Tracking the course of the manufacturing process in selective laser melting

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ABSTRACT

An innovative optical train for a selective laser melting based manufacturing system (SLM) has been designed under the objective to track the course of the SLM process. In this, the thermal emission from the melt pool and the geometric properties of the interaction zone are addressed by applying a pyrometer and a camera system respectively. The optical system is designed such that all three radiations from processing laser, thermal emission and camera image are coupled coaxially and that they propagate on the same optical axis. As standard f-theta lenses for high power applications inevitably lead to aberrations and divergent optical axes for increasing deflection angles in combination with multiple wavelengths, a pre-focus system is used to implement a focusing unit which shapes the beam prior to passing the scanner.

The sensor system records synchronously the current position of the laser beam, the current emission from the melt pool and an image of the interaction zone. Acquired data of the thermal emission is being visualized after processing which allows an instant evaluation of the course of the process at any position of each layer. As such, it provides a fully detailed history of the product

This basic work realizes a first step towards self-optimization of the manufacturing process by providing information about quality relevant events during manufacture. The deviation from the planned course of the manufacturing process to the actual course of the manufacturing process can be used to adapt the manufacturing strategy from one layer to the next. In the current state, the system can be used to facilitate the setup of the manufacturing system as it allows identification of false machine settings without having to analyze the work piece.

Keywords: selective laser melting, process observation, pyrometry, self-optimization

1. INTRODUCTION

Prerequisite for a quality targeted optimization of a manufacturing process is information about its input output relation [1]. In selective laser melting (SLM) the product is being built layer by layer which offers the opportunity to document the manufacturing process from start to end. As the product is being built from the powder-bed, one of the main factors for the build-up is melting of the powder.

As such, the product with respect to shape and density is being influenced by the melting process. Energy from the laser source is coupled into the powder, either with a solid product below, 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, the spatially observed course of the melting temperature would allow an assessment of the current layer offering an adaptation of the processing strategy for subsequent layers. As such, the course of the temperature can contribute to setting up a self-optimizing strategy for SLM.

Setting up a SLM manufacturing system involves adjustment of timings for scanning device and for 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 these 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 can be considerably high. In both cases, a standardized set-up / calibration routine could be beneficial to ensure proper operation of the entire manufacturing system which contributes to minimized cost for set up and zero-defect manufacture.

2. SENSOR SYSTEM DESIGN

The general setup of the SLM manufacturing system combines two optical paths. For the processing radiation, the laser source is reflected by a beam splitter before it is focused with a pre-focusing unit. After passing through the two lenses, the focused beam is deflected by the two scanner mirrors. For the sensor system, the emission from the melt pool is reflected by the mirrors, propagates through the pre-focusing unit and is transmitted through the beam splitter. This allows coaxial observation of the interaction zone and relaying the process signals onto the pyrometric detector in the band from 1.2 to 1.9 µm. The pyrometric detector is coupled to the SLM system with a fiber of 200 µm core diameter. In combination with a unity magnification of the optical system, it is ensured that only a 200 µm diameter of the melt pool is monitored.

