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Quality control of laser- and powder bed-based Additive Manufacturing (AM) technologies

Sebastian Berumen[a], Florian Bechmann[a]*, Stefan Lindner[a], Jean-Pierre Kruth[b], Tom Craeghs[b]

[a]*CONCEPT Laser GmbH, An der Zeil 8, Lichtenfels 96215, Germany*
[b]*KU Leuven, Celestijnenlaan 300B, Heverlee B-3001, Belgium*

Abstract

The quality of metal components manufactured by laser- and powder bed-based additive manufacturing technologies has continuously been improved over the last years. However, to establish this production technology in industries with very high quality standards the accessibility of prevalent quality management methods to all steps of the process chain needs still to be enhanced. This publication describes which tools are and will be available to fulfil those requirements from the perspective of a laser machine manufacturer. Generally five aspects of the part building process are covered by separate Quality Management (QM) modules: the powder quality, the temperature management, the process gas atmosphere, the melt pool behaviour and the documentation module. This paper sets the focus on melt pool analysis and control.

Keywords: Additive manufacturing; laser melting; quality control; melt pool; realtime

* Corresponding author. Tel.: +49-9571-949233; fax: +49-9571-949239.
E-mail address: f.bechmann@concept-laser.de.

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1. Introduction

During the last years the usage of Additive Manufacturing (AM) technologies has spread to many industries and applications. With laser melting machines it is possible to directly build metal parts that have the same physical properties as parts produced with conventional technologies. Nevertheless quality and repeatability are often cited as the 'Achilles Heel of Additive Manufacturing' [1] which impedes the usage of such technologies in applications where highest quality standards have to be met like aircraft or medicine industry. To introduce the technology in those applications the prevailing quality management methods have to be implemented throughout the whole process chain. CONCEPT Laser, a manufacturer of industrial laser melting machines, has set up a program to meet this growing demand from the machine side. It covers the five determining areas of the building process: the powder quality, the temperature, the process gas atmosphere, the melt pool itself and the documentation of process parameters. This publication deals with the new melt pool control module.

2. Process basics

LaserCUSING® is from its technical principle a micro welding process. At each layer metal powder is welded together placing one weld seam beside the other. Typically a cooled down weld seam has a width of approximately 150 µm (Fig. 1). The dimension and homogeneity of a weld seam is influenced by various variables during the melting process like heat conduction of the material, scanning speed, laser power, surface tension of the melt, grain size, ascending smoke, plasma formation etc.

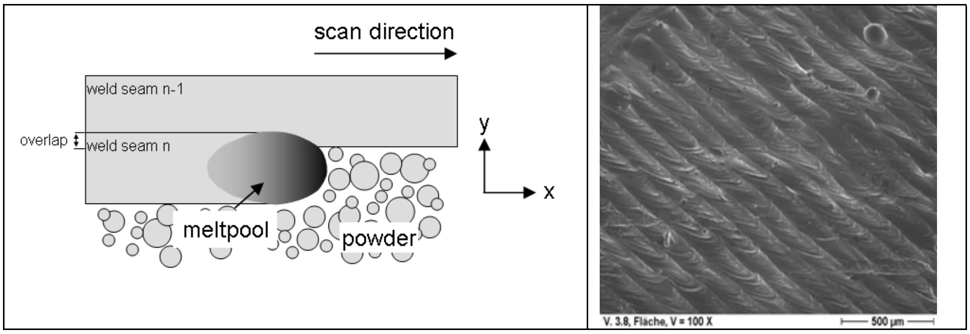


Fig. 1. Schematic drawing of weld seams and melt pool (left), top surface of a part after melting (right)

As the melt pool is glowing it is emitting light. The intensity of the emitted light is depending on the temperature of the melt and can be determined with the law of Planck. The emitted light can be detected by a camera whereas the different intensities, which correspond to a certain temperature, result in different gray values.

