ONLINE QUALITY CONTROL OF SELECTIVE LASER MELTING

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Abstract

Selective Laser Melting (SLM) is an Additive Manufacturing technique which allows producing three-dimensional metallic parts from powder material, using a layer-by-layer fashion. Typical applications of this technology are parts with high geometrical complexity or internal features such as biomedical implants or casting molds with conformal cooling channels. In order to break through in industries with very high quality standards (such as aerospace industries), an important issue to be addressed is quality monitoring and control during the actual building process. Online quality control can significantly increase the robustness of the process by enabling to check the quality of the building process in the earliest possible stage, such that eventually corrective actions can be taken during the process. This is in contrast with on-line and a posteriori quality control which does not allow taking corrective measures if the quality of the part does not meet the desired quality standard. The development of a framework for online quality control of Selective Laser Melting is the subject of this paper. The framework consists of two complementary systems: a system for visual inspection of powder deposition and a system for online and real-time monitoring of the melt pool. A combination of these two systems enables to guarantee the quality of SLM parts with high confidence.

Introduction

Selective Laser Melting (SLM) is an Additive Manufacturing technique mainly used to process metallic materials which enables the production of complex functional metallic parts with good mechanical properties. A schematic overview of a typical SLM machine is shown in figure 1. In the SLM process, a thin layer of metal powder is first 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 means of a laser source [1]. After scanning a layer, the build platform moves down over a fixed distance equal to the thickness of one layer (in SLM typically 20 to 40 µm) and a new layer is deposited and scanned. The sequence of depositing and scanning is repeated until the part(s) is (are) fully built. The SLM process has a large potential for manufacturing a wide range of applications, due to the almost infinite geometrical freedom, no need to design or make dedicated tools for production and flexibility for production of customized individual parts. Since material properties of SLM parts are nowadays comparable to the properties of the corresponding bulk material [2, 3], applications of the process can be found in domains like the medical sector [4], in tool making industries [5–8], machine construction, automotive, etc.

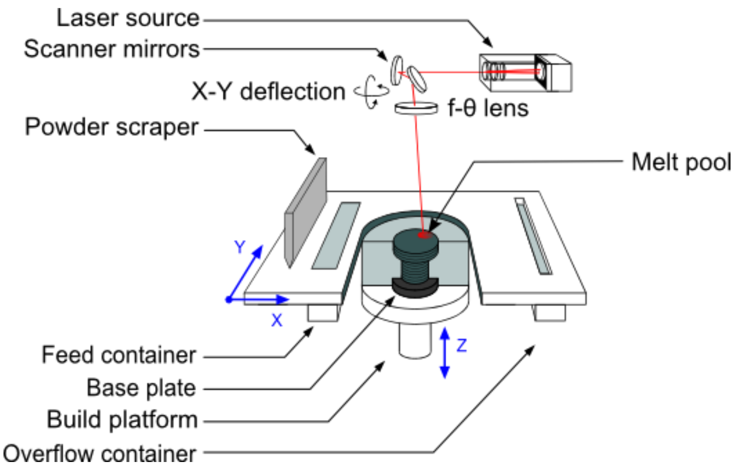


Figure 1: schematic overview of the SLM process

In recent years the SLM technology has made an enormous progress in machine construction, production speed and part quality. However, for a large breakthrough of SLM in industries with high quality demands, an important issue to be addressed is online quality control of the process [9]. Online control can increase the robustness by enabling to check the quality of the building process in the earliest possible stage, such that eventually corrective actions can be taken during the process. This is in contrast with off-line and a posteriori quality control which does not allow taking corrective measures if the quality of the part does not meet the desired quality standard. Furthermore, during an off-line analysis it is not always possible - or expensive - to check the whole part, for instance inner structures, in a non-destructive way.

The development of a framework for online quality control of Selective Laser Melting is subject of this paper. First section 2 will discuss the global methodology for online quality control of SLM. Section 3 will discuss the LM-Q machine of KUL-PMA as a prototype SLM machine with integrated quality control modules. It will become clear that the global framework makes use of several subsystems, of which two will be presented in this paper: section 4 will therefore discuss a visual inspection system to monitor the deposition of powder and section 5 presents a system for online monitoring of the melt pool. Throughout the paper it will be shown that these systems can detect a wide range of processing problems in SLM.

Methodology

Figure 2 schematically shows the methodology for this research. Central in the scheme is the actual melting process, which is in theory influenced by more than 50 parameters [10]. These parameters can be divided in two domains: *input parameters*, which are parameters that can be adjusted by the machine operator, and *boundary condition parameters*, which are parameters that are determined by external requirements or conditions, for instance the choice of material depends mainly on the application (e.g. use of Ti-6Al-4V for medical implants). The input parameters can be classified into *atmosphere parameters* (e.g. oxygen content in the process chamber), *powder deposition* *parameters* (e.g. layer thickness) and *scanning parameters* (e.g. laser power, laser focus setting, scan velocity). The boundary conditions parameters can be subdivided in parameters of the *material*, the *geometry* to be processed and the *machine parameters* (e.g. type of laser source). The input parameters influence the melting process resulting in an effect on the resulting part quality. If one of the input parameters varies, in theory this influences the actual melting process. For instance, a larger layer thickness with the other process parameters kept constant, causes a different melt pool behavior, and the density of the produced part will decrease, or if the oxygen content in the process chamber increases, the resulting material will become more brittle.