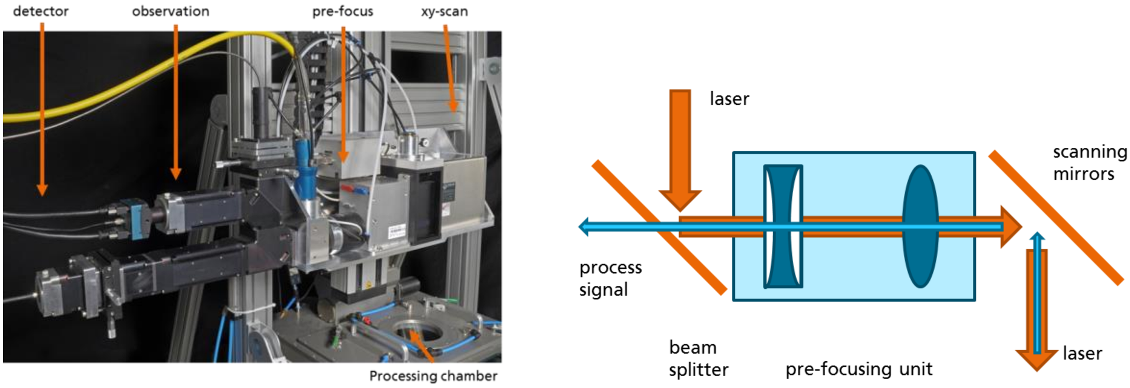

Figure 1: Optical train with sensor system (left) and sketch of the optical path (right)

The pyrometric signal with its t_{95} time of 10 µs is quantized with an AD converter at 100 kHz and acquired synchronously with the position of the scanner. In practice, this acquisition is realized on an FPGA to ensure proper timing. Together with an optional camera image, the data is transferred into PC memory for recording and later processing.

The synchronous timing of the signals is defined on the FPGA and the acquired signals are packed to data blocks which are transferred via DMA. Each frame of this data transfer has its time stamp allowing a precise analysis of all data packets received. However, as the computer system is not real-time enabled, the current set up cannot guarantee a fixed cycle time. Therefore, it is restricted to influencing the processing on a layer per layer basis.

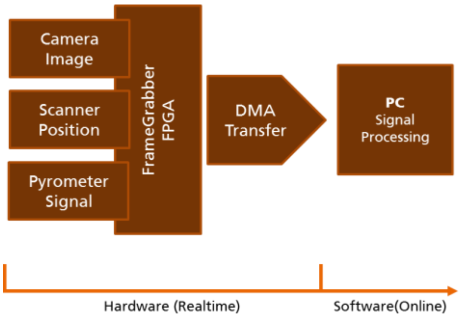

Figure 2: Signal processing

3. OPTICAL SYSTEM DESIGN

Several approaches have been reported which use f-theta lenses for coaxial thermal analysis of the melt pool [2]. Since particularly for high power laser applications off-the-shelf f-theta lenses are designed only for the wavelength of the processing laser – typically 1 µm – those components provide different properties at wavelengths in the 1.2 to 1.9 µm range, where a considerable amount of the thermal emission of metal at melt 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 point of interaction. Two types of chromatic errors can be distinguished as axial and lateral aberrations. Axial aberrations lead to different focal positions in direction of propagation, resulting in a defocused observation while the processing laser is focused as shown in Figure 3 on the left side. On the right side of Figure 3 it is sketched how lateral aberrations lead to different lateral focus positions for observation and processing wavelengths – an effect which increases with larger angles of the processing beam against the optical axis of the system. Usually, both effects overlay, making coaxial observation an ambitious target [3] [4].

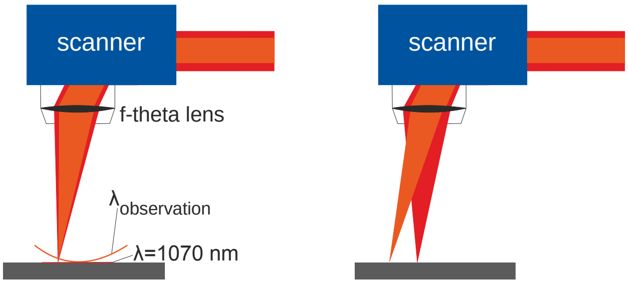

Figure 3: Axial (left) and lateral (right) chromatic aberrations in f-theta lenses

The implemented system design with a pre-focusing unit is shown in Figure 4. It overcomes these limitations and is optimized for all required wavelengths. It combines the optical paths of processing radiation and observation.

