# Melt Pool System Identification and Feedback Control for Selective Laser Melting

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ABSTRACT: Observation of the melt pool, formed during a normal Selective Laser Melting (SLM) build process, shows a non-uniform melt pool intensity distribution throughout one layer and scan track. The associated variation of the melt pool intensity can cause unwanted defects (e.g. pores). The change in melt pool intensity and possible defects cannot only be observed within one layer but will propagate itself throughout all the layers. To counteract the change in melt pool characteristics, a system identification was performed on the melt pool intensity, during several layers, in function of the laser power. The system identification provides a mathematical model of the melt pool intensity that was used for the development of a feedback controller. The benefit of the feedback controller was simulated.

## 1 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 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 (Kruth et al. 2007) 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.

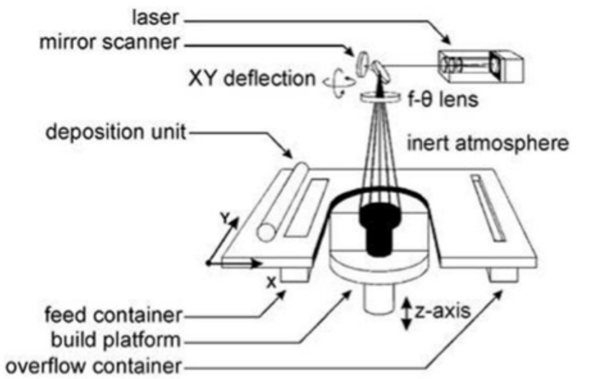


**Figure 1 Schematic overview of the SLM process**

Recent machine developments allow us to monitor, and have an insight in, the behavior of the melt pool characteristics during the SLM process (Van Vaerenbergh 2008, Craeghs 2013). 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. (Kempen et al. 2012)

Within this paper it will be shown that online and real-time feedback control of the melt pool will result in homogenizing the intensity throughout the different layers and scan track. Less pores will be formed resulting in higher quality parts.

## 2 PROCEDURE

### 2.1 *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. In this research only the melt pool temperature and dimension are of interest and will further be correlated and named as the melt pool intensity. For the monitoring and loggings of the melt pool intensity, the machine is equipped with an optical system consisting of a high-speed near infrared (NIR) camera that can measure the melt pool dimension, and a photodiode that gives an indication of the melt pool intensity. These sensors are installed coaxial with the laser beam in such a way that the emitted light 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.

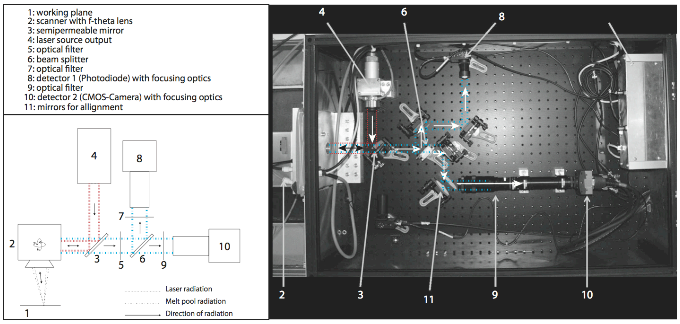


**Figure 2 Optical set-up of SLM machine.**

## 2.2 *Material and process parameters*

Melt pool characteristics and thermal behavior strongly depend on the processed material and the employed process parameters.
All test parts in this work were produced in Ti6Al4V. The used powder has a grain size of 15 to 45 µm and was 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-full-dense parts (99.8 %).

# 3 RESULTS AN DISCUSSION

## 3.1 *Detection*

### 3.1.1 *Throughout one layer*

When a layer is processed by SLM, low thermal conductivity of the material results in heat accumulation. This gradually heat accumulation will be ‘pushed’ further throughout the scan direction and affects the melt pool intensity during the scanning of the layer. This change in intensity can be measured by the photodiode.

Using this data a 2D ‘melt pool intensity map’ (2D pixel image) can be generated when the melt pool intensity (represented by a local image pixel) is allocated to the laser scanning position (X,Y). Plotting melt pool intensity versus XY position of the melt pool allows easier interpretation of melt pool intensity. Figure 3 represents such a generated ‘melt pool intensity map’ for one layer in a square part. Low melt pool intensities are represented as dark pixels whereas high melt pool intensities are represented as bright pixels. This layer is scanned in zig-zag mode, starting at the left (where the powder layer is initially cold) and gradually progressing to the right. Consequently a ‘heat-front' is build up that preheats the powder layer to the right of the current vector being scanned).