3. Necessary local and temporal resolution of a melt pool control

Because the melt pool moves with a scan speed up to 2500 mm/s, it is necessary to have a very high frame rate to ensure detailed observation of the molten area and to have the possibility to control the laser parameters in realtime. Since observation at infinite frequencies is impossible one decided to observe at least equidistant areas of 150 µm length which is roughly the weld seam width. The required frames per second *fps* can then be calculated as the quotient of the scan speed v_{scan} and the weld seam width w_{seam}:

$$fps = \frac{v_{scan}}{w_{seam}}$$

Eq. 1. Calculation of required frames per second

Assuming this weld seam width of 150µm, typically being used in laser melting machines, frame rates of 3333 fps at 500 mm/s, 6666 fps at 1000 mm/s, and 13333 fps at 2000 mm/s are needed for real-time control of the melting process. As one would use 2000x2000 pixels of a camera sensor to observe the whole building platform of 250x250mm² the resolution would be 125x125 µm per pixel. As the melt pool width is about 150 µm the whole melt pool would be described by only four to nine pixels. With that number of pixels the detection of melt pool characteristics like shape, length or width would be more than inaccurate (Fig. 2).

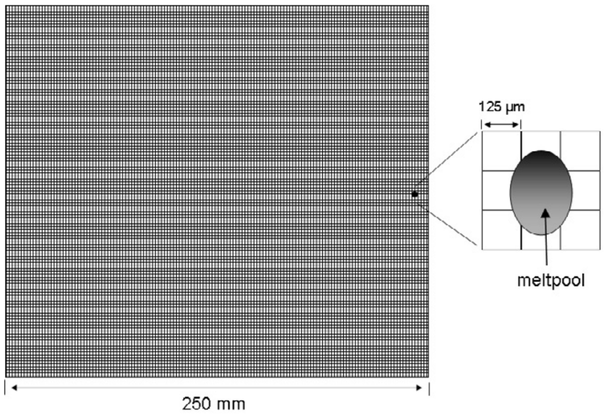


Fig. 2. Camera sensor monitoring the whole building platform

4. Data processing

Another problem of such a setup is the high amount of image data being produced. The amount of data per second is the product of the x-resolution res_x, the y-resolution res_y, the bit depth of the image *bd* and the framerate *fps*:

$$data / s = res_x \bullet res_y \bullet bd \bullet fps$$

Eq. 2. Calculation of image date per second

An 8 bit grayscale image with a resolution of 2200x2200 Pixels has a size of 4.62 MByte. At a frame rate of 16666 fps this leads to 75.1 GByte of image data every second. This would technically be impossible to transfer and to process. Decreasing the resolution or reducing the frame rate would make this setup even more inaccurate.

5. Inline process control

At the Katholieke Universiteit Leuven a very good solution for this problem has been developed by Kruth, Mercelis and Craeghs [2,3]. The idea is to look through the scan head to directly observe the zone of interaction of laser beam and powder bed (Fig. 3). The light that is emitted by the melt pool is hereby transmitted through the f-theta objective and the scanhead to the sensor unit. A semi-transparent mirror is used which reflects the laser wavelength and is transparent for the observation wavelength. This mirror transmits the picture of the melt pool to a high speed camera and a photodiode. The photodiode and the camera complement each other. The camera is used for measuring the dimensions of the melt pool at framerates of about 10 kHz. The photodiode measures the mean radiation that is emitted from the melt pool at even higher frequencies. This setup eliminates the necessity to simultaneously look at the whole build platform because the field of view is moving with the laser beam. The approach has been patented and is exclusively licensed by CONCEPT Laser. In Cooperation with Katholieke Universiteit Leuven it is developed further and brought to industrial application.