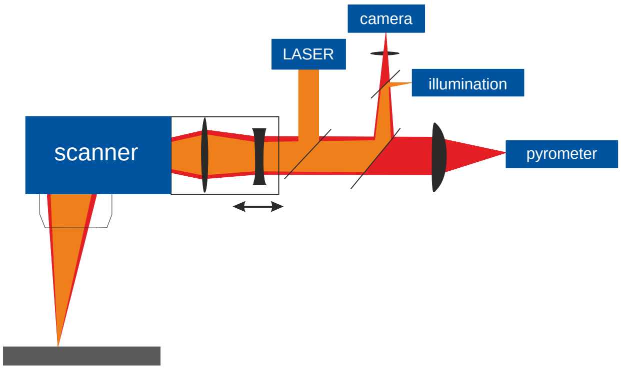

Figure 4: Implemented system design

Pre-focus 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 comprising a negative movable lens and a positive fixed lens. Thus, the working distance can be increased, while the effective focal length is kept constant. Moreover, only the comparatively small negative lens has to be moved and can therefore be accelerated faster.

The pre-focus system is designed to correct the field curvature but also facilitates a chromatic correction. Lateral errors do not occur at all, since the chief rays of all beams are on the main optical axis. Remaining axial aberrations can be corrected using additional lenses in the optical path of the detection system. Thereby, also other materials than fused silica can be considered to correct chromatic aberrations, since no high power radiation has to be transmitted through such comparatively strong absorbing components. The most aspired design method is an optimization of all beam paths simultaneously. It minimizes imaging errors and ensures a minimum of required lenses in total. Moreover, the designed optical components provide optimized anti-reflective coatings in order to maximize the transmitted energy for all wavelengths used – the processing wavelength, visible radiation and thermal radiation.

In the current application with a fiber laser at 1.07 µm 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 1.6x, resulting in a working distance of 620 mm, keeping the effective focal length at 380 mm. With these boundary conditions, the expected focal size based on the $1/e^2$ definition is 114 µm in diameter with a Rayleigh range of about 9 mm.

4. EXPERIMENTS

4.1 Verification of the optical system

In order to confirm the expectations, a camera-based laser beam characterization is conducted. The usage of reflective attenuators in front of the camera permits measurements up to several hundred Watts at a minimum of thermally induced optical influences out of the measurement equipment. Besides the focal behavior also the caustic, thermal lensing and transient effects are to be analyzed. The resulting diagram in Figure 5, proves the expectations.

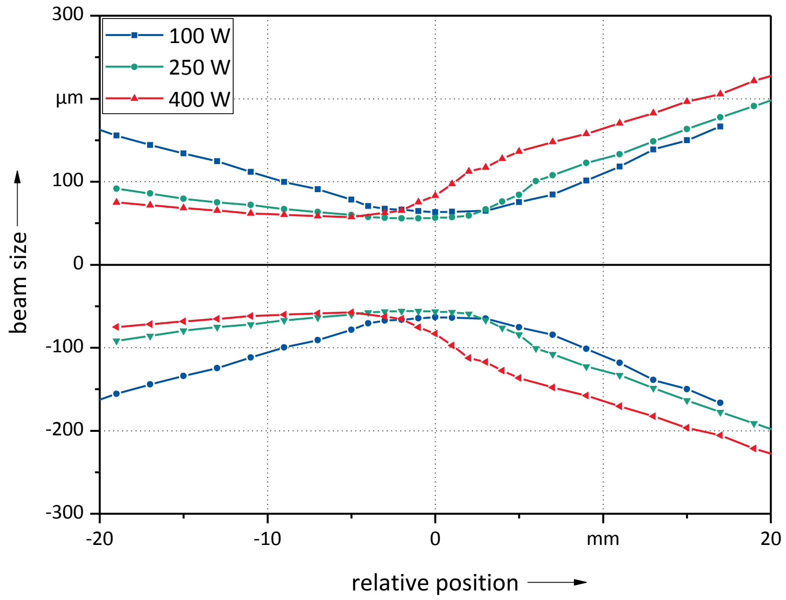

Figure 5: Caustic of the laser at different power levels

The measured spot diameter lies between 111 µm and 120 µm in all cases, which is a plausible result since the pixel size of the used camera and thus the magnitude of errors is 4.4 µm. Moreover, the focal shift in steady state amounts to about 5 mm between 100 W and 400 W, which is depicted in Figure 6. Along with the thermally induced focal shift, also higher aberrations occur, which lead to an asymmetric change in beam propagation before and after focal position.