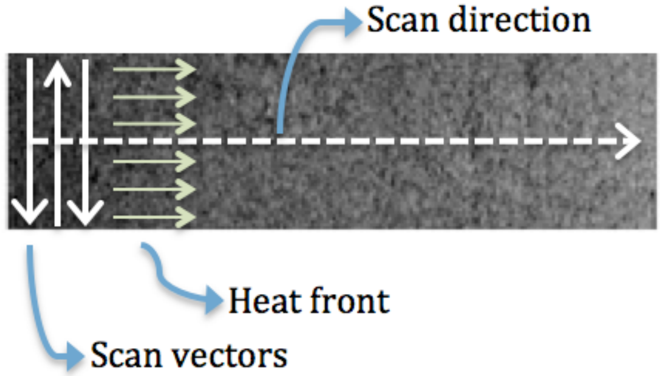


**Figure 3 Melt pool intensity map of one layer**

Figure 4 represents the melt pool intensity of one layer on a time axis. From this plot it can be seen that the average melt pool intensity increases, until a steady state is reached, throughout a layer due to the heat that was cumulatively built up during scanning.

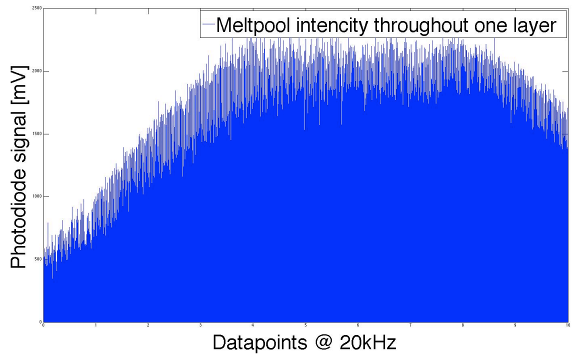


**Figure 4 Melt pool intensity throughout one layer**

### 3.1.2 *Throughout one scan track*

Figure 5 represents the melt pool intensity throughout one scan track. A sharp intensity peak can be detected at the beginning of the scan track. This phenomenon can be observed for every individual scan track. The cause of this intensity peak 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 some amount of time. (Buls et al. 2013) During this acceleration, the laser is already at nominal laser power resulting in a higher energy density at the beginning of every scan track.

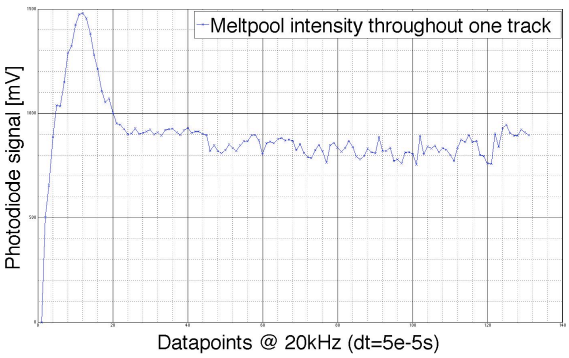


**Figure 5 Melt pool intensity throughout one scan track**

These observations prove that the melt pool intensity changes throughout the layers and scan tracks, even with constant process parameters (viz. scan speed, laser power). These changes can lead to unwanted defects (e.g. pore formation) and can cause bad quality products or even failure of the SLM process.

The goal of this work is to homogenize the melt pool intensity distribution, both throughout one layer, as throughout one scan track. This is obtained in two phases. First, system identification techniques are used to model the behavior of the melt pool (in casu melt pool size) versus dynamic variation. In the next fase, this model is used for the development of a real-time and online feedback controller.

## 3.2 *System Identification*

In order to be able to control the melt pool intensity, a mathematical model was estimated from data measured during the production of
a rectangular block (10 x 70 x 10 mm), built with a 'zig-zag' scan strategy.

The melt pool intensity in function of the laser power was averaged and used as time data for the estimation of a linear parametric model. The result of the Output-Error polynomial model estimator is a model with a certainty of 95.13%. Equation 1 represents the melt pool intensity model.

$$Melt\ pool = \frac{0.000284z^{-1} - 0.0005819z^{-2} + 0.00035z^{-3}}{1 - 2.432z^{-1} + 1.913z^{-2} - 0.479z^{-3}}$$

z = discrete laplacian

**Equation 1 Melt pool intensity model**

## 3.3 *Feedback Control*

To counteract the change in melt pool intensity throughout one scan track and throughout one layer, a feedback controller was designed based upon the model described in section 3.2. The feedback controller will alter the laser power based on the signal provided by the photodiode (which represents the melt pool intensity). Figure 6 depicts the schematic overview of the feedback controller.

