Homogenizing the melt pool intensity distribution in the SLM process through system identification and feedback control

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Abstract

The common scanning strategies in Selective Laser Melting lead to an inhomogeneous melt pool intensity distribution throughout the different layers and scan tracks. This results in various defects such as porosity at the edges, residual stresses, or even excessive warping and delamination. In this research, this issue is resolved by the implementation of an on-line and real-time PID feedback controller. The PID feedback controller will alter the laser power based upon the melt pool intensity resulting in a homogeneous intensity distribution throughout the different scan tracks and layers. 2D intensity maps can be generated from the on-line monitoring system during the production of a benchmark part and will serve as validation for the PID feedback controller.

Introduction

Selective Laser Melting (SLM) is an Additive Manufacturing technique, which enables the production of complex functional metallic parts. A schematic set-up of a typical SLM machine is shown in Figure 1. In the SLM process, first, a thin layer of metal powder is deposited on a build platform by means of a powder coating system. After depositing, the powder layer is melted selectively according to a predefined scanning pattern, by a laser source [1] and a laser deflection system. After scanning a layer, the build platform moves down over a fixed distance equal to the thickness of one powder layer (in SLM typically 20 to 40 µm) and a new powder layer is deposited and scanned. The sequence of depositing and scanning is repeated until the part(s) is (are) fully built.

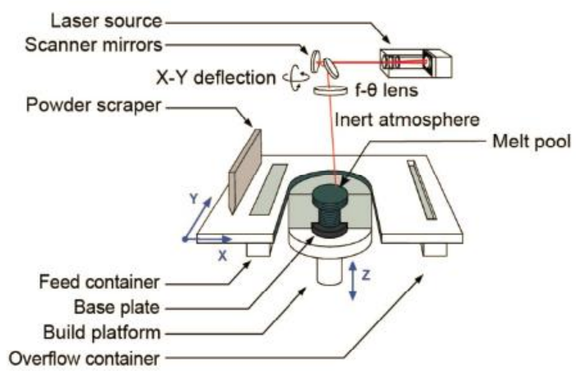

Figure 1: Schematic overview of the SLM process

Recent machine developments allow us to monitor, and have an insight in, the behavior of the melt pool characteristics during the SLM process [2]. These observations prove that the melt pool characteristics (e.g. intensity, dimensions) change throughout one layer and scan track, even with constant process parameters (e.g. scan speed, laser power). These changes can lead to unwanted effects (e.g. pore formation) and can cause bad quality products or even failure of the SLM process. [3]

Throughout this paper it will be shown that the development and implementation of an on-line and real-time PID feedback controller will result in homogenizing the melt pool intensity throughout the different layers and scan tracks.

Materials and methods

Equipment

All measurements concerning the behavior of the melt pool characteristics were performed on an in-house developed SLM machine of KU Leuven, equipped with a Yb:YAG 300 W fiber laser. To monitor and control the melt pool, the machine is equipped with an optical measurement system consisting of a high-speed near infrared (NIR) camera that can measure the melt pool dimension (length/width), and a photodiode that provides an indication of the melt pool intensity Figure 2. These sensors are installed coaxial with the laser beam. The emitted energy by the melt pool is captured, processed and logged at a sample rate of 20 kHz. Figure 2 represents the general set-up of the optical system. For this research only the melt pool intensity, which is measured by the photodiode, is of interest.