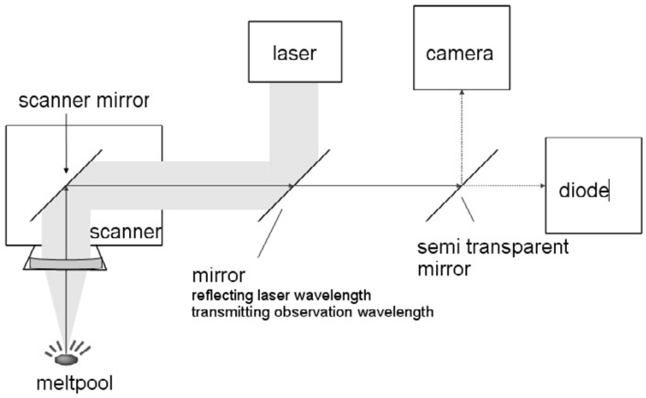


Fig. 3. Schematic assembly of in-line process control

Using this assembly it is possible to reduce the resolution of the camera significantly. Therewith a picture size of 200x200 Pixels is sufficient, which results in an image size of 39 KByte instead of 4.62 MByte. This decreases the image data that has to be processed to 636 MByte per second at 16666 fps and makes it therefore technically possible to handle. The resolution that can be reached with the proposed setup is about 10 µm per Pixel. This means that the melt pool width is represented by 15 Pixels and the melt pool area by more than 225 Pixels. In this case the resolution is only limited by the light emitted by the melt pool and by the spectral response of the camera.

6. Application

Fig. 4 shows two measurements of the photodiode voltage. The voltage at the y-axis represents the radiation that is emitted from the melt pool. The x-axis shows the number of samples that are taken, a multiplication of this number with the sample rate gives time. The measurements were taken during a building process of the same part at layer 50 and layer 150. Due to dirt on the f-theta lens the mean (red) decreases from layer 50 to layer 150 (green) from 0,60V to 0,52V. This deviation can be detected by the analyzing unit of the system, so that appropriate actions in the machine can be taken.

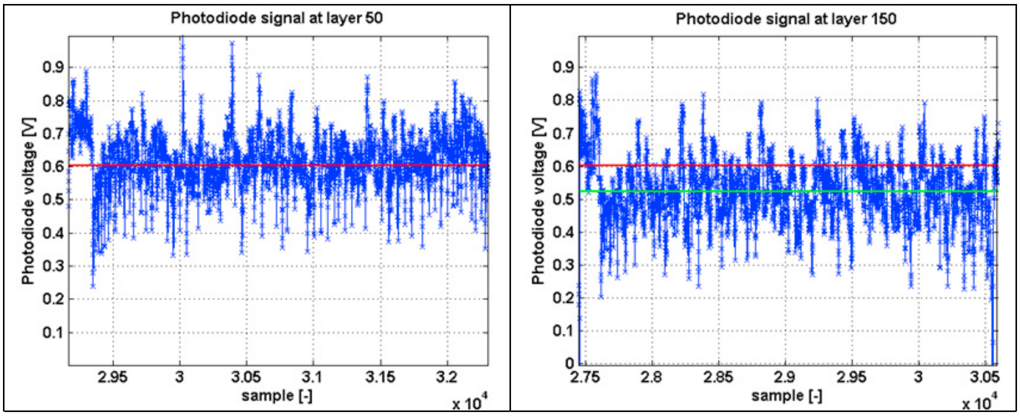


Fig. 4. Comparison of the mean of the photodiode signal at different building layers: layer 50 (left), layer 150 (right). The mean decreases because of dirt on the f-theta lens

In the second example the consequences of an error in the z-axis-adjustment of the building platform are demonstrated. The building platform stuck at layer 1600, so no powder could be provided to it any more. At layer 2000 the building platform moved 400 layers down in one step and was stuck again. This procedure was repeated five times. In the cycle during which the building platform moved 400 layers an unusual thick layer of powder was deposited on top of the part. As the heat conductivity of the powder is much lower than the heat conductivity of the molten material the temperature and dimensions of the melt pool rose. This resulted in more light emitted from the melt pool which leaded to a higher photodiode amplitude (Fig. 5).