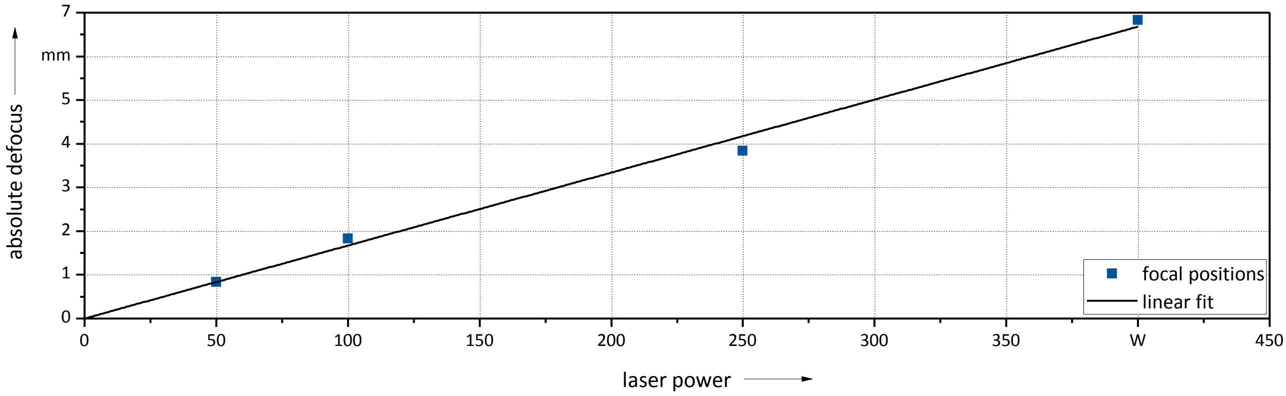

Figure 6 Focal position depending on laser power

The transient behavior can be evaluated tracing the peak intensity on the camera in time since this behavior corresponds to a focal shift in axial direction. Measurements of the system at different laser powers lead to the result depicted in Figure 7 and provide a similar behavior for all states.

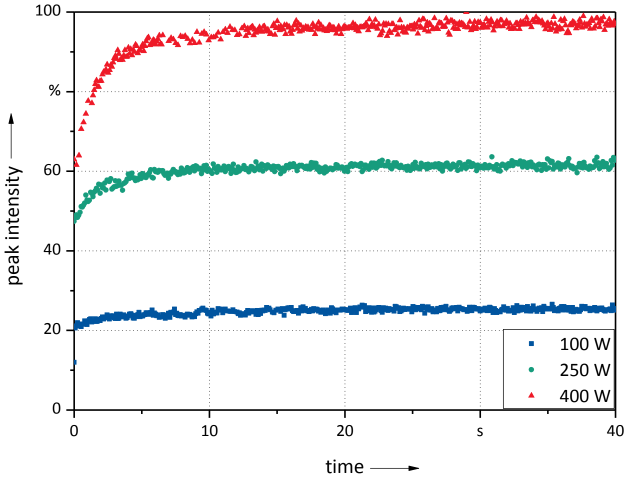

Figure 7: Transient behaviour of optical system for different laser powers

This behavior is in line with the expectations provided by theory. If no temperature-dependent material properties have to be considered, the time constant for steady state is independent of the induced laser power. This statement can be assumed to be true since temperature increase within high quality fused silica lenses usually constitutes only a few Kelvins. The time constants, being defined as the time until 95 % of the steady state value is reached, all 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 a glowing halogen bulb. The temperature of the filament can be expected to range between 2.800 K and 3.100 K while it can be assumed that the glass tube is made from silica. Thus, the radiation which propagates through the glass can be detected by the sensor system and displayed as a temperature map as shown in Figure 8.