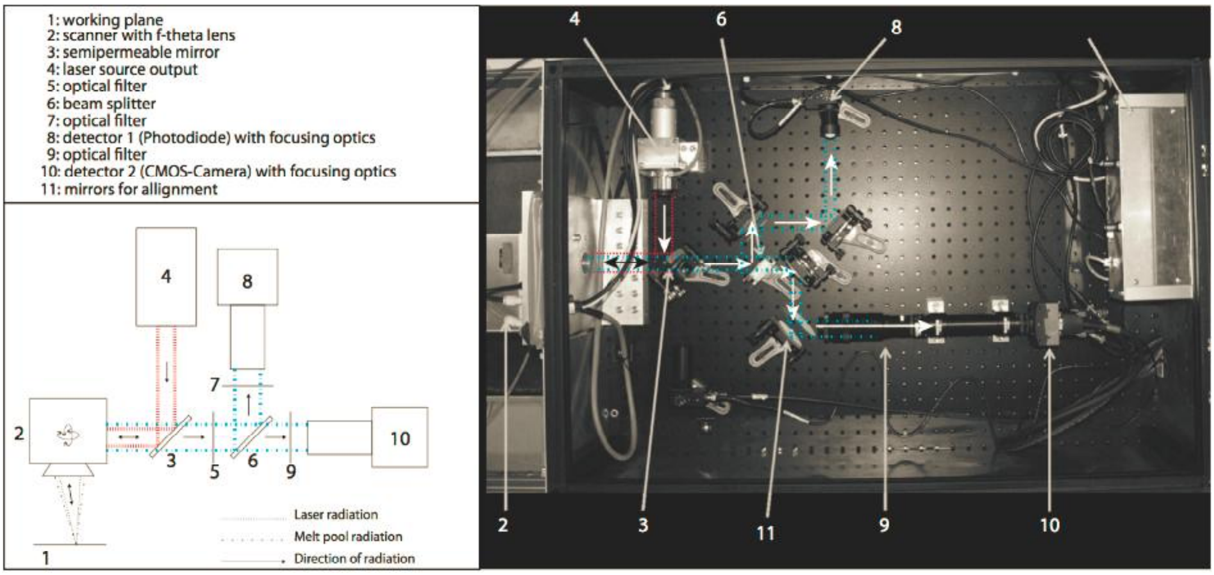

Figure 2: Optical set-up of monitoring system; schematic lay-out (left) and physical lay-out (right)

Melt pool characteristics strongly depend on the processed powder material and the employed process parameters. During this work all parts were produced in Ti6Al4V with a grain size of 15 to 45 µm and were processed with the following process parameters: scan speed of 1600 mm/s, hatch spacing of 75 µm and a laser power of 250 W. These parameters were optimized to result in nearly fully dense parts (99.8 %).

Results and Discussion

Inhomogeneity throughout one layer

When a layer is processed by SLM, limited thermal conductivity of the (powder) material results in heat accumulation and the generation of a 'heat front'. This heat front will be 'pushed' a front in the scan direction and affects the melt pool intensity during the scanning of the layer. The dynamic intensity change can be measured by the photodiode in time. As an example, Figure 3 represents the melt pool intensity throughout one layer measured by the photodiode versus time. This particular rectangular layer (see Figure 4) is scanned in an unidirectional scan pattern in the Y direction starting from the top right with each following scan moved one hatch space distance (75µm) in the negative X direction with the final scan being completed at the bottom left. It is clearly visible that the average melt pool intensity increases due to the accumulated heat front, described above, until it reaches its steady state (see Figure 3).