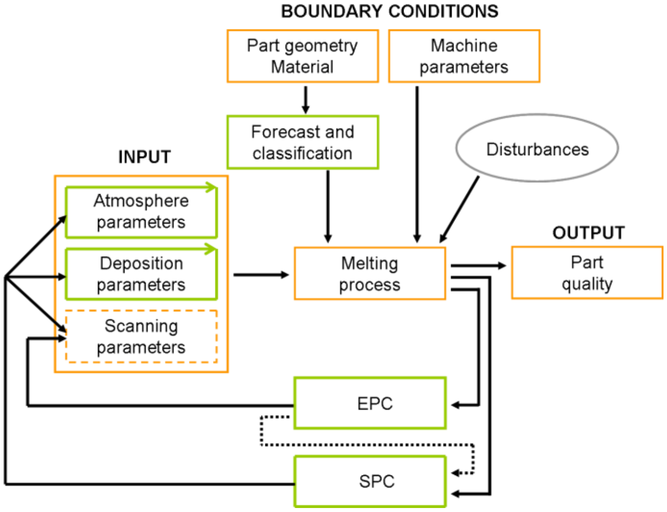


Figure 2: methodology for online quality control of the SLM process

The influence of parameter variations can be seen in the melt pool behavior, but in order to achieve a robust system for online quality control of the process it is not sufficient to only monitor the melt pool. If an input parameter variation affects the melting process and it is detected by a melt pool sensor (for instance a raise in oxygen content in the process chamber leads to a more elongated melt pool which can be detected using a camera), in most cases it is too late to take appropriate counteractions. It is thus important, besides monitoring the melt pool, to also monitor and control the input parameters themselves. A good online quality control system therefore should monitor and control the process atmosphere, the powder deposition and the melt pool itself.

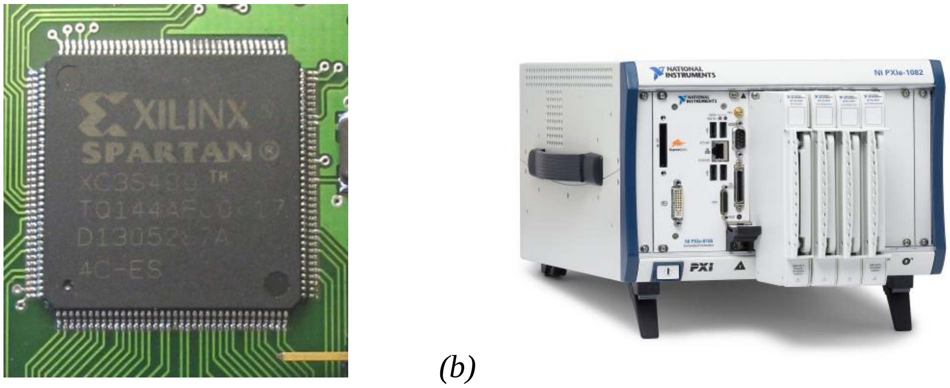
Monitoring of the melt pool can be used further to give feedback to the process input parameters. This can be done in two ways: using engineering process control (EPC) algorithms, such as PID-control, to control in real-time the scanning parameters (laser power and scan velocity) or using methods from statistical process control (SPC) to detect ‘abnormal’ variations in the melt pool output, which are likely to be caused by a disturbance. Closed loop control will not be discussed further in this work, but can be found in other publications [11, 12]. In this paper, online control of powder deposition and monitoring of the melt pool will be discussed.

The LM-Q machine of KUL-PMA

Since the start of research concerning of AM processes, the university of Leuven (KUL) has been developing prototype machines for layered manufacturing. KUL owns an in-house developed SLM machine, which enables flexible testing of new software and hardware configurations. Figure 3 shows this in-house developed machine for SLM. This machine is controlled using an industrial PXI system from National Instruments.

Figure 3: in-house developed SLM machine of K.U.Leuven (KUL)

Figure 4(b) shows such industrial PXI system. The system mainly consists of a real-time CPU, which communicates with two hardware boards having an embedded Field Programmable Gate Array (FPGA). An FPGA chip is a programmable silicon chip consisting of unconnected gates (see figure 4(a)). The use of FPGA enables the user to define and re-define the functionality of a chip: the user defines the chip behavior in software after which dedicated compilers translate the software into a certain connection of the gates. An FPGA chip is typically used in applications where custom hardware is needed or when there is reconfiguration required after deployment of the chip. The LM-Q machine makes use of three FPGA chips. The LM-Q machine is the platform at which all hardware developments discussed further in the text have been done.



(a) *(b)*

Figure 4: (a) example of an FPGA chip (source: XILINX). (b) PXI system (National Instruments) used as central control system for the LM-Q machine.

Visual inspection of powder deposition

The distribution of the powder particles in each deposited layer should be as even as possible, since the smoothness of the powder bed is directly reflected in the resulting surface roughness, as shown in figure 5. Figure 5(a) shows an image of the build platform after scanning a layer. Clear stripes are visible in the powder bed, due to several damages in or severe wear of the coater. In figure 5(b), showing an image of the top surface of final part, the effect of these stripes on the resulting surface roughness is clearly visible. As stated above, it is important to detect these variations before laser melting of the layer.