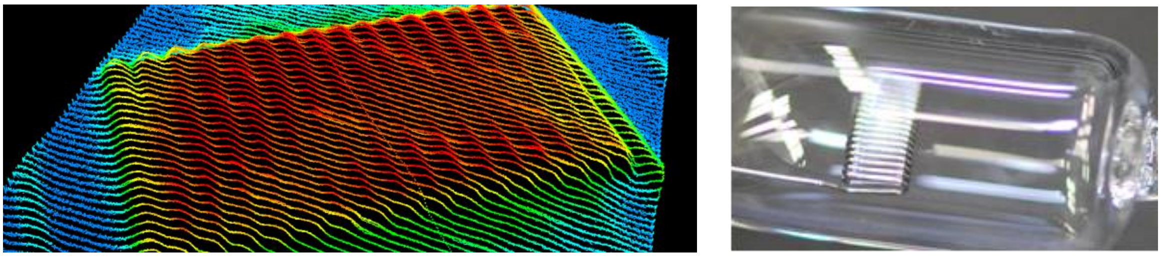

Figure 8: Temperature map of filament (left) from halogen bulb (right)

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 Watts at a feed rate of 400 mm/s and a resulting track width of 200 µm. The microscopic image of the sample in Figure 9 shows a comparable change of radiation being detected in the vicinity of the groove. The geometry of the groove is 400 µm in width and 400 µm in depth.

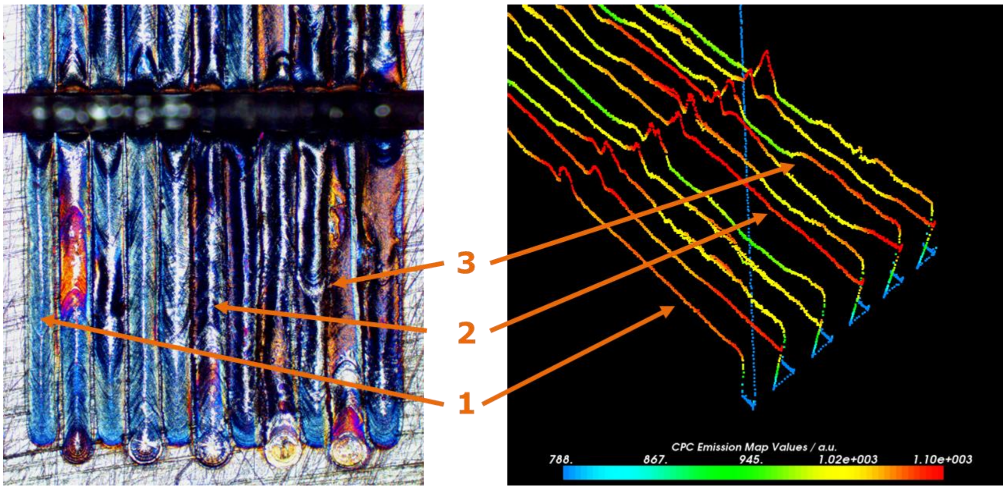

Figure 9: Sample with re-molten metal surface (left) and temperature map (right), processing parameters: laser power 200 Watt, track width 200 µm, feed rate 400 mm/s

The processing of the sample has been executed with constant setting parameters and without interruption. The scanner has been operated with a bidirectional scan strategy, processing each track only once. Without knowing exactly 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 shows a corresponding 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. Comparable correlations of features on the sample to features in the temperature map can be found by comparing the two images.

In the same way, Figure 11 shows the overheating of the melt pool in the areas denoted with “A” and “B” as dark spots on the sample. Correlating to this event, the temperature map shows an excessive emission in 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.

