12 bit	1.6

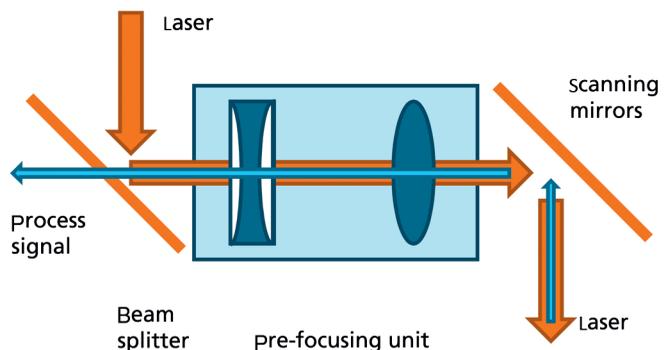
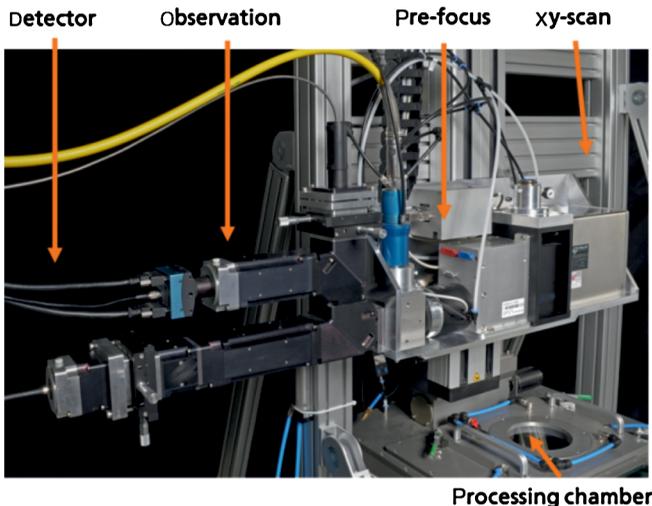


Fig. 2 Optical train with sensor system (a) and sketch of the optical train (b).

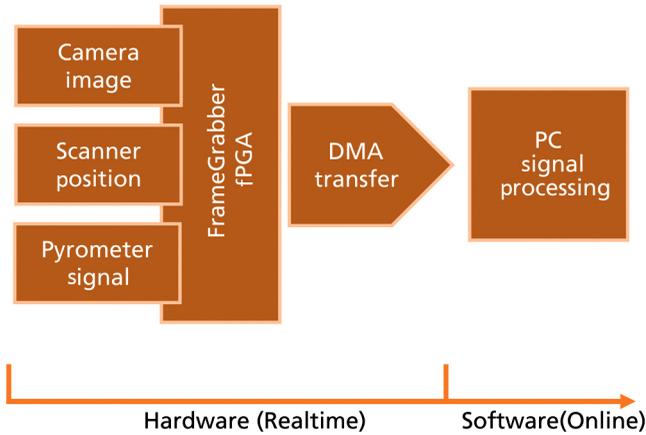


Fig. 3 Signal processing.

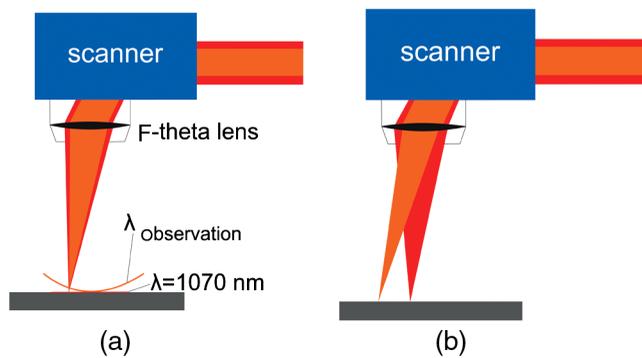


Fig. 4 Axial (a) and lateral (b) chromatic aberrations in *f*-theta lenses.

through the beam splitter. This system realizes a coaxial observation of the interaction zone by relaying the process signals onto the pyrometric detector in the band from 1.2 to 1.9 μm . The system monitors only a 200- μm diameter of the melt pool because the emission is relayed with a unity magnification and the pyrometric detector is coupled to the SLM system with a fiber of 200- μm core diameter.