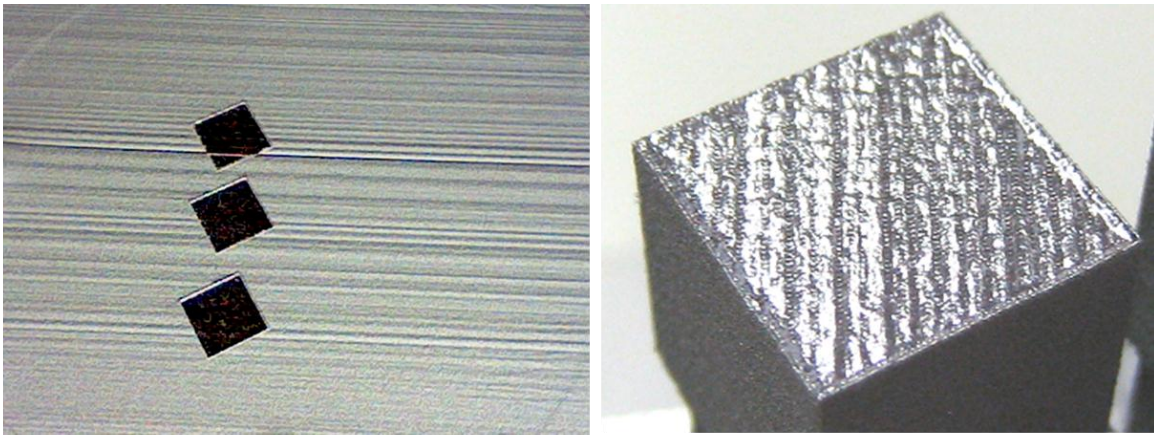


Figure 5: (a) Stripes in the powder bed due to damaged coater blade; (b) Image of the part after production. The resulting roughness is highly influenced by the stripes in the powder bed during processing.

Deterioration of the smoothness of the powder bed is mainly caused by three reasons: parts curling up (rising higher than the powder surface) due to the high thermal stresses in SLM, damage or wear of the coater blade due to the scratching of the parts at the coater blade (causing stripes in the powder bed parallel to the movement of the coater) and short of feed powder (such that after coating not all zones of the build platform are homogeneously covered with new powder). With a visual camera and a good choice of illumination of the powder bed, these defects can be detected very well using straightforward image processing algorithms. In this paper as an example detection of wear and local damage of the coater blade will be discussed.

Hardware set-up

The experimental set-up consists of a visual camera with focusing lens to monitor the build platform. Furthermore three light sources are present, such that light can be projected on the powder bed coming from three different positions with respect to the build platform. Figure 6 shows a schematic overview of the set-up, showing the position of the camera and the three light sources. The direction from the coater blade movement is horizontally over the platform. During scanning of a layer, the coater is - in the case of the LM-Q machine - at the left side of the build platform and directly after scanning it moves from left to right. Then the feed platform moves up and the build platform moves down. The coater movement from right to left then deposits the new powder layer.

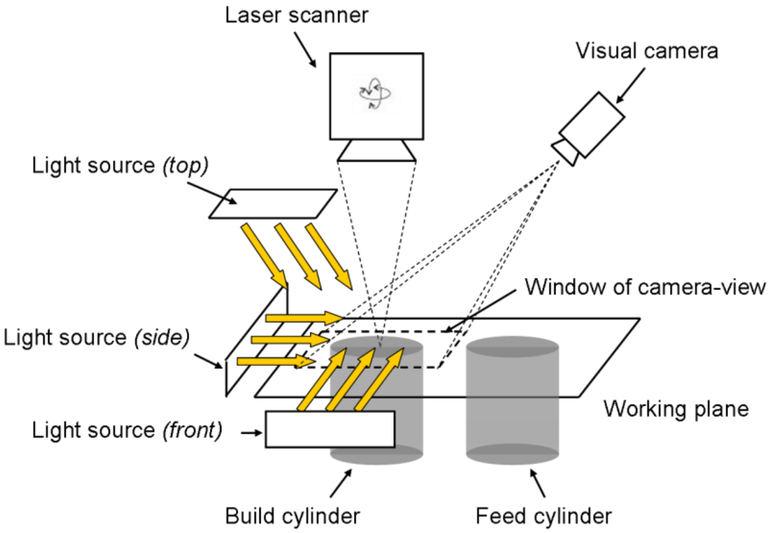


Figure 6: Principle of the visual inspection system for monitoring of the powder layer top surface.

As shown in figure 6, the aimed field of view is the build platform and therefore to minimize the perspective error in the image, the optical axis of camera must be as close as possible to the center line of the build platform. With a camera having a static position with respect to the build platform this is however not possible, since the optical path of the laser beam crosses the build platform center. A proper solution is to use calibration algorithms to correct for the perspective error. This solution is chosen since a simple calibration algorithm is able to correct for the distortion as will be shown below. With the three light sources, the build platform can be illuminated from three directions: front light (perpendicular to the coater movement), side light (parallel with the coater movement) and top light (perpendicular to the building platform). These different directions are needed to detect different problems, since some defects are only visible using illumination from a certain direction. This is mainly due to the creation of shadow lines around defects, only visible with illumination from a certain direction.