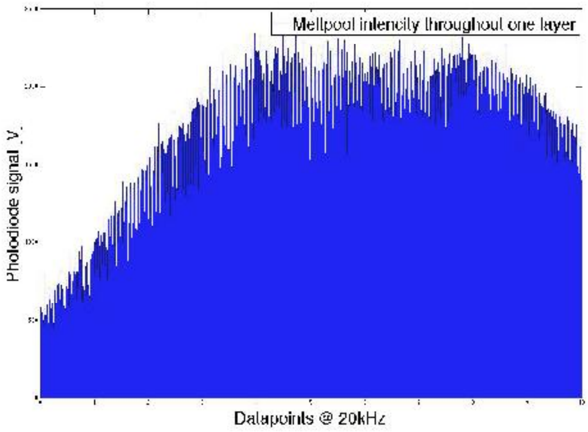

Figure 3: Melt pool intensity throughout one layer

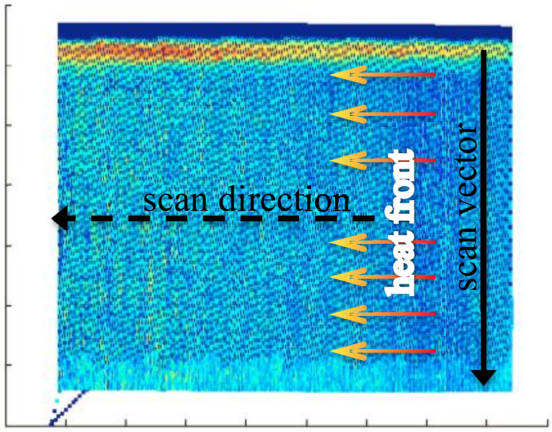

Figure 4: Colour map of photodiode vs. XY coordinates

A clearer interpretation of this phenomenon can be visualised by 2D colour mapping the photodiode signal on the XY coordinates of the laser scanner. Figure 4 is an example of such a 2D colour intensity map of one layer in a rectangular part. Low melt pool intensities are represented as blue pixels whereas higher melt pool intensities are represented as a gradual transition to red pixels. Here the pixels tend to migrate from blue to lighter blue according to the scan direction (right to left) and from blue to red along the edge of the part/layer (top to bottom) along upper edge in Figure 4. Complementary to the photodiode time-plot the 2D colour intensity map proves the existence of the inhomogeneous intensity distribution throughout one layer.

Inhomogeneity throughout one scan track

The 2D intensity plot (Figure 4) also clearly reveals the existence of an inhomogeneous intensity distribution throughout one scan track. Bright red pixels indicate high melt pool intensity peaks at the start point of each scan track. The cause of these high intensity peaks can be explained by the dynamic behavior of the laser beam deflection system (galvano scanner). The deflection system has a finite acceleration speed meaning that the nominal scan speed will be reached after a certain amount of time. [4] During this acceleration, the laser is already at nominal laser power resulting in a higher energy density input at the beginning of every scan track. These peaks can also be observed in the photodiode time-plot when zoomed-in. Figure 5 is a zoomed plot of Figure 3 and shows the photodiode time-plot of only one scan track.

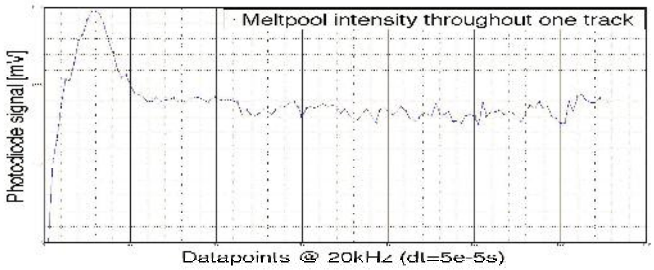

Figure 5: Melt pool intensity throughout one scan track

Implementation of on-line real-time PID feedback controller

To achieve homogeneous melt pool intensities throughout one scan track and throughout one layer, an on-line real-time PID feedback controller was designed based upon the system identification of the melt pool. Figure 6 represents a schematic overview of the single-input/single-output (SISO) closed loop system.

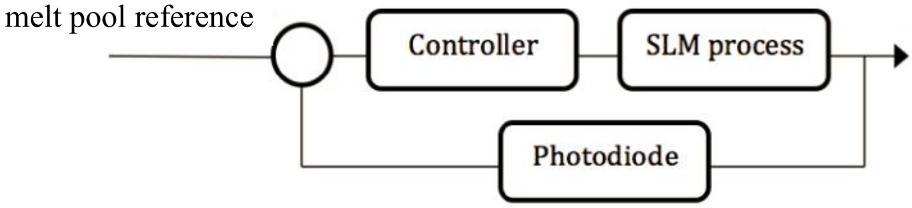

Figure 6: Schematic overview of SISO feedback controller

The melt pool model was estimated with a discrete autoregressive exogeneous model estimator (ARX). As a result Equation 1 shows the output model of the ARX model estimator with a fit of 96,3%.