The pyrometric signal with its t_{05} time of 10 μs is quantized with an AD converter at 100 kHz and synchronously acquired with the position of the scanner. Proper timing of the acquired signals is realized by acquiring them with a field programmable gate array (FPGA). Together with an optional camera image, the data is transferred into PC memory for recording and later processing as shown in Fig. 3.

The synchronous timing of the signals is ensured by the deterministic execution of the code implemented on the FPGA. The acquired signals are packed to data blocks that are transferred to PC memory in the DMA transfer mode. Each frame of this data transfer is associated to a time stamp which allows a precise identification and analysis of all data packets received. The FPGA ensures a real-time relation between the different signals which is documented by time stamps. The PC with its standard operating cannot be used to control setting parameters during the processing of a layer. It can, however, calculate new processing parameters for the subsequent layer based on the acquired data.

3 Optical System Design

Several approaches to a coaxial thermal analysis of the melt pool use *f*-theta lenses.⁶ Particularly, for high-power laser applications, off-the-shelf *f*-theta lenses use quartz glass to achieve a low absorption. As these lenses are designed only for the processing wavelength, which is typically 1 μm , they provide different imaging properties at wavelengths in the 1.2 to 1.9 μm range. It is especially in this range that a considerable amount of the thermal emission of metal at melting temperature contributes to the detected radiation. The major problem with these approaches is that the focus position of the thermal radiation does not coincide with the position of the interaction. There are two types of chromatic errors, axial and lateral aberrations. Axial aberrations lead to different focal positions in the direction of the propagation, resulting in a defocused observation while the processing laser is focused as shown in Fig. 4(a). In Fig. 4(b), the sketch shows how lateral aberrations lead to different lateral focus positions for observation and processing wavelengths – an effect which increases with the angle between the processing beam and optical axis of the system. Usually, both effects overlay, making coaxial observation an ambitious target.^{9,10}

The plots in Fig. 5 show the amount of displacement of the chief ray. While in the center position, all rays coincide, the deflection of 8 deg in the *x* and *y* directions yields a position of (69.6,72.4) in the working plane. The size of the 1.7 and 2.1 μm ray spots result from the single lens relay optics for the infrared radiation. While the ray patterns are not relevant to this discussion, the position of the chief rays is. Table 2 gives the absolute values of displacement for a position of 7 \times 7 cm off axis on the powder bed. The displacement for the 2.1 μm ray amounts to nearly 1.2 mm.

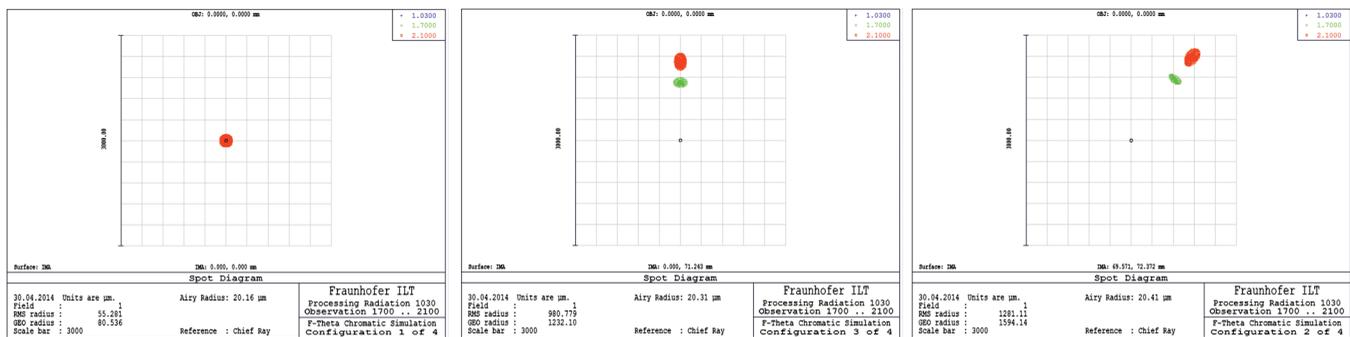


Fig. 5 Displacement of the chief rays for different wavelengths and deflection angles relative to the 1030 nm chief ray (1030 nm in blue, 1700 nm in green, and 2100 nm in red).