Case study: detection of wear and local damage of the coater blade

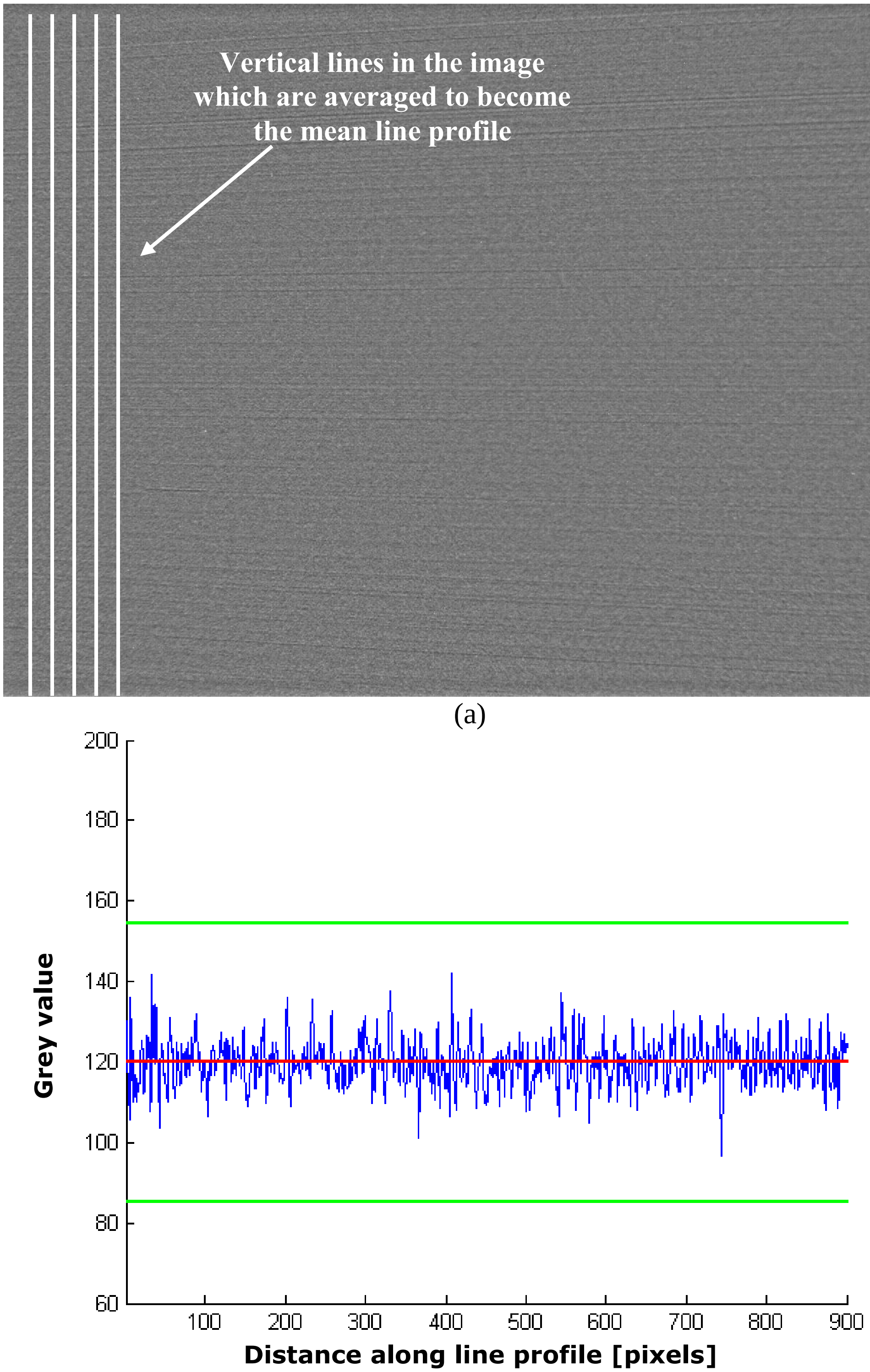
In this case study it will be shown that with the visual inspection system two types of coater defects can be easily detected: *wear* of the coater blade, which leads to small scratches in the powder bed but all over the powder bed, and *local damage* of the coater blade, which leads to locally but deep scratches in the powder bed. In order to detect wear and damage of the coater blades, front illumination is used since wear and damage of the coater blade will cause horizontal lines in the powder bed (parallel with the movement of the coater blade), and thus produce horizontal shadow lines in the image.

In order to detect these coater flaws, a so called ‘line profile’ is constructed. The line profile is defined as the average of five vertical lines in the image of a powder bed (as shown in figures 7(a) and 8(a), see the white lines on the left in the image). These lines are taken at the left, since the camera sees the build cylinder on the right side of the image, and therefore the part of the image on the left is never ‘disturbed’, for instance by parts visible outside of the powder bed. Figure 7(b) shows such line profile of an ‘ideal’ powder bed deposited with a new coater. The mean value of the line profile is about 120 (units are in ‘grey value’) and the standard deviation of the line profile is 5.75. This line profile is used as the reference profile for comparison with the profiles of other layers.