$$Discrete - time\ ARX\ model:$$
$$A(z)y(t) = B(z)u(t) + e(t)$$
$$A(z) = 1 - 1{,}8z^{-1} + 1{,}039z^{-2} - 0{,}1663z^{-3}$$
$$B(z) = 0{,}0007098z^{-4} + 0{,}0007098z^{-5} + 0{,}0007098z^{-3}$$

Where: u(t) is the input vector, y(t) is the output vector, e(t) is the error vector

Equation 1: Melt pool model

This model is further used to obtain the parameters for the PID controller with a response behaviour described in Table 1. The actual parameters for the feedback controller are shown in the feedback controller constraints Table 2.

Rise time	0.5 ms
Settling time	1.5 ms
Overshoot	0.5%

Table 1: SISO feedback controller constraints

Kp	13.586
Ti	0.2145 ms
Td	5.3624e-2 ms

Table 2: SISO feedback parameters

A discrete PID controller can be described as show in Equation 2. This equation together with the parameters from Table 2 is implemented on the SLM machine of KU Leuven to achieve a closed loop system.

$$u(n) = K_p.e(n) + K_i \sum_{k=0}^{n} e(k) + K_d\big(e(n) - e(n-1)\big)$$

Where u(n) is the controller output and e(k) is the error at time step at step k

Equation 2: SISO feedback controller

$$K_i = \frac{K_p.T_s}{T_i}$$
$$K_d = \frac{K_p.T_d}{T_s}$$
$$T_s = 5.10^{-5}s$$

Validation of on-line real-time PID feedback controller

To validate the benefits of the implemented PID controller the same part is built again with the PID controller enabled. The laser power will now be on-line altered according to the measurement of the photodiode and a fix photodiode reference value (800mV) resulting in a stable uniform melt pool intensity. The fixed photodiode reference value was obtained by the average steady state value of the photodiode in Figure 3. Figure 7 shows the 2D intensity map of the part being built with the PID controller enabled. Compared to Figure 4, where the controller was not implemented, the melt pool intensities are significantly more homogeneous throughout the different scan tracks and layer. Small peaks at the start of each scan track are still noticeable and can be decreased when optimizing the PID control parameters.

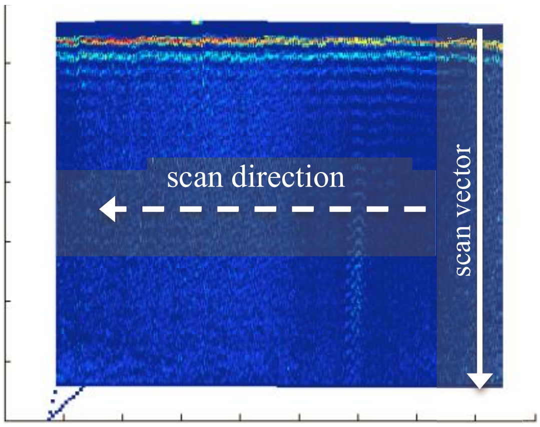

Figure 7: 2D intensity map with controller

Conclusion

The aim was to achieve a homogeneous intensity distribution throughout the different scan tracks and throughout one layer by implementing an on-line real-time PID controller based on the system identification of the melt pool. To prove the existence of inhomogeneous melt pool intensities, measurements were taken by the photodiode in real-time and 2D intensity maps were generated.

Based on the system identification of the melt pool, the parameters for the PID controller were obtained and implemented on the SLM machine of KU Leuven. After processing a part with the PID controller enabled, new 2D intensity maps were created where more homogeneous melt pool intensities throughout the different scan track and layers could be noticeable.

Moreover, it was shown that in case of inhomogeneous melt pool, with high intensity melt pools at the start of the scan vectors, pores were induced at the start of the scan vector. Those pores could be avoided by imposing a move homogeneous melt pool intensity using the PID control system

References

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