Table 2 Amount of chromatic displacement of chief rays through f -theta lens.

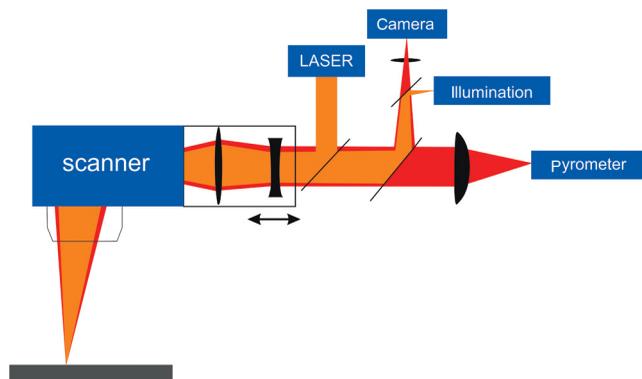
Wavelength (nm)	Position in the field (mm)		Difference (mm)	
	x	y	x	y
1.030	69.571	72.372	0,0	0,0
1.700	70.192	73.238	0.621	0.866
2.100	70.434	73.55	0.863	1.178

In the described situation, the image of the interaction zone might still fall onto an FPA sensor as its surface is large compared to the aperture of a pyrometer. In the case of an optical system where the interaction point is relayed onto a small aperture in the range of some μm , the pyrometer will not be able to measure the radiation from the melt pool.¹¹

The implemented system design with a prefocusing unit shown in Fig. 6 is free of these problems. It is optimized for all wavelengths that are of interest to the process observation and ensures that the focal plane is the same for all wavelengths. It combines the optical paths of processing radiation and observation.

Prefocus systems, however, require larger working distances compared to f -theta lenses in order to keep the working area constant. At the same time, an increase in focal length is undesirable since it increases the focal diameter. Therefore, a retro-focus construction is realized which comprises a negative movable lens and a positive fixed lens. At a constant effective focal length, this setup increases the working distance. Moreover, only the comparatively small negative lens has to be moved, which enables faster movement.

The prefocus system is designed to correct the field curvature but it also facilitates a chromatic correction. Lateral errors do not occur at all, since the chief rays of all beams are on the optical axis. Remaining axial aberrations can be corrected using additional lenses in the optical path of the detection system. Thereby, materials other than fused silica can also be considered to correct chromatic aberrations, since no high power radiation has to be transmitted through such comparatively strong absorbing components. The most desired design method is the simultaneous optimization of all beam paths. It minimizes imaging errors and ensures a minimum of required lenses in total. Moreover, the designed

**Fig. 6** Implemented system design.

optical components provide optimized antireflective coatings in order to maximize the transmitted energy for all wavelengths that are used—the processing, visible, and thermal radiation.

In the current application with a fiber laser at $1.07\ \mu\text{m}$ and a maximum power of 400 W, the focus shifter carries the negative lens on a solenoid. The magnification of the retro-focus setup is designed to be $1.6\times$, resulting in a working distance of 620 mm, keeping the effective focal length at 380 mm. Based on these parameters, the simulation predicts a $1/e^2$ focal size of $114\ \mu\text{m}$ in diameter with a Rayleigh range of about 9 mm.