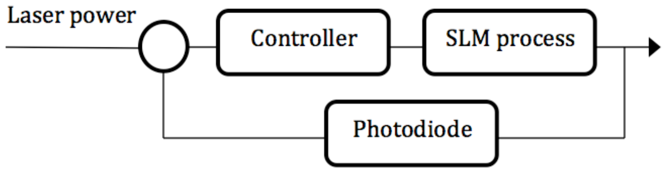


**Figure 6 Schematic overview of feedback controller**

A stable feedback controller was designed, based on the system identification model of the melt pool intensity. The control parameters were optimized, resulting in a proportional gain of 0,145 and an integral time constant of 2,89.10$^4$ s.

Implementation of this feedback controller should lead to a homogenized melt pool intensity, both throughout a scan track and throughout a layer.

## 3.4 *Validation*

**To validate the benefits of the feedback controller, simulations were performed on verification data sets.**

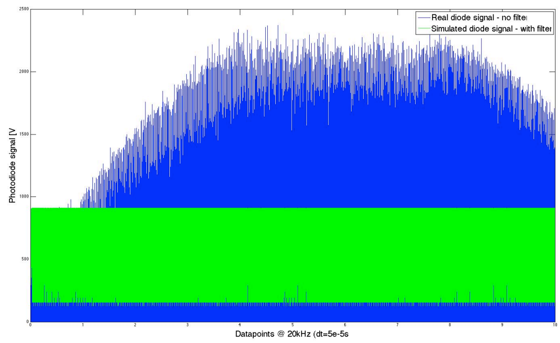

Figure 7 represents the melt pool intensity throughout one layer with and without control. It can be seen that, with control, the average intensity does not change anymore throughout one layer in comparison to the uncontrolled setup.

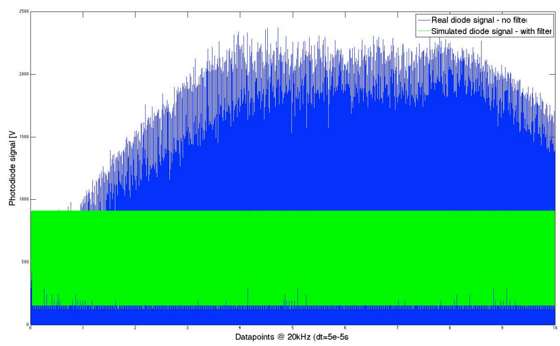

**Figure 7 Melt pool intensity throughout one layer**

Not only can the benefits be seen throughout one layer but also the overshoot in melt pool intensity in the beginning of a scan track is eliminated. Figure 8 represents the simulated melt pool intensity of one scan track with and without control.

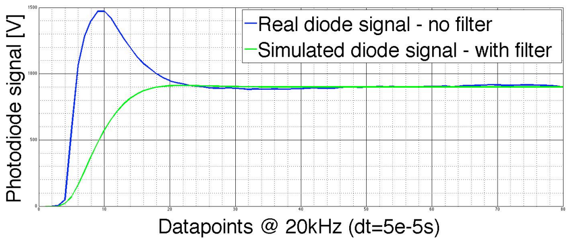


**Figure 8 Melt pool intensity throughout one scan track**

## 4 CONCLUSION

Due to both the dynamics of the laser galvano scanner and of heat absorption and transfer during the SLM process, melt pool intensity is not homogeneous during part production. This can lead to defects and process instability.

Automated laser power adaptation in order to have a stable melt pool throughout an entire process was the goal of this work.

This melt pool intensity control was established by; in a first step, identification of a parametric model for the dynamic behavior of the melt pool. In a second step, a control system was designed based on this mathematical model, to homogenize the melt pool intensity by altering the laser power.

Simulation experiments using melt pool intensity signals measured by a photodiode during a not controlled SLM build job have shown that the melt pool instabilities both within one layer, as within one scan track were controlled. The result obtained by simulation will be further verified by performing real SLM tests with the implemented control system using the real melt pool intensity, as measured in real-time by the photodiode.

## 5 REFERENCES


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