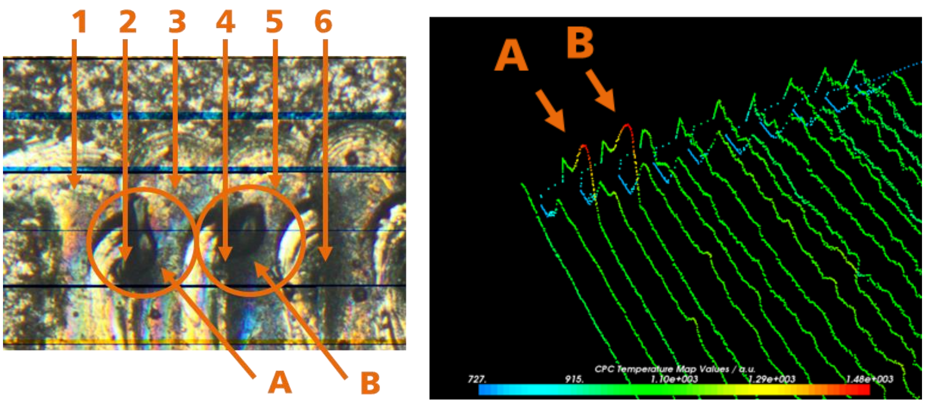

Figure 10: Occurrence of overheated melt pool on sample (left) and in the temperature map (right)

4.4 Detecting motion during scanning

Using an aluminum sample, the outline of some figures was scanned with setting parameters for laser power of 100 Watts, a feed rate of 400 mm/s and a focus diameter of 200 µm as shown in Figure 11. After observing peaks in the temperature map, the motion of the scanner was analyzed. The result is plotted in the lower images and shows that the scanner remains static during several time steps at all positions where the track width deviates from the expected width without switching off the processing laser. This confirms the adjustment of the polygon delay parameter in the scanner set-up has been too long for this application.

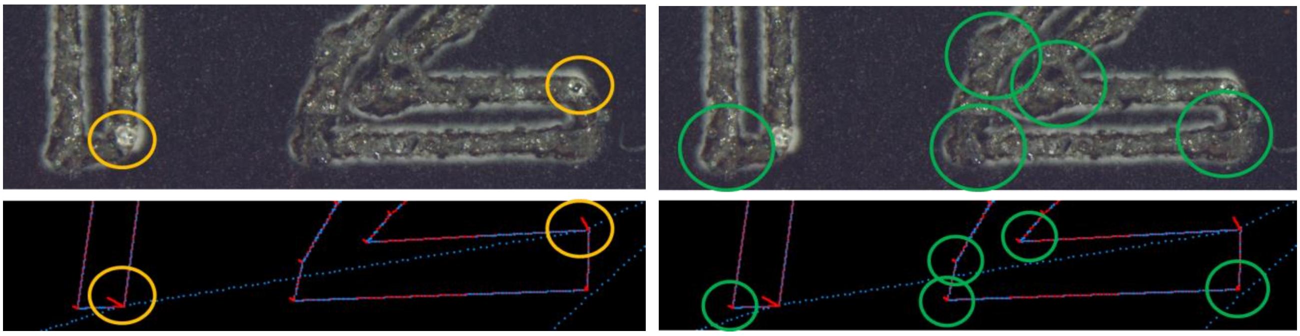

Figure 11: Microscope image of an aluminum sample with re-molten spots (top) and plot of the number of same positions per unit time

5. CONCLUSION

The performance of a system is being reported which allows the spatially resolved tracking of the melt pool temperature in SLM. It is shown that features in the acquired signals are correlated to features on the work piece and that the performance of the optical system is appropriate for continuous processing of SLM parts. The map shows a misalignment of starting the laser emission to starting of the geometry and it shows a delay of the motion in writing polygons. Small deviations in the melting behavior can also be seen at the same positions on the samples as on the temperature map.

Results from the experiments show that the system is suitable for detecting even small errors in setup and during melting of a sample surface. This ability to detect malfunctions of the SLM manufacturing system helps in setting up a system and to survey it during manufacture. With the possibility of displaying the course of the melting temperature for each layer of the manufacturing process, it can be considered an enabler for tracking the course of the manufacturing process.

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