4 Experiments

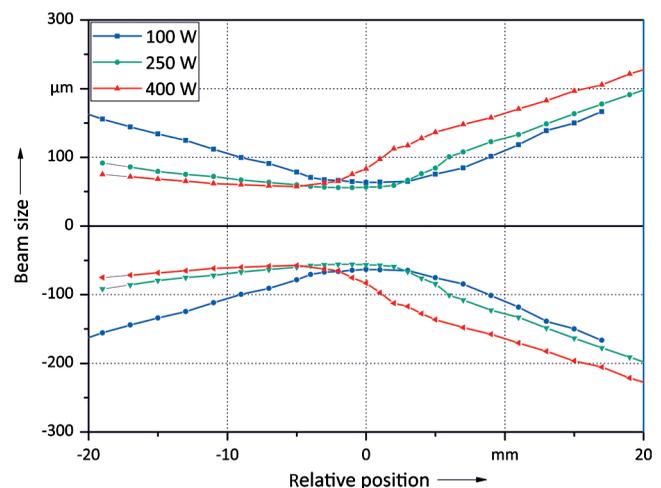
4.1 Verification of the Optical System

To validate the expectations, the laser beam is characterized with a camera-based measurement system. Reflective attenuators in front of the camera enable measurements up to several 100 W at a minimum of thermally induced optical influences on the measurement equipment. Besides the focal behavior, the caustic, thermal lensing and transient effects are also analyzed. The resulting diagram in Fig. 7 proves the expectations.

The measured spot diameter lies between 111 and $120\ \mu\text{m}$ in all cases, which is a plausible result since the pixel size of the camera and thus the magnitude of errors is $4.4\ \mu\text{m}$. Moreover, the focal shift in the steady state amounts to about 5 mm between 100 and 400 W, which is depicted in Fig. 8. Along with the thermally induced focal shift, higher aberrations also occur. These influence the energy distribution and lead to an asymmetric change in beam propagation before and after the focal position.

The transient behavior is determined by tracing the peak intensity on the camera in time since this behavior corresponds to a focal shift in the axial direction. Measurements of the shift at different laser powers lead to the result depicted in Fig. 9 and provide a similar behavior for all states.

This behavior is in line with the expectations provided by theory.^{12,13} If no temperature-dependent material properties have to be considered, the time constant for the steady state is independent of the induced laser power. This statement can be assumed to be true since temperature increase within

**Fig. 7** Caustic of the laser at different power levels.

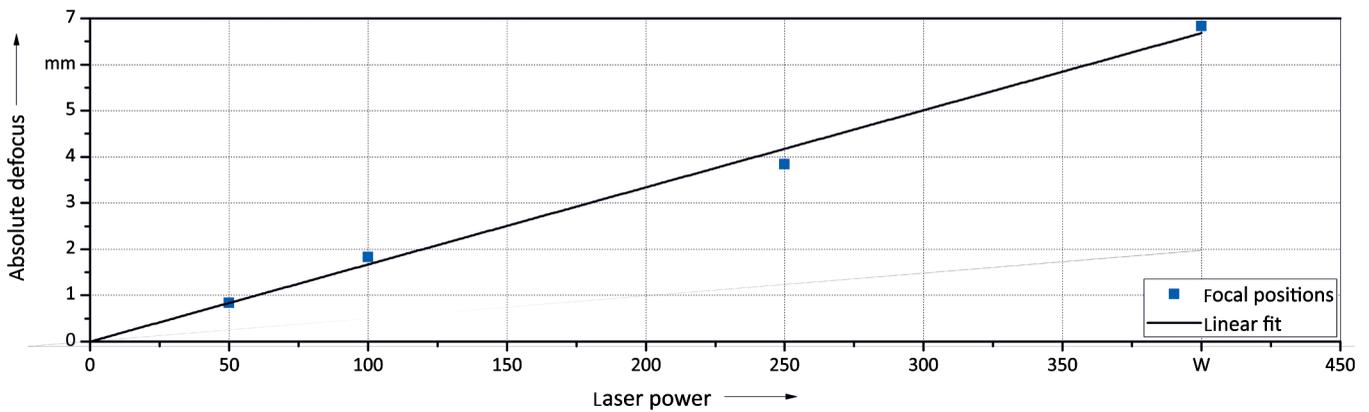


Fig. 8 Focal position depending on laser power.