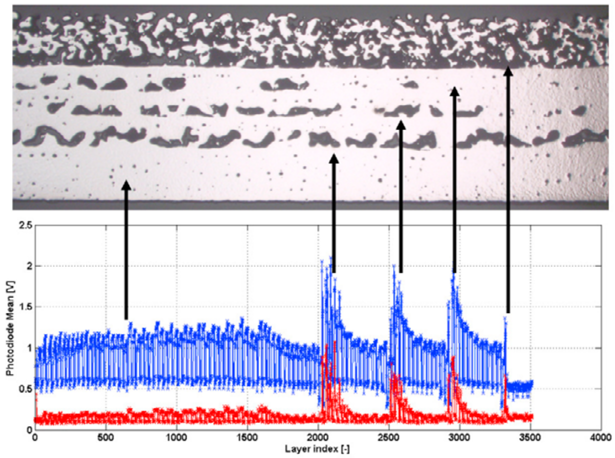
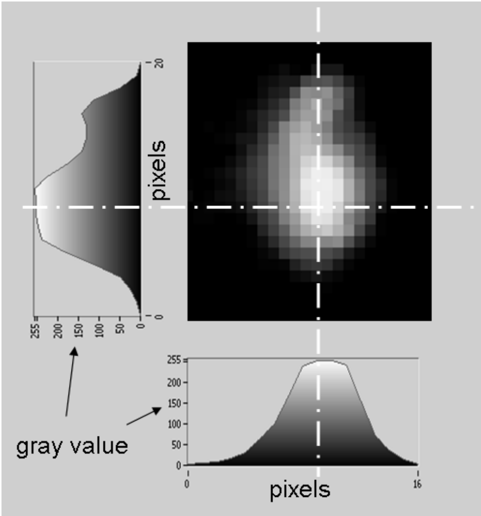


Fig. 5. Microsection and mean photodiode signal (blue) and standard deviation (red) of the part which was build with a building platform adjustment error

The examples show that for the detection of some - mostly simple - errors during a building process a photodiode sensor can be sufficient. However, for the full documentation and control of part quality the application of a camera with high temporal and local resolution of the melt pool is indispensable. Fig. 6 shows a melt pool image which was taken from a process with stainless steel powder on a M1cusing machine at 10 kHz and a resolution of 20x16 Pixel. Beside are the corresponding gray value profiles along the length and width of the melt pool.



Based on such images the characteristics of the melt pool can be analyzed very detailed. Currently algorithms and tools are under development which will allow to detect when the melting process tends to leave its default process window. Depending on the deviation pattern the machine control will either take countermeasures in realtime, or the operator has to take action after being informed. Otherwise the building process will be interrupted.

Beside those control tasks the sensor system is as well employed to document the building process for quality management purposes. Together with the sensor information from all other quality modules of the machine the melt pool system stores its process relevant parameters in a database for each building job. After the process has finished the user has the possibility to generate customized reports for his documentation requirements. In addition the database can be integrated in a production management system.

7. Conclusion

Inline process control offers decisive advantage compared to conventional camera systems, which monitor the whole building area. Only by assembling the camera and photodiode sensor directly in the optical path of the laser machine melt pool control with sufficiently high temporal and local resolution is attainable.

For the first time realtime documentation and control of the building process in laser-based Additive Manufacturing machines is possible in industrial environment. Thereby the quality of this production process is enhanced and its interaction with quality management systems is strongly improved.

References

[1] T. Wohler, *Wohlers Report 2009*

[2] P. Mercelis. *Control of Selective Laser Sintering and Selective Laser Melting Processes*. PhD thesis, K.U. Leuven, April 2007

[3] T. Craeghs, J. Kruth, *Online Monitoring and quality control of Selective Laser Melting using optical sensors*, Optimess, Antwerp, 2009