Figure 8(a) demonstrates a powder layer deposited with a *worn* and *damaged* coater and figure 8(b) shows the corresponding line profile. When compared with the ‘ideal’ line profile of figure 7(b), two observations can be made. First it can be seen that the mean is statistically equal (in both cases 120), but the standard deviation of the line profile in figure 8(b) is about two times larger (10.0 in the case of the damaged coater versus 5.75 in case of the new coater). The standard deviation of the mean line profile is likely to be a good indicator for general wear of the coater blade, since wear of the coater causes many smaller shadow lines in the image of the powder bed. Second, in figure 8(a) at different location more profound shadow lines are visible. These shadow lines are caused by larger but local damage of the coater blade, and are reflected in the line profile by high peaks or valleys, see figure 8(b). The location of eventual local damage of the coater can be detected where the line profile crosses certain critical borders (indicated by the green lines in the figures 7 and 8), which are typically chosen to be six times the expected standard deviation (in this case 5.75) above or below of the expected mean value (in this case 120).

The choice of the acceptance limits depend on the desired tolerances and desired part properties (concerning allowed surface roughness etc.). These values furthermore are strongly influenced by the camera settings (e.g. exposure time), the illumination (e.g. type of light source or luminosity), the material and powder type, … Therefore for every material and every machine a calibration step is needed in order to tune the parameters of the control system.

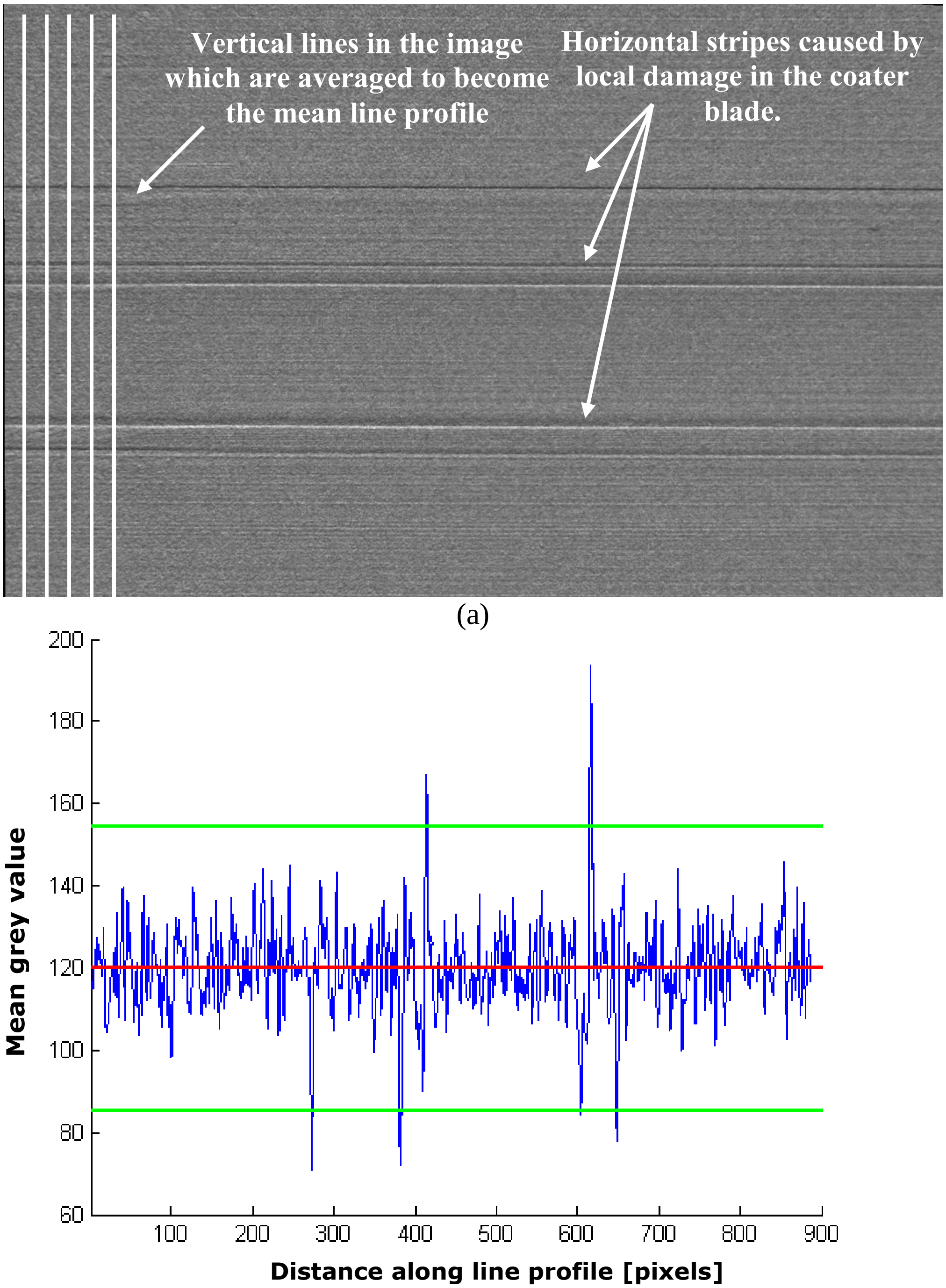
By detecting this kind of layer ‘defects’ before the actual melting of the layer, appropriate measures can be taken during the coating phase to improve the quality of the layer. These defects can also certainly be detected using melt pool sensors (see next section) during the scanning phase, but when detected during the scanning phase the quality of the part will already be affected irreversibly.



(a)

(b)

Figure 7: (a) Image of ideally deposited powder bed (front illumination); (b) Line profile of the ideal powder bed with mean 120 and standard deviation 5.75. The red line represents the expected average and the green lines indicate the allowed tolerances for detection of coater damage.