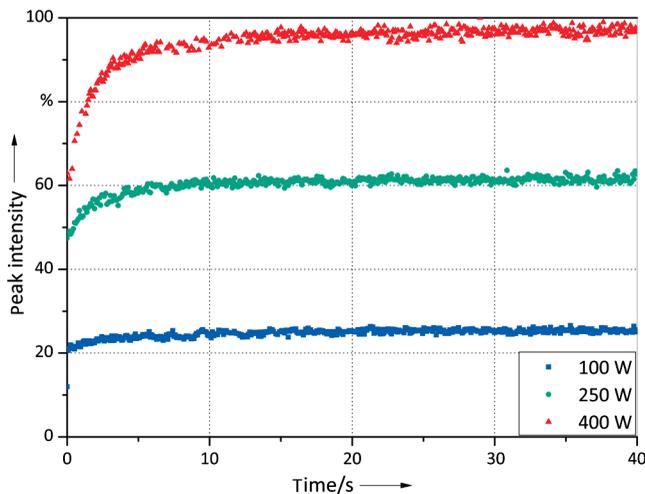


Fig. 9 Transient behavior of optical system for different laser powers.

high-quality fused silica lenses usually constitutes only a few kelvins. The time constants, defined as the time until 95% of the steady state value is reached, range close to 10 s for the measured load cases.

4.2 Verification of the Sensor System by Scanning a Halogen Bulb

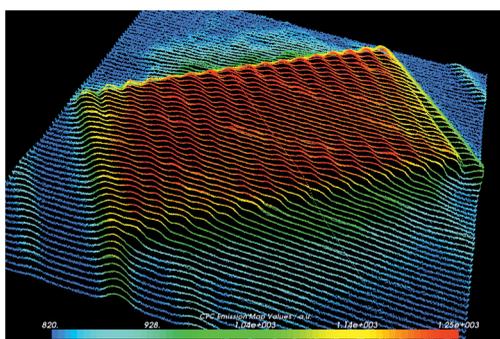
A first step to verifying the synchronicity between thermal signals and position signals is realized by scanning an

irradiating halogen bulb. The temperature of the filament can be expected to range between 2,800 and 3,100 K. The radiation which propagates through the glass can be detected by the sensor system and displayed as a temperature map as shown in Fig. 10.

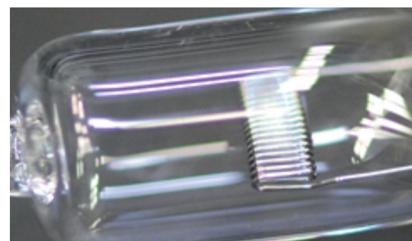
4.3 Detecting Melting Temperatures by Scanning a Grooved Sample

Changes of the melting temperature are observed by scanning a grooved stainless steel sample with a laser power of 200 W at a feed rate of 400 mm/s and a resulting track width of 200 μm . The microscopic image of the sample in Fig. 11 shows a change of radiation in the vicinity of the groove. The geometry of the groove is 400 μm in width and 400 μm in depth.

The processing of the sample has been executed with constant setting parameters and without interruption. The scanner used a bidirectional scan strategy, processing each track only once. Without exactly knowing the underlying reason for the deviations, the sample shows different properties in track width, in track height, and in color. The leftmost track, denoted “1,” shows a very constant width and shape. The temperature map of this track correspondingly shows a constant temperature. The track denoted with “2” has a higher temperature level in the temperature map and results in a thicker track on the sample. Looking at the track denoted with “3,” it can be seen that the amount of the emitted radiation changes at the same position where the surface of the track on the sample changes its shape.



(a)



(b)

Fig. 10 Temperature map of filament (a) from halogen bulb (b).

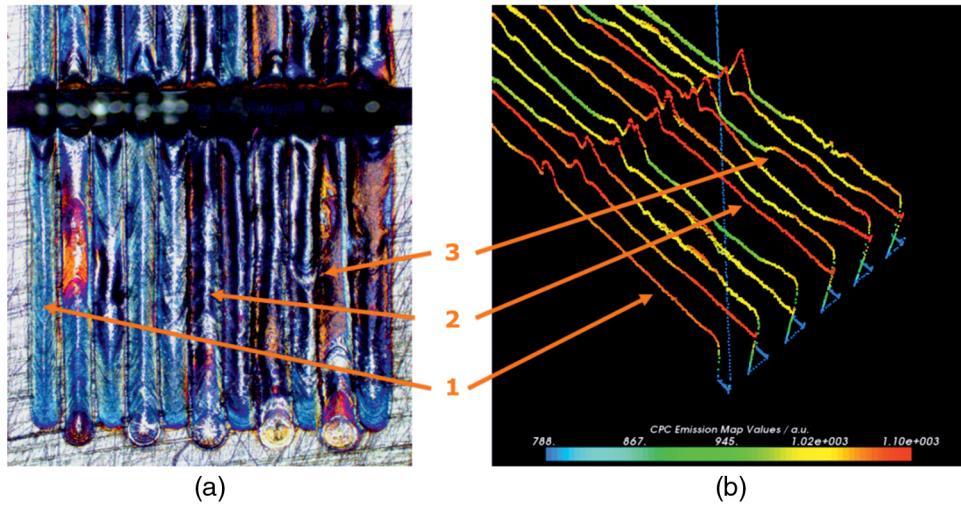


Fig. 11 Sample with remolten metal surface (a) and temperature map (b), processing parameters: laser power 200 W, track width 200 μm , feed rate 400 mm/s.

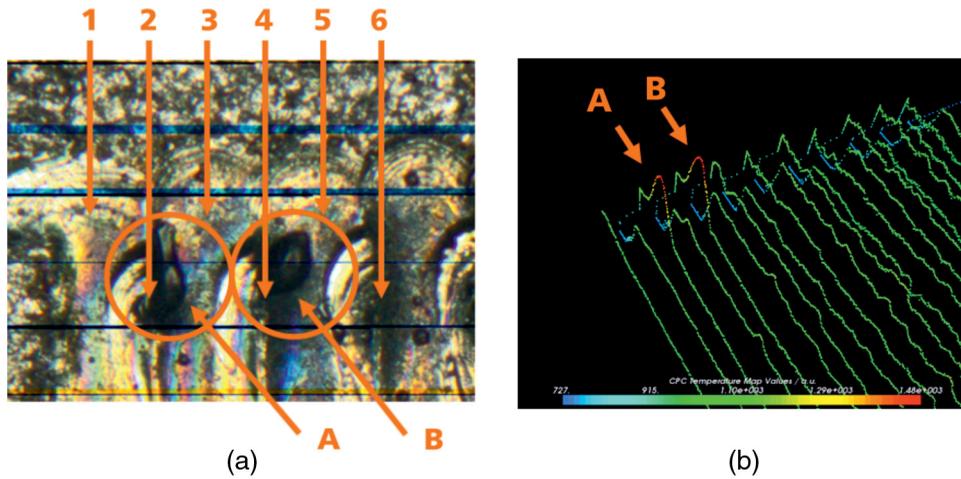


Fig. 12 Occurrence of overheated melt pool on sample (a) and in the temperature map (b).