(a)

(b)

*Figure 8: (a) Image of deposited powder bed with worn coater blade using front illumination; (b) Line profile with mean 120 and standard deviation 10. The high standard deviation indicates that **wear** of the coater is present. Furthermore the line profile crosses the green lines at five places, which indicates that coater **damage** is present at five locations (one crossing and corresponding line stripe in the image is indicated as an example).*

Melt pool monitoring

This section discusses a melt pool monitoring system for SLM and three case studies which prove that such system can monitor and detect undesired process behavior leading to decrease of the quality in SLM.

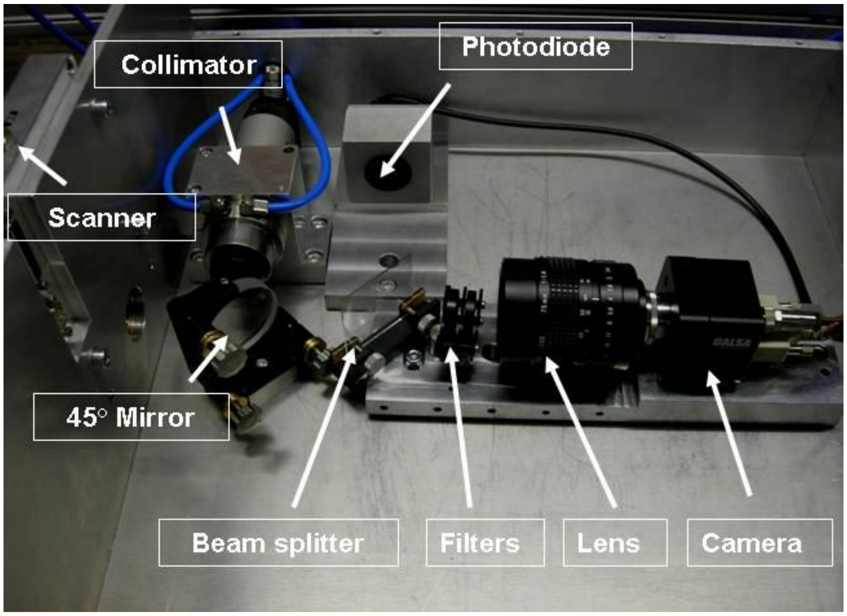


Figure 9: Design of the optical monitoring system for SLM [13]

Figure 9 shows the optical set-up of the LM-Q together with the prototype camera monitoring system [13]. The principle working of the monitoring system is as follows. The laser light is deflected by means of a semi-reflective mirror towards a galvano scanner with focusing lens. This focusing lens is a so called f-θ lens. The laser source of the LM-machine of KUL is an Ytterbium (Yb) fiber with a wavelength of 1064nm. The radiation from the melt pool is transmitted through the f- θ lens, scan head and semi-reflective mirror towards a beam splitter, which separates the radiation towards a planar photodiode and a high-speed CMOS camera. With the law of Planck it can be seen that the radiation energy at the melting point of metals (roughly around 1500K) is highest in the near infrared region, around 1000 nm. However, the reflectivity of a typical semi-reflective mirror coated for 1000 nm in a band around the central wavelength is nearly 100 percent. Therefore the melt pool radiation can only be captured in a range of wavelengths at a certain spectral distance from the wavelength of the laser beam, which is 1064 nm for the Yb fiber laser used in the set-up. Therefore the upper bound of the wavelength range to be captured by the sensors is chosen as 950 nm. The lower bound needs to be higher then 700 nm because visible light (from e.g. illumination in the process chamber) is not of interest for this set-up and will cause unwanted measurements. Nevertheless, the lower bound is still chosen somewhat higher (780 nm). The f- θ lens, necessary for focusing the laser beam on a flat surface, induces achromatic aberrations for wavelengths others than 1064 nm. For this reason the bandwidth of the captured radiation energy cannot be too large: 780 nm to 950 nm is a good trade-off between the different demands. Finally a beam splitter separates the radiated light towards a planar photodiode and a high-speed CMOS camera. Both photodiode and camera are sensitive to wavelengths in the range of 400-900 nm.

High-speed image processing on FPGA

The fast dynamics of the SLM process demands very fast image processing (order of magnitude 10 kHz). If the laser beam moves at a speed of 1000 mm/s, image rates of 10 kHz imply that an image is taken every 100 µm. This high speed can only be achieved when processing the data from the camera directly in hardware, using a chip to process the images. The FPGA performing the image processing is embedded on the FlexRIO card with Camera Link front end. The pixel data can enter the FPGA per 10 at 75 MHz. On the FPGA then the individual pixel data can be accessed. The power of FPGA can be optimally used when the image processing algorithm can be split in several sub-algorithms which can run in parallel. FPGA has further the advantage that algorithms running on it can still be adapted, which is especially during the research phase.

In order to obtain useable information from the melt pool images, an image processing algorithm must derive the information from the image, namely the melt pool area and the melt pool length-to-width ratio. With these two parameters enough information can be obtained for real-time feedback control to the melt pool input parameters, the laser power and the scan velocity. For real-time feedback control based on melt pool information from the camera, processing must be done in real-time and due to the fast dynamics of the SLM process, the processing rate must be at least around 10 kHz. The best suitable image processing algorithm for this application makes use of the well known image processing algorithm of calculating the moments of an image. These moments can be used in order to find the best fit ellipse, which closely resembles the melt pool. The long axis of the ellipse A is then the melt pool length, the short axis B is the melt pool width area of the ellipse and the area of the ellipse is the melt pool area.