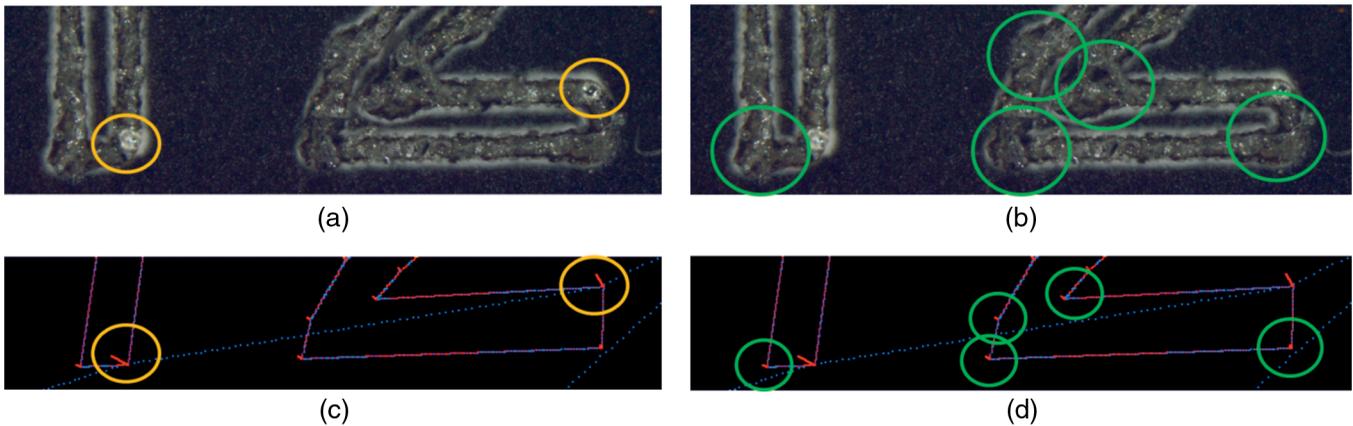


Fig. 13 Microscope image of an aluminum sample with remolten spots (a, b) and plot of the number of same positions per unit time (c, d). (a, c) Image with orange circles shows start and end point of the contour, (b, d) image with green circles shows the corners.

Further correlations of features on the sample to features in the temperature map can be found by comparing the two images.

Similarly, the circles in Fig. 12, denoted with “A” and “B” show dark spots on the sample where material is missing. Correlating to this event, the temperature map shows an excessive emission at the same positions which interestingly occurs when scanning the next track top down, and not when the laser emission stops at this position at the end of track two.

4.4 Detecting Motion during Scanning

Continuous motion at constant laser parameters leads to constant boundary conditions for the melting process. In this experiment, an aluminum sample was scanned with setting parameters for the laser power of 100 W, a feed rate of 400 mm/s, and a focus diameter of 200 μm to mark the outline of some characters. The temperature map showed peaks in the emission where the sample showed deviations in track width. In Fig. 13, the positions of these peaks are marked on the work piece images with circles. The images below represent a motion map which displays the number of time units per position in color and height (blue = 1, red > 1, height = number of time units). So, this kind of map visualizes where the scanner stands still for a longer time.

It is not unexpected that the track width deviates from the expected width at those positions where the stand stills are detected. What can be seen as an advantage is that the sensor system is shown to be useful for detecting faulty execution of motion autonomously.

5 Conclusion

Process observation is a key requirement for the advance of SLM. Especially in high power-SLM, f -theta lenses create problems for process observation due to their monochromatic design and the resulting aberrations. This set up demonstrates an optical system which fulfills manufacturing requirements with respect to focus properties like size and position stability and it fulfills process observation requirements with respect to relaying thermal radiation to a fast detector. The signal processing system with its synchronous acquisition of position and thermal radiation has proven to acquire relevant information which enables the addition of cognitive capabilities to the manufacturing system.

The maps provide information about timing errors between the start of the laser emission and motion of the mirrors which enables corrective action toward the machine set up prior to detecting a defective product at the end of the entire manufacturing task. Deviations of the melting temperature were detected on grooved samples as well as misalignment of geometries and polygon writing.

The concept of using a controlled retro-focus system to focus the processing beam to the work piece and to relay the process emission onto a suitable sensor provides significant advantages against the use of f -theta lenses in this special application. With the acquired information, the system can potentially determine its current operating point which is considered to be a major step on the path toward a self-optimizing manufacturing system.

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