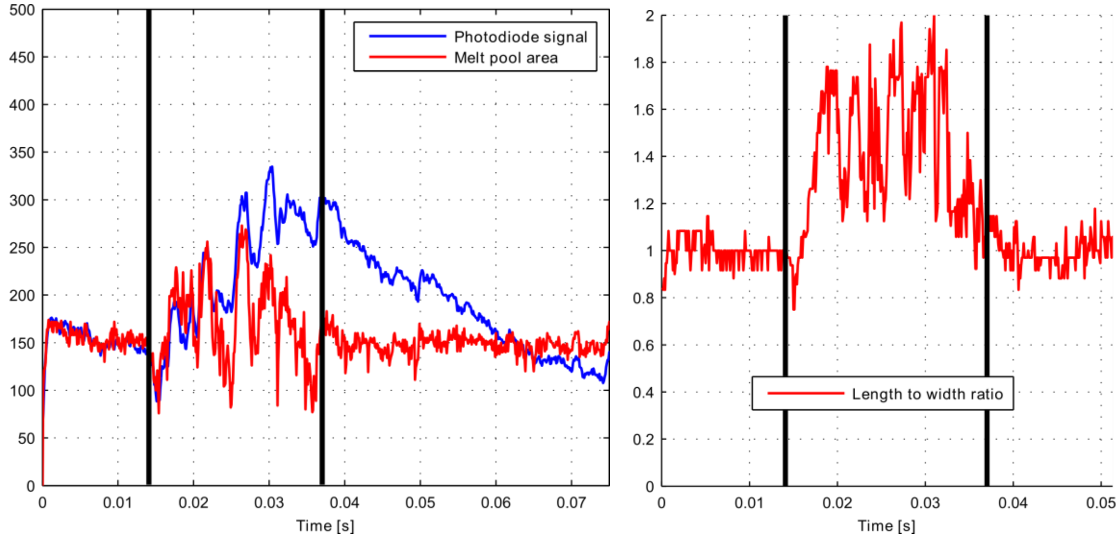


Figure 10: (a) Measured photodiode signal and melt pool area during perpendicular scanning of the square overhang (sample rate: 10 kHz); (b) Determined length-to-width ratio.

Following sections will discuss three case studies which show how the system can be used to monitor the SLM process in order to detect process deviations leading to undesired quality.

Monitoring of balling during scanning of an overhang structure

In order to study the transition between scanning on a solid substrate and the overhang zone, figure 10(a) shows, in function of time, the melt pool area and the photodiode signal during transition from solid to overhang and vice versa. Figure 10(b) shows for the same recording the length to width ratio of the melt pool (based on the same series of camera images). When the laser beam is passing the square overhang, it can be seen from figure 10(b) that the length to width ratio increases significantly at the overhang zone. The variations in the melt pool area signal are due to the Rayleigh instabilities. When the melt pool length grows too large it will split up in separate droplets which cool down faster such that the total melt pool will decrease. Then the melt pool will grow large again and the whole cycle will be repeated. Due to the overheating and the occurrence of balling at the overhang zones [14], the surface roughness of downfacing surfaces is typically very high. Moreover, the material is not completely dense in these zones and mostly large deformations occur due to thermal stress [15]. It is clear that the processing parameters should be altered to process these structures with an acceptable quality. One option is real-time feedback control to the process input parameters in order to stabilize the melt pool in these situations. In [11], the photodiode was used as feedback control sensor, but due to the fact that it still observes light from the past, only small improvement could be achieved. Future work therefore comprises MIMO control based on the melt pool area and length-to-width ratio in order to control the laser power and scan velocity.

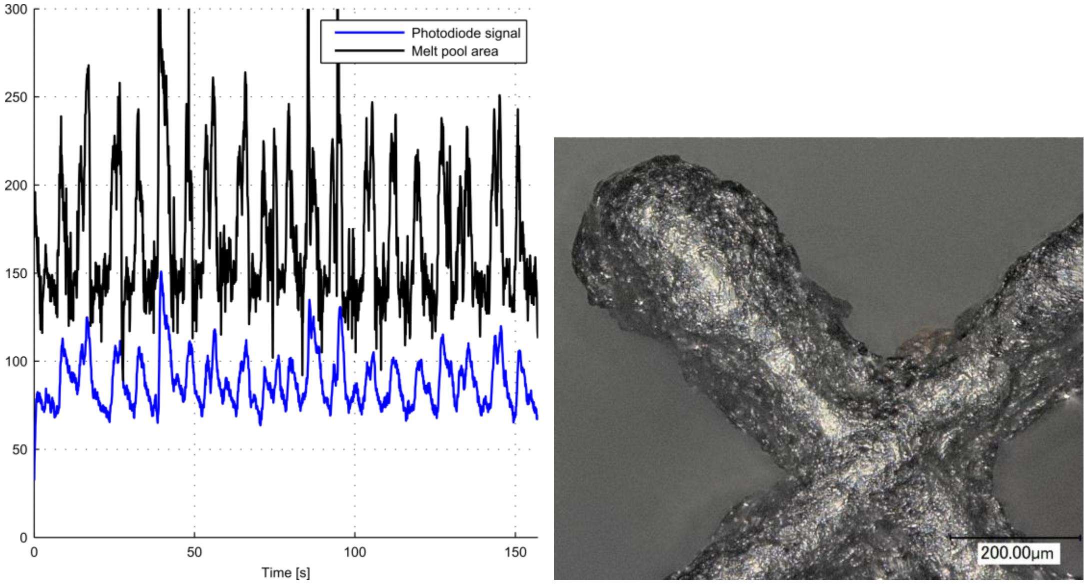


Figure 11: (a) Melt pool area and photodiode signal measured in real-time during scanning of the scaffold at 10 kHz. (b) Resulting blob formation at the U-turn of the scaffold.

Monitoring of overheating during production of acute corners

This study involves monitoring of overheating during scanning of acute corners, often encountered as a problem in production of tissue engineering scaffold structures, meant for repairing large bone defects [16]. These porous scaffold structures can be produced by SLM as a framework of horizontal beams. During scanning of the scaffold, the laser makes several subsequent U-turns, i.e. acute turns of 180°. At the point of rotation, the melt pool is for almost three quarters surrounded by powder material. Since the laser must accelerate again in the reverse direction, the laser is standing still for certain amount of time at the outer point of the scaffold strut. The combination with the diminished heat flux, leads to larger melt pools at every U-turn, as shown in figure 11(a). These larger melt pools cause blob formations at the edges of the struts, as shown in figure 11(b).

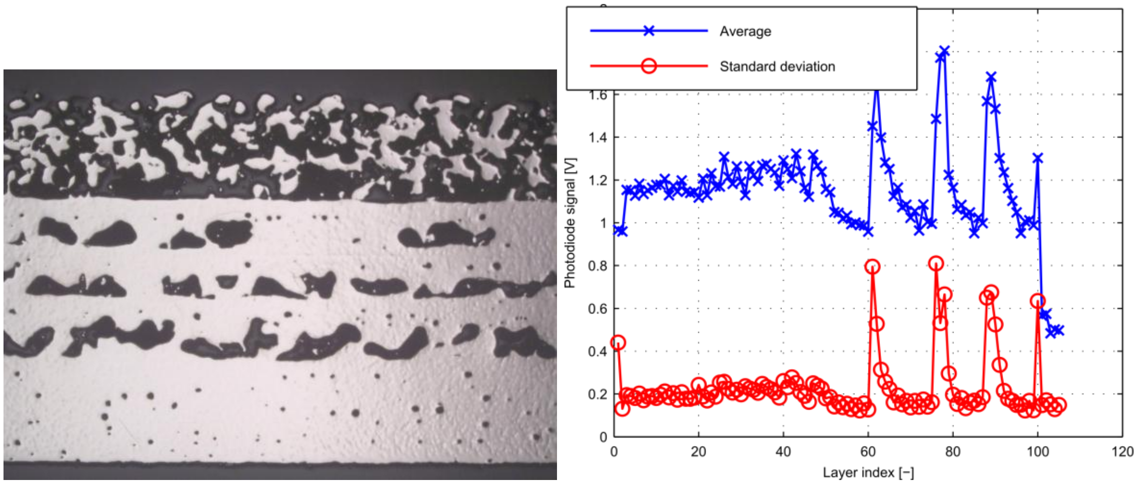


Figure 12: (a) cross-section of the part under the microscope; (b) control charts of mean and variance of the photodiode signal (per layer) during scanning of a bioreactor part.

Detection of process errors

The optical monitoring system can be used to detect abnormal variations in the melt pool behavior, which are caused by disturbances. This section will discuss one case study showing the principle. During scanning of a test part for tissue engineering application, a ’bioreactor’, a part of the motor of the build platform broke down, leading to large differences in layer thickness: several layers after each other the build platform stands still while after a certain amount of layers the platform moves down at a distance equal to multiple layers. Where an overly thick layer is deposited, figure 12(a) shows that the resulting part is very porous. As clearly visible in figure 12(a), this phenomenon happened three times during the build process. Figure 12(b) shows the mean and standard deviation of the photodiode signal captured during the whole layer (data captured during scanning of jump vectors are always omitted from the data). As shown in figure 12(b), the scanning of three overly thick layers is clearly visible in the averaged signals. What is however more interesting, is that this phenomenon could already been seen in the averaged signals before the quality of the part was totally deteriorated. The averaged signals between layers 30 to 45 already show a great deal of unexpected processing behavior.

Conclusions

This paper presents an online quality control system for Selective Laser Melting (SLM). For SLM to break through in industries with very high quality demands, online control of the process is a very useful tool. It is important to detect processing defects in the earliest possible stage of the process, such that eventual corrective actions can be taken. In this paper two subsystems have been presented: a visual inspection system to monitor the deposition of powder layers and a system to monitor in real-time the melt process. The hardware of these systems is embedded in the in-house developed SLM machine of KUL-PMA, which is controlled with an industrial PXI system from National Instruments. The system makes use of the technology of field programmable gate array (FPGA) chips, which enable very fast and real-time processing of the melt pool images. With these two systems very valuable information on the process can be gathered. This information can be used to control the quality of the process by controlling whether all parts of the process behave according to the expected behavior. This framework is a first important step to convince more industries on the reliability of SLM products.

Acknowledgments

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